POWER DELIVERY AND UMBILICAL CABLE OPTIMISATION FOR LONG OFFSET TIEBACKS

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Abstract
In this paper we present a study into the physical and practical limitations of different power transmission techniques for long offset tiebacks. The results from the study present a definitive operating envelope for varying offset tiebacks and subsea power demands. The study is supported by in-depth performance analyses covering a range of power transmission techniques and umbilical cable designs. We also include the economic considerations when evaluating the different power delivery and umbilical cable selections.
1 Introduction

Over the past 10 years there have been a number of examples of subsea field developments where the tieback distance has been defined as 'long offset', typically with the flow-line and umbilical lengths being over 70km and up to 150km.

To date, the electrical power transmission techniques and umbilical designs have simply been 'extensions' of the technology used for more conventional 'short offset' developments. There is a trend for ever increasing offset distances and higher power demands from subsea consumers, typically subsea processing equipment. The higher power levels and increasing offsets means that there is now more focus on power delivery capacities as well as the installed umbilical costs.

Extensive work has been undertaken to re-evaluate the physical and practical limitations of different power transmission techniques and to assess the impact of different umbilical designs on these limitations.

This study supported by in-depth performance analyses covering a range of power transmission techniques, umbilical cable designs has resulted in a family of definitive operating envelopes. Economic evaluations of the different solutions considered Operational Expenditure (OPEX), Capital Expenditure (CAPEX) and installation costs to ensure that full technical and commercial comparisons could be made for a wide range of field development scenarios.

2 Subsea Electrical Distribution Architectures

Within the Subsea Oil and Gas Production Control System (PCS) sector, a variety of system electrical distribution architectures are used, ranging from the simple ‘bus-bar’ Electrical Distribution Unit (EDU) based systems, to transformer based EDUs and the more complex systems incorporating to 1.2kV for the power transmission across the main umbilical. There are of course a few exceptions to this that include three phase at up to 3kV.

3 Electrical Models

As part of the study a number of electrical models and simulation methods were developed to help determine the operating parameters of the various system voltages, loads and cable types.

3.1 System Model

The electrical systems are simulated applying the two port network technique using the ABCD parameter method. A general block diagram representation of a two port network is shown below.
Using this method, the relationship between an electrical systems supply and load parameters is given by:

\[
\begin{bmatrix}
V_{sup} \\
I_{sup}
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
V_{load} \\
I_{load}
\end{bmatrix}
\]

Where the \( A B C D \) matrix parameters are defined as:

\[
A = \frac{V_{sup}}{I_{load}}_{I_{load}=0} \\
B = \frac{V_{sup}}{I_{load}}_{I_{load}=0} \\
C = \frac{I_{sup}}{V_{load}}_{I_{load}=0} \\
D = \frac{I_{sup}}{I_{load}}_{I_{load}=0}
\]

In the case of the power transmission systems analysed as part of the study, the \( A B C D \) matrix represents the transmission line (i.e. umbilical/electrical cable). The \( A B C D \) parameters are calculated by the methodology described below.

### 3.2 Transmission Line Distributed Element Model

It is well known that the line constants of a transmission line (resistance \( R \), capacitance \( C \) and inductance \( L \)) are uniformly distributed over entire length of the line. Due to the significant lengths of transmission lines, electrical models were created based on the distributed element transmission line model.

Fig. 2 below shows the equivalent circuit of a transmission line whose length is divided into \( n \) sections (in this case \( n = 3 \)). As is apparent, the line constants are uniformly distributed across the length of the line.

