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.

1 Introduction

Over the past 20 or more 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.

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 and umbilical cable designs has resulted in a family of definitive operating envelopes.

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 Subsea Router Module (SRM) technology to enable communications distribution and active power monitoring and switching.

In spite of the variety of system architectures, the majority of these systems utilise single phase AC, 50/60Hz or DC at voltages up 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.

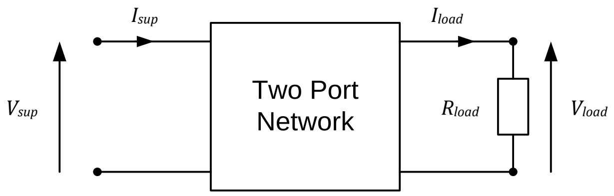

Fig. 1. General Two Port Network

Using this method, the relationship between an electrical system's 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:

$$A = \frac{V_{sup}}{V_{load}}\bigg|_{I_{load}=0} \qquad B = \frac{V_{sup}}{I_{load}}\bigg|_{V_{load}=0} \qquad C = \frac{I_{sup}}{V_{load}}\bigg|_{I_{load}=0} \qquad D = \frac{I_{sup}}{I_{load}}\bigg|_{V_{load}=0}$$

In the case of the power transmission systems analysed as part of the study, the $ABCD$ matrix represents the transmission line (i.e., umbilical/electrical cable). The $ABCD$ 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.

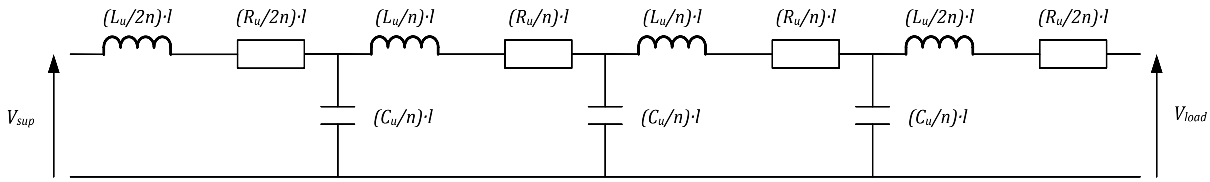

Fig. 2. General Distributed Element Transmission Line Model

The $ABCD$ parameters for a single section of the transmission line model (as shown in Fig. 3) can be mathematically calculated by:

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

where

R_u	= Resistance/Unit Length	l	= Total Transmission Line Length
L_u	= Inductance/Unit Length	n	= Number of Stages
C_u	= Capacitance/Unit Length		

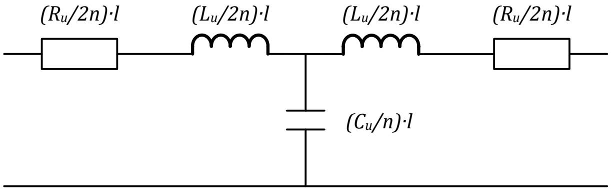

Fig. 3. Transmission Line – Single Section

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.

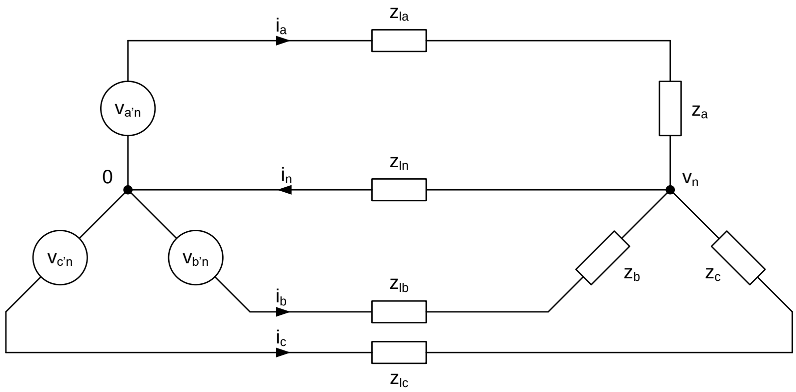

Fig. 4. General Three Phase Wye-Wye Circuit

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

$$v_{a'n} = V\angle 0 \qquad v_{b'n} = V\angle 120 \qquad v_{c'n} = V\angle 240$$

With ideal source impedance (i.e., $z_{source} = 0$), it can be shown that the sum of the loop currents is:

$$i_a + i_b + i_c - i_n = \frac{v_{a'n} - v_n}{z_{la} + z_a} + \frac{v_{b'n} - v_n}{z_{lb} + z_b} + \frac{v_{c'n} - v_n}{z_{lc} + z_c} - \frac{v_n}{z_{ln}} = 0$$

For a balanced system, the following definitions apply:

$z_{la} = z_{lb} = z_{lc} \equiv z_l$	Equal transmission line impedance in each phase
$z_a = z_b = z_c \equiv z$	Equal load impedance in each phase (i.e., balanced load)
$v_n = 0$	Voltage at the neutral point is zero

Therefore, zero current flows in the neutral wire $\left(\frac{v_n}{z_{ln}} = 0\right)$ 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.

