ROV Power Cable Ampacity in Areas with High Ambient Temperatures

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Abstract

Offshore operations, using Robotically Operated Vehicles (ROVs) in areas with high ambient temperatures require ampacity limitations to be established.
Specifically, the risk of overheating ROV umbilicals and tethers when running at high power, due to multiple layers on winch drums is a concern in areas like the Red Sea where the sea water at 1000m water depth is 27 DegC, compared to 5 DegC in other parts of the world.
When working in the shallow water of the Red Sea and Arabian Gulf water temperature can be above 32 Deg C.
Understanding the effects of reduced cooling will have on the ampacity of an ROV power supply system is therefore critical to understand with accuracy to avoid a system failure due to overheating.
The ROV electrical power systems has been analysed using the COMSOL Multiphysics AC/DC and Heat Transfer modules. The heat buildup and current distribution on the power conductors that operate at 3000V, 60 Hertz were simulated considering the electromagnetic effects in the frequency domain as a first study, followed by second study considering the heat transfer effect in the time domain; the results have been compared to the international standard IEC-60287.
Full scale validation testing to compare the simulated result with a real-time temperature measurement using Distribute Temperature Sensing was carried out and the results provided.

Keywords: ROV Electrical Power Systems, Umbilicals, Tethers, High Ambient Subsea Operations.

I. Introduction

ROVs utilize a Tether Management System (TMS) that is loaded with an Aramid reinforced cable known as a tether. The TMS is a winch that is lowered on the main lift umbilical. The tethers can be 300m – 1200m long and are used in a horizontal direction of travel, whereby the umbilical is 1000m to 3500m long and is normally used for the vertical deployment and recovery. Umbilicals are normally Steel wire armored and classed as lifting equipment.
It is common practice with some cable designers providing these systems to only consider Ampacity using DC calculations and the authors considered it important to compare both Direct Current (DC) and Alternating Current (AC) results to check if this assumption was correct on these types of systems.
The results have been compared to a manual calculation approach following international standard IEC-60287.

The system modelled consisted of two different winches, one fabricated in steel and located on the vessels deck for the 1600m umbilical , the other for the 650m tether was a winch in aluminum and normally submerged.
The normal range of phase current was considered with a maximum of 30 Amps and minimum of 17 Amps, in ROV jargon this equates to *'full stick'* and *'half stick'* on a typical 150 HP work-class ROV system.
The simulation included the cool-down rate for both the umbilical and tether when the tether management system (TMS) is recovered to deck at 0 Amps after a period of work subsea.
Based on the simulation results, ROV Ampacity limitations have been proposed for this type of Subsea work in similar ambient conditions.
The physics model used has been validated using a distributed temperature sensing (DTS) system, utilising an internal optical fiber running the length of the winched tether cable, during this test the temperature rise under a steady electrical load and cool down was monitored. The results demonstrated the accuracy of the COMSOL Multiphysics model and the parameters used.

The study validated the decision to reduce the length of the main lift umbilical by 50% to 1650m and to operate with a buoyant tether in the shallow water area, this was to ensure more tether cable could be deployed from the TMS to help reduce heat buildup.

II. literature Review

(M. L. Nuckols, 1988), proposed a computerized modeling approach that considered steady state and transient temperature distribution for an umbilical on a winch, allowing for cooling to the winch core and cheeks. This approach can be applied to both submerged and on-deck winches. The author modelled the problem, using a Fortran-based computer program, to obtain the steady state temperature distribution on the winch drum at prescribed operational conditions.
Furthermore, the simulation was complemented by using a transient model utilizing finite differences technique to arrive at a more accurate temperature prediction at the winch mid-line. The approach is very similar to the way COMSOL Multiphysics® heat transfer module works, in that the cable cross-section is broken down into elements with their own thermal conductivity values (k) applied. The approach did not model or mention the magnetic field effect on the conductor

resistance and inductance; neither did it distinguish between the A.C. or D.C. power situation. However, he provided graphs illustrating the heat loss per meter of cable in W/m derived from the I^2R relationship and proposed the expected change in heating based on the number of cable layers.