The \( A B C D \) parameters for a single section of the transmission line model (as shown in Fig. 3) can be mathematically calculated by:

\[
\begin{bmatrix}
A_n & B_n \\
C_n & D_n
\end{bmatrix} =
\begin{bmatrix}
1 & \frac{(R_u + j\omega L_u)}{2n} \\
0 & \frac{1}{j\omega C_u n} \\
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
1 & \frac{(R_u + j\omega L_u)}{2n} \\
0 & \frac{1}{j\omega C_u n} \\
\end{bmatrix}
\]
Where

\[ \begin{align*}
R_u &= \text{Resistance/Unit Length} \\
L_u &= \text{Inductance/Unit Length} \\
C_u &= \text{Capacitance/Unit Length} \\
I &= \text{Total Transmission Line Length} \\
n &= \text{Number of Stages}
\end{align*} \]

![Diagram of Transmission Line – Single Section](image)

The complete transmission line can be derived by simply cascading the \( n \) elements together, thus given by:

\[
\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} A_n & B_n \\ C_n & D_n \end{bmatrix}^n
\]

### 3.3 Three Phase Systems

For the purposes of this study, a simplified single phase equivalent model for three phase systems was used for the analysis process as shown in Fig. 4. This methodology not only provides results that allow a fair comparison between the different technology types, but also simplified the simulation models required.

![Diagram of General Three Phase Wye-Wye Circuit](image)

For a general three phase system, the supply voltages are defined by:

\[
\begin{align*}
V_{a'n} &= V \angle 0 \\
V_{b'n} &= V \angle 120 \\
V_{b'n} &= V \angle 240
\end{align*}
\]

With ideal source impedance (i.e. \( z_{\text{source}} = \infty \)), it can be shown that the sum of the loop currents is:
\[ i_a + i_b + i_c - i_n = \frac{v_{a'n} - v_n}{z_{l_a} + z_a} + \frac{v_{b'n} - v_n}{z_{l_b} + z_b} + \frac{v_{c'n} - v_n}{z_{l_c} + z_c} - \frac{v_n}{z_{ln}} = 0 \]

For a balanced system, the following definitions apply:

\[
\begin{align*}
    z_{l_a} &= z_{l_b} = z_{l_c} \equiv z_l & \text{Equal transmission line impedance in each phase} \\
    z_a &= z_b = z_c \equiv z & \text{Equal load impedance in each phase (i.e. balanced load)} \\
    v_n &= 0 & \text{Voltage at the neutral point is zero}
\end{align*}
\]

Therefore, zero current flows in the neutral wire (\( v_n = 0 \)) and the equation for the sum of the loop currents can be reduced to:

\[
\frac{v_{a'n}}{z_l + z} + \frac{v_{b'n}}{z_l + z} + \frac{v_{c'n}}{z_l + z} = 0
\]

It can be seen that the voltages and currents associated with each phase are equal in amplitude and frequency, but are out of phase. Thus, an equivalent single phase circuit can be constructed for the A-phase, as shown in Fig. 5 below. Once the associated parameters (line current, load voltage & power factor) have been calculated, the values for B and C phase can be determined as they will have the same amplitude and frequency but will be out of phase.

4 System Modelling

In terms of important operating characteristics the following were recorded where system operation was found to be technically possible (i.e. the system is able to support the desired load):

Load Voltage, Supply Power, Line Current, Power Factor and Efficiency

4.1 Supply Voltage

The following system operating voltages have been identified for analysis in this study:

- 1kV
- 10kV
- 25kV
- 3kV
- 15kV
- 33kV
To ensure that the study provides a fair comparison and encompasses as many applicable technologies as possible, for each supply voltage analysis would be undertaken on the following system configurations:

- DC Monopole (2 Wire)
- AC 50Hz Three Phase (3 Wire)
- AC 50Hz Single Phase (2 Wire)
- AC 16.7Hz Three Phase (3 Wire)
- AC 16.7Hz Single Phase (2 Wire)

4.2 Offset Tieback Distances

Analysis was performed with simulated system tieback distances of:

- 50km
- 100km
- 150km
- 175km
- 200km
- 250km
- 300km
- 400km
- 500km
- 550km
- 600km

4.3 System Loading

A range of system loading parameters were applied to each of the identified system supply voltages. An area of interest in this study set as a base case is a small well cluster with a 175km subsea to beach tieback. As such, particular consideration is given to the estimated power levels required to operate a system of this configuration. Table 1 details the estimated power requirements of this field development, both for the electrohydraulic and all-electric case.