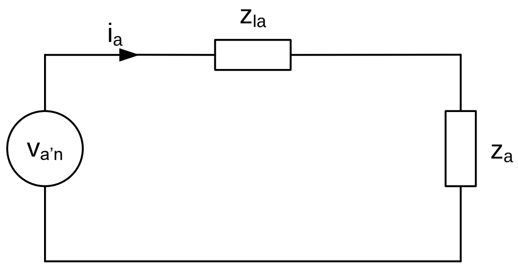

Fig. 5. Single Phase Equivalent Circuit

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 were used for analysis in this study:

- 1kV
- 3kV
- 10kV
- 15kV
- 25kV
- 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 Single Phase (2 Wire)
- AC 16.7Hz Single Phase (2 Wire)
- AC 50Hz Three Phase (3 Wire)
- AC 16.7Hz Three Phase (3 Wire)

4.2 Offset Tieback Distances

Analysis was performed with simulated system tieback distances of:

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

4.3 System Loading

A range of system loading parameters were applied to each of the identified system supply voltages.
Analysis was undertaken over a variety of loads, as detailed in Table 1 below, to allow a comprehensive evaluation of the different technology types.

Table 1. System Load Parameters

System Loads	Description
1kW	Small Non-Redundant Electrohydraulic System
2kW	Small Redundant Electrohydraulic System
10kW	Large Electrohydraulic System
35kW	Small All-Electric System
50kW	
100kW	Large All-Electric System
200kW	

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) and at these lengths is generally below the requirements of the loads identified previously (as per Table 1);
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_u), capacitance (C_u) and inductance (L_u) 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:

$R_u = {}^{38}/_{CSA} \frac{\Omega}{km}$ 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 (ρ) and cross sectional area (A) is given by:

$$R = {}^{\rho L}/_{A}$$

where	ρ = Resistivity Coefficient (Ω·m)	= 17 x 10^{-9}	for Copper @ 20°C
	L = Length (m)	= 1 x 10^{-3}	
	A = Area (m^2)		

Note: L has been converted from m to km.

For copper conductor @ 20°C, ρ = 17 x 10^{-9}.

$$\therefore \quad R = (17x10^{-9} \cdot 1x10^{-3})/A$$

where the CSA is in mm^2 (=1x10^{-6} m^2), the resistance per km is:

$R_u = 17/CSA\ \Omega$ @ 20°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 (α) of 4.0 x 10^{-3}/K as follows:

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

$$R_u = {}^{17}/_{CSA} \cdot (1 + 30 \cdot \alpha)$$

$R_u = {}^{19}/_{CSA}\ \Omega$ per km @ 50°C

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

$R_u = {}^{38}/_{CSA}$ Ω/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 associated 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 to 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;

$$C_{u\_mv} = 2.7697 \times 10^{-6} \left(\frac{V}{CSA}\right)^{-0.4504} \; F/km \qquad \text{Medium Voltage XPLE Cable}$$

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.