(IEC 60287, 2006), provided calculations for losses in A.C. and D.C. cabling. The formula for calculating the A.C. resistance based on the D.C. resistance, cable geometry and frequency, was helpful. Moreover, the heat loss formula results in units (W/m) could be compared with the results from the COMSOL Multiphysics® simulations. IEC 60287 does not explain the electromagnetic field effects of multiple layers of power cable on a winch. Instead, multiple cables in steel pipe are considered, and equations for calculating the skin and proximity effects are provided.

(Riba, 2015), provided useful insight into A.C. resistance on conductors compared to D.C. situations. It also explained certain aspects of the finite element modelling process going beyond the calculations provided in IEC 60287, potentially resulting in more accurate modeling of complex cable designs.

(N. Vedachalam, 2016) research presented ampacity derating for subsea cables on winches related to a 7000m main lift umbilical constructed with Aramid fiber reinforcing supplying a deep-sea mining trencher. The research described the heating mechanism caused by multiple wraps of cable conducting heat to adjacent layers, leading to a higher core temperature on the winch mid-line layers. In terms of an ROV application the overheating problem was directly applicable to the surface winch used for the umbilical, and partially, for the sub-surface TMS winch used for the tethers. An electromagnetic study was performed, and ampacity guidance was provided.

The RMS phase current (I_{RMS}) for the motor load is given by:

$$I_{RMS} = (Motor\ input\ (kW) * 1000)/(E * Pf * \sqrt{3})$$

E is 3000VAC,
Pf is power factor at 0.8.
I_{RMS} is 26.9A

The peak current (I_P) for the motor load is given by:

$$I_P = I_{RMS} * \sqrt{2}$$

I_P is 38.04A.

This I_P value was used as the coil current input by the COMSOL Multiphysics® software simulations.

Cable losses dissipated as heat are increased when carrying harmonic currents due to elevated I^2R losses. (American Bureau of Shipping, 2006).

In a distorted current waveform, the I_{RMS} is given by:

$$I_{RMS} = I_{FUND}\ \sqrt{1} + \left(\frac{I_{THD}}{100}\right)^2$$

I_{FUND} is 26.90 A
I_{THD} is 5%
I_{RMS} is 26.934A

Most offshore vessels equipped with ROV systems are diesel electrically powered and typically use large semi-conductor variable speed A.C. drives for the heavy consumers, like thrusters. Depending on the drive philosophy, significant harmonics can be present on the ship power supply. However, (DNV-GL, 2015), states that the distribution systems acceptance limits for voltage harmonic distortion shall not exceed 8%. In addition, no single order harmonic shall exceed 5%.

Our conclusion is that the additional heat from Harmonics, if a system is < 5% Total Harmonic Distortion (THD) could be ignored.

(Riba, 2015), explained that with the D.C. resistance the current density distribution within the power conductor is uniform. However, when dealing with the A.C. supply, the current density may no longer be uniform due to skin and proximity effects. At higher frequency and larger diameter conductors the density tends to be concentrated towards the periphery of the conductor. The A.C. resistance value is of paramount importance for calculations as it allows to estimate the current carrying capacity or ampacity and operating temperature. In addition, a problem like this requires a calculation of the eddy current effects.

Considering the tether cable:

(IEC 60287, 2006). 2.1.1 Given the conductor D.C. resistance at 20 ºC, the resistance at the maximum operating temperature is given by:

$$R' = Ro(1 + \alpha 20) * (\Theta - 20)$$

R_O is the D.C. resistance of the conductor at the reference temperature of 20 ºC (Ω/m), 2.4 Ω /Km
$\alpha 20$ is the constant mass temperature coefficient of copper at 20 ºC, 3.93e^{-3}
Θ is the maximum operating temperature of 90 ºC
R' is the D.C. resistance of a conductor at maximum operating temperature calculated above as 0.169 (Ω/m)

The permissible current rating of the DC cable in equation is given by:

$$Icont = \left(\frac{\Delta\Theta}{(R'T1 + 3R'T2 + 3R'(T3 + T4))}\right)^{0.5}$$