In addition to the specific power levels identified, additional analysis was undertaken over a variety of loads, as detailed in Table 2 below, to allow a comprehensive evaluation of the different technology types.

Table 1. Base Case 175km Tieback Power Requirements

<table>
<thead>
<tr>
<th></th>
<th>Quantity</th>
<th>Electrohydraulic</th>
<th>All-Electric</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xmas Tree (Idle)</td>
<td>5</td>
<td>0.3kW</td>
<td>1.5kW</td>
</tr>
<tr>
<td>Xmas Tree (Valve Operation)</td>
<td>1</td>
<td>0.3kW</td>
<td>0.3kW</td>
</tr>
<tr>
<td>Subsea Router Module</td>
<td>2</td>
<td>0.1kW</td>
<td>0.2kW</td>
</tr>
<tr>
<td>Scale Inhibitor Pump</td>
<td>1</td>
<td>N/A</td>
<td>10kW</td>
</tr>
<tr>
<td>Wax Inhibitor Pump</td>
<td>1</td>
<td>N/A</td>
<td>10kW</td>
</tr>
<tr>
<td><strong>Sub Total</strong></td>
<td></td>
<td><strong>2kW</strong></td>
<td><strong>35kW</strong></td>
</tr>
<tr>
<td>Resident ROV (Periodic)</td>
<td>1</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>2kW</strong></td>
<td><strong>85kW</strong></td>
</tr>
</tbody>
</table>
Table 2. System Load Parameters

<table>
<thead>
<tr>
<th>System Loads</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1kW</td>
<td>Small Non-Redundant Electrohydraulic System</td>
</tr>
<tr>
<td>2kW</td>
<td>Small Redundant Electrohydraulic System</td>
</tr>
<tr>
<td>10kW</td>
<td>Large Electrohydraulic System</td>
</tr>
<tr>
<td>35kW</td>
<td>Small All-Electric System</td>
</tr>
<tr>
<td>50kW</td>
<td></td>
</tr>
<tr>
<td>100kW</td>
<td>Small All-Electric System + ROV</td>
</tr>
<tr>
<td>200kW</td>
<td></td>
</tr>
</tbody>
</table>

4.4 Umbilical Cable / Electrical Cable Types

A range of cables with different Cross Sectional Area (CSA) has been examined as part of this study. The specific CSA selected are as follows:

- 16mm$^2$
- 25mm$^2$
- 35mm$^2$
- 50mm$^2$
- 70mm$^2$
- 95mm$^2$

It is known that cables of this size are generally larger than those installed on traditional production control systems, which typically have a CSA within the range of 6mm$^2$ to 16mm$^2$ (or occasionally 25mm$^2$), depending upon the specific system requirements. The reasons for the choice of cable CSA larger than those usually utilised are:

1. The lengths examined are significantly longer than those involved in conventional systems. The power delivery capability of smaller CSA cables at lower voltages (1kV and 3kV) at these lengths is generally below the requirements of the loads identified previously (as per Table 2);
2. The smaller CSA cables are unlikely to be capable of supporting the larger loads associated with all-electric systems;
3. Medium Voltage (6kV to 33kV) cables are not generally available with CSA less than 16mm$^2$.

4.5 Transmission Line Parameters

The following values for the transmission distributed resistance ($R_0$), capacitance ($C_0$) and inductance ($L_0$) per kilometre (km) were used in the system electrical analysis models.
### 4.5.1 Distributed Resistance

The distributed resistance value used in the electrical analysis can be calculated by the following formula:

\[ R_u = \frac{38}{CSA \ km} \]

Where \( CSA = \) Cable Cross Section Area (mm\(^2\))

The approximation for distributed resistance is widely known and can be derived as follows.

Resistance (\( R \)) of a wire of a given material with a resistivity (\( \rho \)) and cross sectional area (\( A \)) is given by:

\[ R = \frac{\rho L}{A} \]

Where  
- \( \rho = \) Resistivity Coefficient (Ω⋅m) \( = 17 \times 10^{-9} \) for Copper @ 20°C
- \( L = \) Length (m) \( = 1 \times 10^{-3} \)
- \( A = \) Area (m\(^2\))

For copper conductor @ 20°C, \( \rho = 17 \times 10^{-9} \).

\[ R = (17 \times 10^{-9} \cdot 1 \times 10^{-3})/A \]

Where the CSA is in mm\(^2\) (=1\( \times \)10\(^{-6}\) m\(^2\)), the resistance per km is:

\[ R_u = 17/CSA \ \Omega \ \text{at} \ 20^\circ\text{C} \]

Under normal operation it is likely that the cable will be operating at a temperature somewhere between that of the ambient surroundings (~4°C) and the operating maximum (90°C), dependent upon the exact operating and loading conditions. For the purposes of this study a worst case conductor operating temperature of 50°C has been assumed. The resistivity of copper increases with temperature and can be calculated using the associated temperature coefficient (\( \alpha \)) of 4.0 \( \times \) 10\(^{-3}\)/K as follows:

\[ R = \frac{\rho L}{A} + \left[ \alpha (50 - 20) \cdot \left( \frac{\rho L}{A} \right) \right] \]

\[ R_u = \frac{17}{CSA} \cdot (1 + 30 \cdot \alpha) \]

\[ R_u = \frac{19}{CSA} \ \Omega \ \text{per km @ 50°C} \]

The total loop resistance, accounting for the supply and return paths is therefore:

\[ R_u = \frac{38}{CSA} \ \Omega/km \]
4.5.2 Distributed Capacitance

It is known that the distributed capacitance associated with electrical cabling is heavily dependent upon the specific construction of the cable, specifically the insulation type, conductor separation and screening methodology. Thus it is not possible to derive a simple, theoretical relationship between the distributed cable capacitance and CSA in a similar method to that demonstrated for the distributed resistance.

Conversely, it is essential when modelling the AC electrical systems to ensure the capacitance values employed are as accurate as possible as the capacitance has a significant impact on system operation, specifically regarding the associated cable charging current, power factor and system efficiency.

It can be observed that, in general, for a given CSA, an increase in voltage rating results in a reduction in the value of distributed capacitance, primarily due to the increased thickness of the insulation and associate increase in conductor and conductor/screen separation. It can also be observed that, for a given voltage rating an increase in the cable CSA results in an increase in the value of distributed capacitance, due the relative reduction in conductor and conductor/screen separation.

In order to ensure that the analysis results reflect real world operating parameters as closely as possible, the following relationship between cable CSA, voltage rating and distributed capacitance was derived by plotting typical capacitance values gathered from various manufacturers data sheets against the ratio of Voltage Rating to CSA.

Fig. 6 shows this relationship for medium voltage Cross Linked Polyethylene (XPLE) cable, which can be approximated by the formula;

\[ C_{u, mv} = 2.7697 \times 10^{-6} \left( \frac{V}{CSA} \right)^{-0.4504} F/km \]  

Medium Voltage XPLE Cable

This was found to be correct to within 15% of the values specified on manufacturer’s datasheets for medium voltage cable, for both three core and single core cable. It did not, however, provide accurate results when applied to lower voltage cabling of the type used in conventional electrohydraulic umbilicals. This is due to the significant differences in the construction of the two different cable types.
Therefore a second relationship applicable to low voltage cable was derived, as shown in Fig. 7 below. This can be approximated by the formula:

$$C_{sv,lv} = 1.3419 \times 10^{-7} \left( \frac{V}{CSA} \right)^{-0.1672} \text{ F/km}$$

Low Voltage Quad

This approximation was found to be accurate to within 10% for both Screened Twisted Quad (STQ) and Unscreened Twisted Quad (UTQ) cable.
Table 3 details the absolute capacitance values applied to each of the cable types on which analysis was performed.