$T1$ is k the thermal conductivity of the conductor insulator at 0.25 W/(m·K)
$T2$ is k the thermal conductivity of the sheath at 0.18 W/(m·K)
$T3$ is k the thermal conductivity of the external jacket at 0.18 W/(m·K)
$T4$ is k the thermal conductivity of the Sea water at 0.6 W/(m·K)
$\Delta\Theta$ is the conductor temperature above reference ambient at 70 ºC
I_{CONT} is the continuous current rating of a D.C. cable with a given value of R', which in this case is giving a value of 11.52A

Considering the requirement to operate with 26.9A the calculated result with the (IEC 60287, 2006) approach is alarming. However, as the cable was submerged and operated at full load for a short period, additional analysis was clearly required.

The skin effect and proximity effects were calculated to be insignificant.

III. Modelling approach

The TMS winch was imported as 2D AutoCAD file and the dimensions were revolved to create a half drum model.

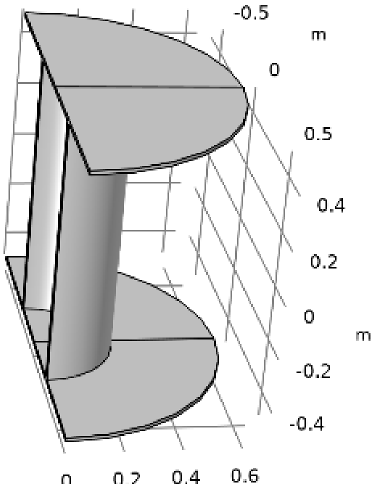

Figure 1. TMS winch model

The tether cable cross section was imported as an AutoCAD cable with an outer jacket, inner jacket, filler material and insulation around the conductors all according to the Manufacturers specification.

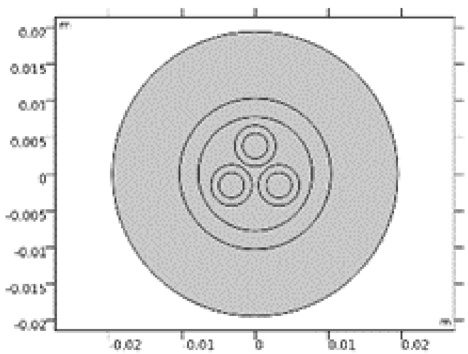

Figure 2. Tether model

An array of tether cross sections was then copied across the winch model to represent a full drum of cable with the correct number of wraps and layers.

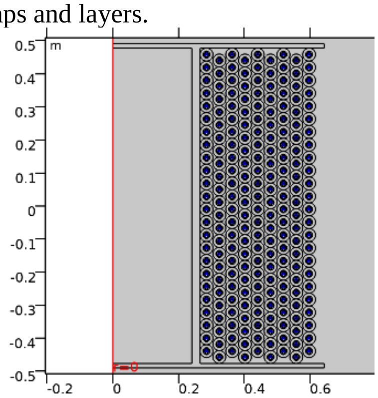

Figure 3. Multiple wraps and layers of Tether arrayed across the drum of the winch model.

A 3D boundary was established around the TMS model that would represent the winch being immersed in seawater or in air when back on deck.
The same approach was used for modelling the umbilical winch.
Two studies were carried out, Study 1. Was an Electro Magnetic analysis the Frequency domain.
This approach is solving the Maxell Ampere equations, Gauss Law and Faradays law.

$\nabla \cdot \mathbf{D} = \rho_v$	Gauss' law
$\nabla \cdot \mathbf{D} = 0$	Maxwell Gauss' law
$\nabla \cdot \mathbf{E} = 0 - \delta \mathbf{B} / \delta t - j\omega\ B$	Faraday's law
$\nabla \cdot \mathbf{H} = 0 + \mathbf{J} + \Delta\mathbf{D}/\delta t + j\omega\mathbf{D}$	Maxwell – Ampere's law

Within COMSOL AC/DC module these differential equations are represented and solved as:

$$\nabla \times \mathbf{H} = \mathbf{J}$$
$$\mathbf{E} = -j\omega\mathbf{A}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$
$$\mathbf{E} = -j\omega\mathbf{A}$$
$$\mathbf{J} = \sigma\mathbf{E} + j\omega\mathbf{D}$$
$$\mathbf{n} \times \mathbf{A} = 0$$

Figure 4. Electro Magnetic differential equations.