Table 3. Cable Capacitance (Line to Neutral) per km

<table>
<thead>
<tr>
<th>Voltage CSA</th>
<th>1kV</th>
<th>3kV</th>
<th>10kV</th>
<th>15kV</th>
<th>25kV</th>
<th>33kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 mm²</td>
<td>67.21</td>
<td>55.93</td>
<td>152.49</td>
<td>127.04</td>
<td>100.93</td>
<td>89.07</td>
</tr>
<tr>
<td>25 mm²</td>
<td>72.42</td>
<td>60.27</td>
<td>186.44</td>
<td>155.32</td>
<td>123.40</td>
<td>108.89</td>
</tr>
<tr>
<td>35 mm²</td>
<td>76.61</td>
<td>63.75</td>
<td>216.94</td>
<td>180.73</td>
<td>143.59</td>
<td>126.71</td>
</tr>
<tr>
<td>50 mm²</td>
<td>81.32</td>
<td>67.67</td>
<td>254.74</td>
<td>212.23</td>
<td>168.61</td>
<td>148.79</td>
</tr>
<tr>
<td>70 mm²</td>
<td>86.02</td>
<td>71.59</td>
<td>296.43</td>
<td>246.95</td>
<td>196.20</td>
<td>173.14</td>
</tr>
<tr>
<td>95 mm²</td>
<td>90.53</td>
<td>75.34</td>
<td>340.13</td>
<td>283.36</td>
<td>225.13</td>
<td>198.67</td>
</tr>
</tbody>
</table>

4.5.3 Distributed Inductance and Conductance

Within submarine cables, the distributed resistance and capacitance are known to be the dominant elements in assessing system performance (in contrast to overhead lines where the line resistance and inductance dominate). Therefore in order to simplify the complexity of the simulation exercise, a fixed value for the distributed inductance of \( L_u = 0.6 \, \text{mH/km} \) was selected based on available information.

The scope does not include investigation into the effects of insulation resistance on system performance, therefore a distributed conductance value of \( G_u = 0.0 \, \text{S/km} \) was used through the analysis, representing perfect insulation between conductors.

4.6 Operating Limits

Power transmission systems operating at the theoretical maximum power will exhibit a 50% voltage drop across the transmission line and an operational efficiency of 50%. For practical systems it is often undesirable or not possible to operate under these conditions. Consequently, upon completion of the electrical analysis the optimum operating voltage and cable CSA has been selected for each load and offset, based on the following criteria:

- **Voltage Drop** - Any system where the voltage drop over the length of the main umbilical is greater than 30% of the supply voltage (line to line) shall be deemed unsuitable for use.

- **Cable Current Rating** - Any system where the line current is greater than 80% of the cable’s maximum operating current.
• **Efficiency or Power Factor** - No operating limits are imposed on the efficiency or power factor of the electrical systems evaluated, as these parameters are not deemed critical in subsea applications.

4.7 Assumptions
The following assumptions are used through the electrical analysis study:

1. The load is purely resistive ∴ Power Factor (PF) at the load = 1;
2. For three phase systems, the load is balanced (i.e. equal loading on each of the three phases);
3. The system has an ideal voltage source, i.e. the source impedance = 0;

The supply voltage is rated between conductors i.e. line to line. In the case of three phase systems, the phase voltage (line to neutral) is \( \frac{1}{\sqrt{3}} \) lower.

5 Results
Simulations were carried out on over two thousand different systems with the supply configurations, cable characteristics, offset distances and consumer loads as defined previously. All system modelling and simulation were undertaken using MathCAD v15.

Further work was then carried out to correlate all results to allow a set of performance curves for each of the aforementioned technology types to be produced. These curves, shown in Fig. 8 to Fig. 12 on the following pages, clearly show how the maximum power delivery capability of a system varies as a result of the selected supply voltage and cable CSA.

The percentage values shown in the graphs below are the efficiency values for the load configurations marked on the graphs. It should be noted that these values represent the efficiencies when operating at the maximum load capacity. For a DC system a reduction in the load for a given offset and cable CSA will increase the system efficiency, however for AC systems where the cable charging capacitance dominates it is likely that a reduction in the load will reduce the system efficiency, as the total losses will remain approximately constant.

Note: As per the previous results tables, for AC systems two efficiency figures are included. The first takes into consideration the supply power factor, calculated by \( \frac{P_{\text{out}}}{V_{\text{Ain}}} \times 100 \). Those figures in brackets are calculated by \( \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 \) and are simply the power transfer efficiency.
Fig. 8. Maximum Power Capability v Offset – DC
Fig. 9. Maximum Power Capability v Offset – 50Hz Single Phase

Fig. 9. Maximum Power Capability v Offset – 16.7 Hz Single Phase
Fig. 10. Maximum Power Capability v Offset – 16.7Hz Single Phase

Fig. 11. Maximum Power Capability v Offset – 50Hz Three Phase
5.1 Discussion of Results

It is apparent from the results that, as expected, the optimum supply characteristics for any given system are dependent upon the specific characteristics of the transmission cable/umbilical and the power levels required at the load. However, the relationship between these parameters does not necessarily fit within the normal assumptions and rules that would generally be thought to apply, such as:

1. An increase in system voltage will result in an increase in the offset capability;
2. An increase in the cable CSA will result in an increase in the offset capability;
3. An increase in system voltage will result in an increase in the system efficiency;
4. An increase in the cable CSA will result in an increase in the system efficiency;
5. Three phase power transmission is more efficient than single phase.

With regards to DC systems the first four assumptions are found to hold true at all times, as DC transmission is not impacted by the transmission line reactive components, in particular the high values of distributed capacitance associated with submarine cables. Therefore for DC systems the following general approximations can be applied:

- A doubling of the supply voltage will result in a fourfold increase in the power available at the load;
- A doubling of the cable CSA will result in a two fold increase of the power available at the load;
- A doubling of the offset will result in a 50% reduction in the power available at the load.

It is also the case that in all the systems analysed as part of the study, the transmission efficiencies associated with DC are greater than those found for the equivalent AC system.

In distinct contrast to this, it is clear from examination of the previous plots (Fig. 8 to Fig. 12) the relationship between supply voltage, cable CSA and power delivery capability is far more complex for AC systems. This is particularly true as the supply voltage or offset distances are increased. The primary reason for this is related to the cable charging current, an effect which is known to be especially dominant in submarine cables due to the inherently high levels of capacitance. This is one of the key factors behind the choice of HVDC technology for use in submarine links within the power distribution industry.

Upon closer inspection of the detailed AC system analysis results, it is observed that the power delivery capability and maximum operating distance of lower voltage systems is generally limited by the voltage drop over the line, however as the operating voltage is increased the associated charging current becomes the absolute limiting factor as it tends to exceed the current carrying capacity of the cable. A consequence of this charging current is that increasing the line voltage can result in reduced offset capability. In addition, higher voltage systems exhibit a sharp decrease in the power capability over a certain distance and in some cases a reduction in the maximum achievable offset when the cable CSA is increased. While this appears counterintuitive this can be explained by further examination of the charging current phenomenon.

Fig. 13. No Load Cable Charging Current – 10kV 50Hz AC Single Phase
Figure 13 shows the charging current and associated maximum cable current carrying capacity versus cable length for an unloaded 10kV, 50Hz single phase AC system comprising of 16mm², 50mm² and 95mm² cables with characteristics as defined previously. These specific parameters have been selected in order to investigate the apparent peculiarity that a system utilising 50mm² cable has greater capacity above 160km than an equivalent system based on 95mm² cable, as shown on Fig. 9 however the theory is applicable to all AC systems.