Study 2. Was a Heat transfer analysis in the time domain and involved allowing the system to heat up over a range of times to recognize when the conductor that was situated on the winch mid line would reach the limiting temperature of 85 Deg C. This was carried out with the boundary representing sea water around the immersed winch at 32 DegC and the in-air situation with an Ambient of 50 DegC.

Within COMSOL Heat Transfer module the following thermodynamic equations are solved:

$$\mathbf{q} = -k\nabla T$$
$$Q = Q_0$$
$$-\mathbf{n} \cdot \mathbf{q} = 0$$
$$- \cdot \left(-D_{P1}\nabla G\right) = -q_{r,net}$$
$$= \frac{\varepsilon}{2(2-\varepsilon)}\left(4\pi I_{b,w} - G\right)$$
$$\rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q + Q_{ted}$$

Figure 5. Heat Transfer equations.

IV. Simulation Results

As explained a range of currents were used in the analysis and 26.9A phase current was the main area of interest as it represented the normal full load situation.
Initially considering the tether immersed in Seawater we had the following results.

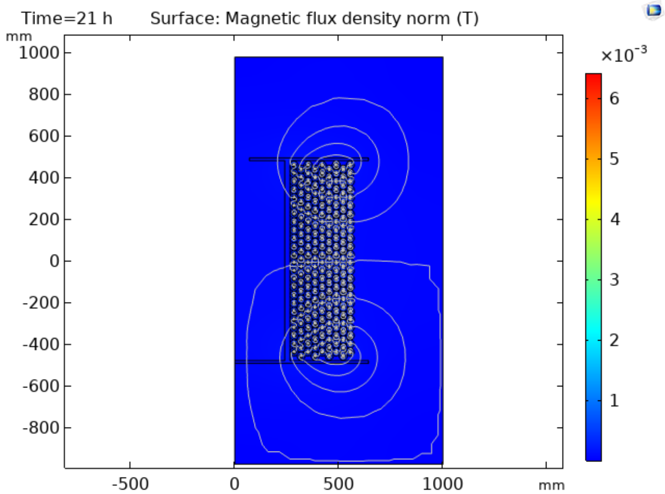

Figure 6. TMS winch flux density.

With the above figure we can see that the flux density of the winch as a coiled system is insignificant.
A separate study was carried out considering a DC situation and a similar result was achieved. This is logical as in both AC and DC cases the field around the coiled of tethers cancel each other out.

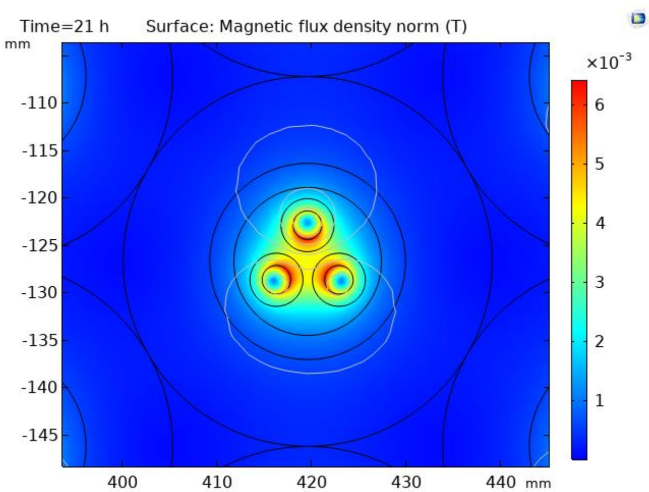

Figure 7. Tether cable flux density.

In the above figure there is a noticeable magnetic field opposing each conductor and this causes a distortion of the current density across the conductor, which logically results in increased impedance. This is the proximity effect and is causing an increase in heat loss.

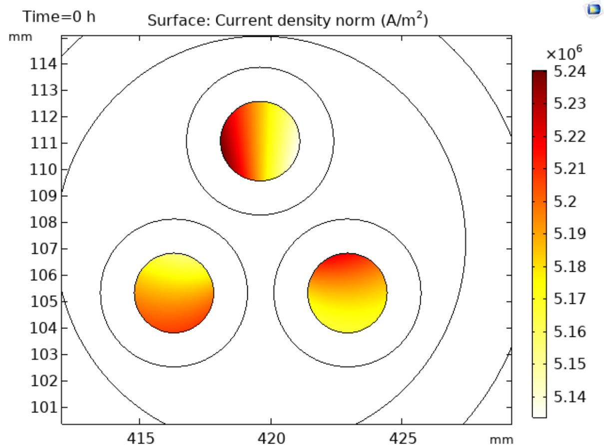

Figure 8. Current density at 26.9A.

The above figure is the current density at 26.9A.
The combined effect of an array of cable coiled on the winch is simulated with 8 hours at 26.9A. this resulted in the conductors at winch mid line reaching the maximum temperature well before the outer layers.

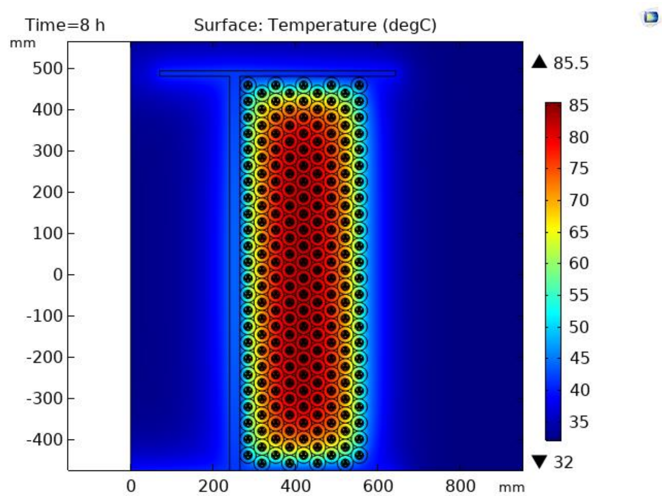

Figure 9. TMS winch after 8 hours at 26.9A.

The operational situation we wanted to understand with the aid of the simulation was that if we have to operate at 30A for how long we can sustain that load and thereafter, what Ampacity limitation do we need to apply to ensure the tether no longer accumulates heat, I.E the heat loss is equal to heat added.

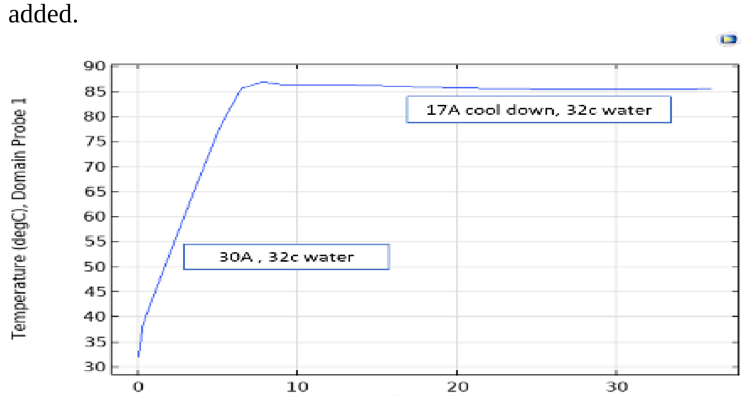

Figure 10. Temperature profile for a higher-risk conductor.

In the above example we have used a domain probe located at the winch line approx. half way along the cable as this is the area with the most intense heating effect as seen in figure 10. 17A is the load that we can maintain operations and can serve as a safe Ampacity in these ambient conditions.
The other option to reduce conductor heat quickly is to stop the system and leave it immersed at 0A for a while. The cable drops in temperature by about 2 DegC every hour.
It would be possible to run the ROV out which would result in a more rapid cooling effect, however this may not always be possible.