Within the parameters of the study, it is observed that the rate of increase in charging current v cable length is greater for larger cross sectional area cables, a result of the increased levels of distributed capacitance associated with larger CSA cables.

It is also clear that the linear relationship between cable charging current, line voltage and cable length \( (I_c = j\omega C_d V l) \) is only accurate for lengths of cable that can be considered relatively short in the context of this study. Beyond the limits of the approximation, the magnitude of charging current no longer increases in a linear fashion, instead rising to a maximum value beyond which an increase in cable length has minimal impact on the level of charging current.

The consequence in systems where the magnitude of the charging current increases beyond the maximum current rating of the cable is that, at approximately the distance at which the charging current and cable current rating intersect, the power delivery capacity of the system will fall sharply to zero. In the case of a 10kV, 50Hz single phase AC system on 95mm² cable, as shown in Fig. 13, this occurs at around 165km. This correlates with the abrupt decrease in system capacity as shown in Fig. 9 above this offset.

In contrast, systems where the maximum charging current reaches the plateau prior to exceeding the cable current carrying capacity will be limited by the voltage drop across the line. This is the case for the 10kV, 50Hz single phase AC system on 50mm² cable and is reflected in Fig. 9 by an increase in the offset capability over that of the equivalent system based on 95mm² cable.

In contrast, in none of the DC systems simulated did the supply current exceed the maximum current carrying capacity of the cable, and in each case an increase in the line voltage or cable CSA resulted in an increase in power delivery capability for a given offset.

It is also noted that even in situations where the magnitude of the charging current does not exceed the maximum cable current rating, the charging current itself may be the dominant contributor to voltage drop and subsequently have a direct impact on the power delivery capability. A direct consequence of these effects is that, an increase in either the line voltage or cable CSA may result in a lower absolute maximum offset capability, or power delivery capability for a given offset.

The effect of the charging current not only severely limits the maximum offset or power delivery capability of higher voltage systems, but also has a significant impact on the overall system efficiency.
Figure 14 provides a comparison of the transmission efficiencies \( (P_{out}/VA_{in}) \) associated with DC and AC technologies for a fixed load (50kW) and cable type (50mm² CSA). It is apparent that DC delivers a significant advantage over AC systems, particularly when operating over the offset distances and high capacitance cables simulated as part of the analysis exercise. A further result of the inherent charging current characteristics is that system efficiency tends to decrease with the application of higher line voltages or an increase in cable CSA. Implementation of optimised power factor correction could potentially improve AC system efficiency, however the levels obtainable are likely to remain far lower than that of the equivalent DC system.

A further observation is that three phase transmission systems, while potentially allowing greater offset distances, are no more efficient than single phase equivalent in terms of power transmission alone. However three phase technology may provide the following advantages over single phase when taking into consideration other system components:

- Three phase motors and generators are more efficient than single phase;
- Three phase equipment is approximately 75% the size of single phase equipment with the same power rating.

It is apparent that power transmission systems capable of operating over 175km and 600km offsets are feasible for both electrohydraulic and all-electric systems. In all cases DC provides the optimum solution with regards to the minimum cable CSA required and in addition, can offer significant efficiency savings over the AC alternative.
For the traditional electrohydraulic systems, both 16.7Hz and 50Hz technologies utilised in either single phase or three phase configuration also provide potential solutions up to 600km, although variations in the cable types needed to deliver the levels of power required and significant differences in the associated system efficiencies are noted. However, it is observed that for distances approaching 600km all AC technologies, with the exception of 16.7Hz three phase, appear to be approaching the absolute limit of operation and would require considered design.