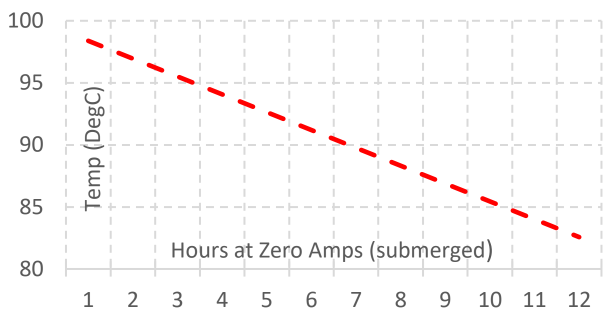

Figure 11. Cool down rate of TMS at 0A submerged 32 DegC.

Should a hot system be recovered to deck it should be a serious concern. The cool down time on deck is very slow and if an ROV team are not aware of the temperature situation on the inner layers they may dive early, and the risk of a conductor burn out is acute.
The main lift umbilical has been modelled, however, the winch is in air at 50 Deg C and it is important to point out that the cable is already cut in half to reduce heating effect. The normal situation with a full-length umbilical is a significantly higher risk. This risk is related to air temperature and not sea water temperature , therefore, it can occur in aa wider range of locations. Solar heating has not been considered as the winch is located inside a steel hanger. Many installations are on deck in direct sunlight and this should also be considered.
The use of real time temperature monitoring is uncommon on ROV systems, this means operators may be unaware of the heating going on in the inner layers of an umbilical winch.

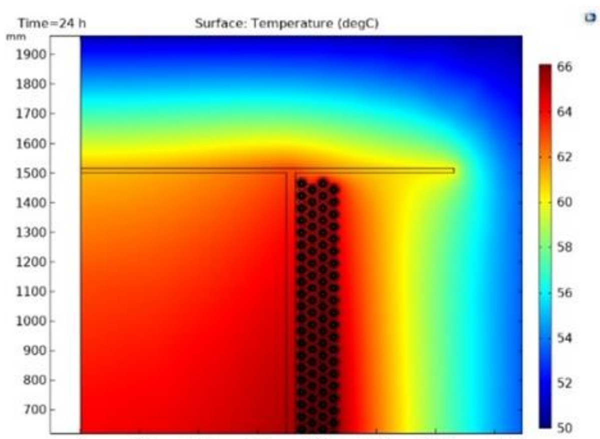

Figure 12. Umbilical winch surface temperature

In the above figure note the heat build up inside the drum, water cooling on the exposed cable and forced ventilation inside the drum would be beneficial.

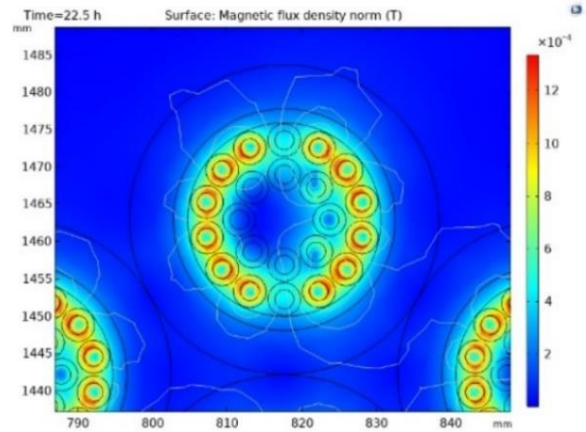

Figure 13. Umbilical flux density.

In the above figure. The magnetic flux density impact on the adjacent conductors has a maximum value of 12.5e^{-4} Tesla. While this is slightly contributing to the proximity effect the current density in the figure below is uniform across the cross section of the conductor, demonstrating that the effects can be ignored when a 60 Hertz supply with conductors of this diameter and similar electrical loading is in use.

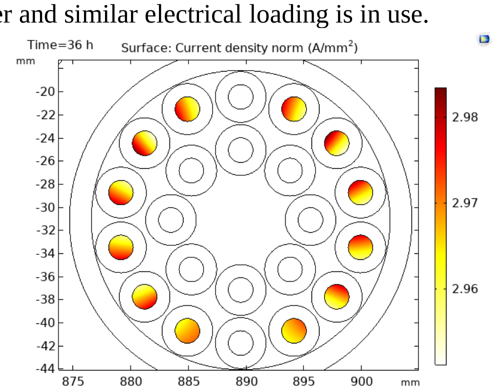

Figure 14. Umbilical current density.

V. Validation testing

The authors consulted with a leading cable design company who produce many of the tethers and umbilicals for the industry. They carried out a comparable analysis using their own tools. This independent study had a -4 hours delta in the time it would take to reach 85 Deg C. If we had followed their recommendations, we would have had to impose stricter ampacity limitations. The results of the COMSOL modelling are sensitive to errors, for example, using phase current in place of peak current on the coil's gives a significant error and we wanted to be sure of the results we were seeing in the simulations.
A test was set up onshore where we applied a steady 30A load using a Load bank directly connected to a tether coiled on a TMS. The voltage with 440V, 60 Hertz 3 phase supply.
From the governing equations it is understood that the electro magnetic effects are independent of voltage and is the phase current and frequency were matched the heating would be equivalent.

We used a LIOS Distributed Temperature Sensing (DTS) system to measure the temperature the full length of the tether cable while it was on the drum. This system uses an optical fiber adjacent to the conductors. The same system had been used offshore to detect overheating in real time as per Figure 16.

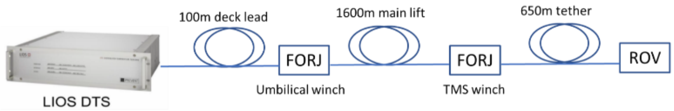

Figure 15. LIOS system as used offshore.

We ran a new simulation using the test tether cross section with the TMS drum in air at the local ambient conditions of 36 DegC.

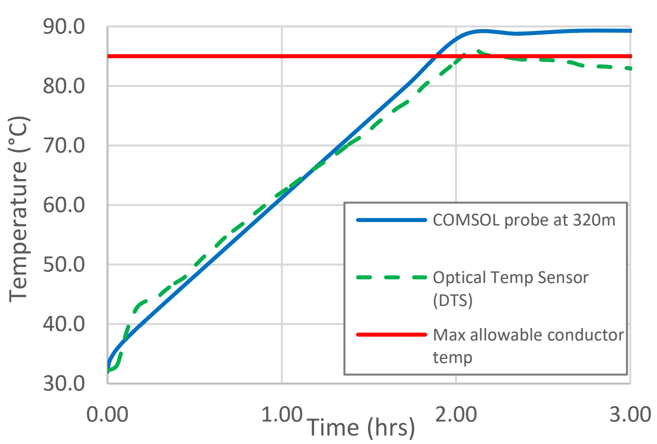

Figure 16. Validation test comparing COMSOL to DTS result.

The results of this test and simulation have been plotted on Figure 17. We can see clear correlation between the Optical DTS measurement and the results of the COMSOL simulation.

VI. Conclusions

From the analysis and subsequent validation testing we have improved confidence in the model results.

The risk of overheating damage to power conductor insulators is very high when operating in ambient high temperature conditions. This is applicable for air or sea water temperature.

One area of major concern for ROV operations in warm water is the risk of diving a system too soon after a previous dive and before the umbilical or tether cable has had enough time to cool down. The study shows the umbilicals and tethers will only drop at about 1-2 Deg C per hour without forced cooling. In this case a system could require to be on deck for 24 hours before it could be safely used again.

17A is approx. equal to half power and if an ROV maintains this level of power for the duration of the dive, then the risk of overheating is very low when operating with similar equipment and conditions.

DTS systems are not used today on ROV systems and the authors, therefore, recommend that when operating with continuous high power then a DTS would be wise investment.

The research we have carried out on the ROV systems described in this paper should be applicable to other deep-water robotic systems that require shipboard umbilical winches for deployment or the equivalent of a TMS located Subsea.

The authors intention is to continue the analysis work by testing a tether installed on a TMS, that is fully immersed in a tank of 32 DegC water and with a variable power load bank attached to the ROV end of the tether. In addition, the same test will be carried out onboard ship with the load bank replacing the TMS and the heat build up in the umbilical winch monitored in both direct sunlight and at night.

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VIII. Acknowledgements

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