In regards to the all-electric solution, where higher power levels are required compared to electrohydraulic, it is clear that the offset limitations associated with AC power transmission technologies are far shorter than those associated with electrohydraulic systems. Three phase 16.7Hz systems offer a potential solution up to 600km, albeit with significant increases in system voltage and cable CSA required when compared to the DC equivalent. In addition, there is a substantial reduction in efficiency when compared to the equivalent DC system. The operational limit of both 16.7Hz single phase and 50Hz three phase systems appears around the 400km distance, while single phase 50Hz may only be considered suitable up to approximately 200km.

### 5.2 Technology Limitations

The results have provided the ability to show an indication of the limitations of electrical power transmission technologies over a range of system offsets and loads investigated as part of this study. Graphically this can be seen in Fig. 15. It should be noted that these limitations are intended to act as a guide only.

It can be seen that DC, theoretically, offers the largest coverage of power versus offset, and would probably be the preferred choice for a long offset tie-back system. The results don’t address the increased complexity associated with converter stations required to replace the well proven and simple AC transformer.

### 6 Commercial Impact

As part of the study the economic costs for the selected power delivery solution were investigated. This section provides an overview on the comparison of the total costs (CAPEX + OPEX) for electrohydraulic and all-electric production control systems at both offset tie-back distances of a 175km and 600km. It is not the intention in this paper to focus on how the detailed calculations were obtained.
For each of the feasible system configuration options identified as part of the earlier electrical analyses, the estimates include the expense associated with the up-front umbilical/cable purchase, the cost of hydraulic fluid required for the initial fill of the hydraulic system, the fluid replenishment costs resultant of the inherent system leakage and valve operation, and the electrical power generation costs. Any cost differentials associated with the following areas have not been taken into consideration; PCS equipment, variances between trees, chemical injection equipment and installation costs.

Fig. 16 and Fig. 17 show the total costs (CAPEX + OPEX) associated with 175km and 600km offset tie-back systems, with an operating lifetime of 30 years. It is apparent from the results of the economic evaluation that within the boundaries of the study, all-electric systems can achieve considerable savings over their traditional electrohydraulic counterparts. The level of savings is wide ranging, from 30% to 60% for a 175km system and 15% to 60% for a 600km tie-back system, depending upon the selected solution. These percentages translate to lifetime savings of up to $55 million for a 175km offset system and in the case of a 600km offset well cluster, potential savings of $180 million.

The major source of these savings is the reduced capital expenditure, resulting from the comparatively low cost of medium voltage submarine cable when compared to the traditional electrohydraulic umbilical.
The CAPEX savings associated with all-electric systems based on AC power distribution technologies are offset to an extent, by the increased operational expenditure required to provide the increased levels of power to the system. This is a direct result of the significant losses associated with poor power factor and cable charging current, itself a direct result of the higher voltages required to transmit the increased levels of power required by all-electric systems.

![Fig. 16. Total Cost for 30 Year Operating Life – 175km Offset](image)
Conversely, as a consequence of the inherent characteristics of a DC systems (i.e. no reactive losses due to line inductance or capacitance), the operational expenditure for all-electric systems utilising DC power is broadly in line with the electrohydraulic DC equivalent, and lower than the more traditional, AC based electrohydraulic systems, thus resulting in significant CAPEX and long term OPEX savings.

7 Conclusions

The subsea oil and gas industry faces a unique challenge in the transmission of relatively low levels of power over ever increasing distances in the submarine environment. Of course the optimum supply characteristics for any given system are dependent upon the specific characteristics of the transmission cable/umbilical and the power levels required at the load.

The results of the electrical analysis and economic evaluation indicate that the all-electric solution could provide not only the most technically proficient solution but also the most cost effective in satisfying the requirement for longer tie-backs and higher power demands. It can also be concluded that there are appropriate power transmission technologies depending on the tie-back offsets and required loads. In all cases, the total costs associated with an all-electric system operating over a 175km tie-back are lower than the traditional electrohydraulic equivalent. The same is true in the case of a 600km offset cluster, however at this tie-back distance further benefit can be achieved by the selection of DC over AC.

Fig. 17. Total Cost for 30 Year Operating Life – 600km Offset

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