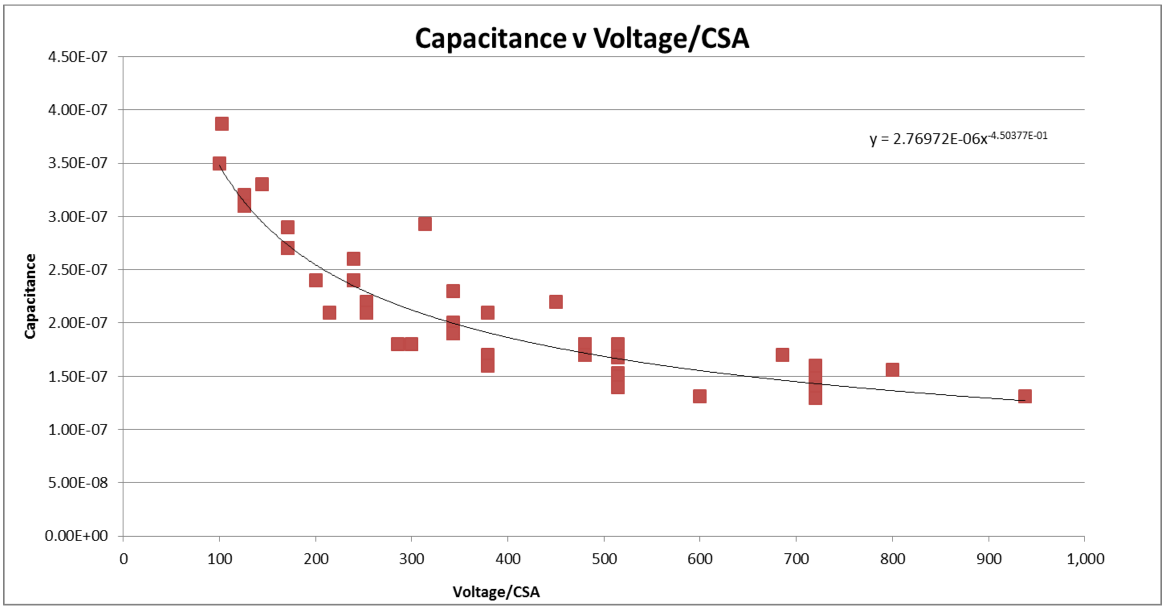

Fig. 6. Medium Voltage Cable - Voltage Rating/CSA v Capacitance

Therefore a second relationship applicable to low voltage cable was derived, as shown in Fig. 7 below. This can be approximated by the formula:

$$C_{u\_lv} = 1.3419 \times 10^{-7} \left(\frac{V}{CSA}\right)^{-0.1672} F/km \qquad \text{Low Voltage Quad}$$

This approximation was found to be accurate to within 10% for both Screened Twisted Quad (STQ) and Unscreened Twisted Quad (UTQ) cable.

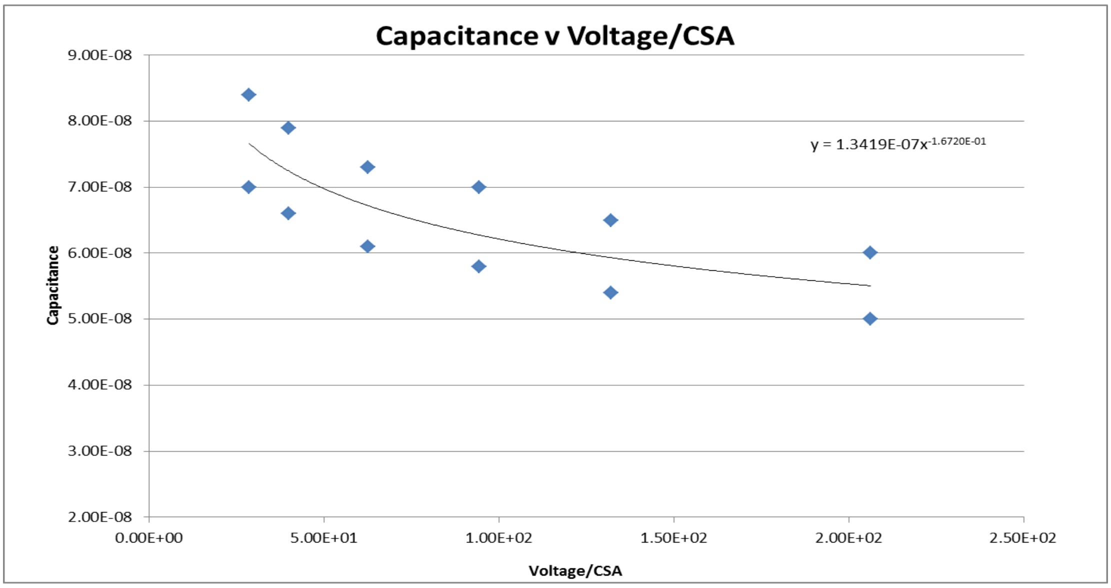

Fig. 7. Low Voltage Cable - Voltage Rating/CSA v Capacitance

Table 2 details the absolute capacitance values applied to each of the cable types on which analysis was performed.

Table 2. Cable Capacitance (Line to Neutral) per km

Cable Line to Neutral Capacitance (nF) per km						
Voltage / **CSA**	1kV	3kV	10kV	15kV	25kV	33kV
16 mm2	67.21	55.93	152.49	127.04	100.93	89.07
25 mm2	72.42	60.27	186.44	155.32	123.40	108.89
35 mm2	76.61	63.75	216.94	180.73	143.59	126.71
50 mm2	81.32	67.67	254.74	212.23	168.61	148.79
70 mm2	86.02	71.59	296.43	246.95	196.20	173.14
95 mm2	90.53	75.34	340.13	283.36	225.13	198.67

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 $L_u = 0.6\ mH/km$ 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 $G_u = 0.0\ S/km$ 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 $\therefore$ 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.

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 $\frac{P_{out}}{VA_{in}} \times 100$. Those figures in brackets are calculated by $\frac{P_{out}}{P_{in}} \times 100$ and are simply the power transfer efficiency.

In each graph, there are coloured bands with an operating voltage shown. These indicate approximately the preferred operating envelope for each. It should be noted that the envelopes do overlap.

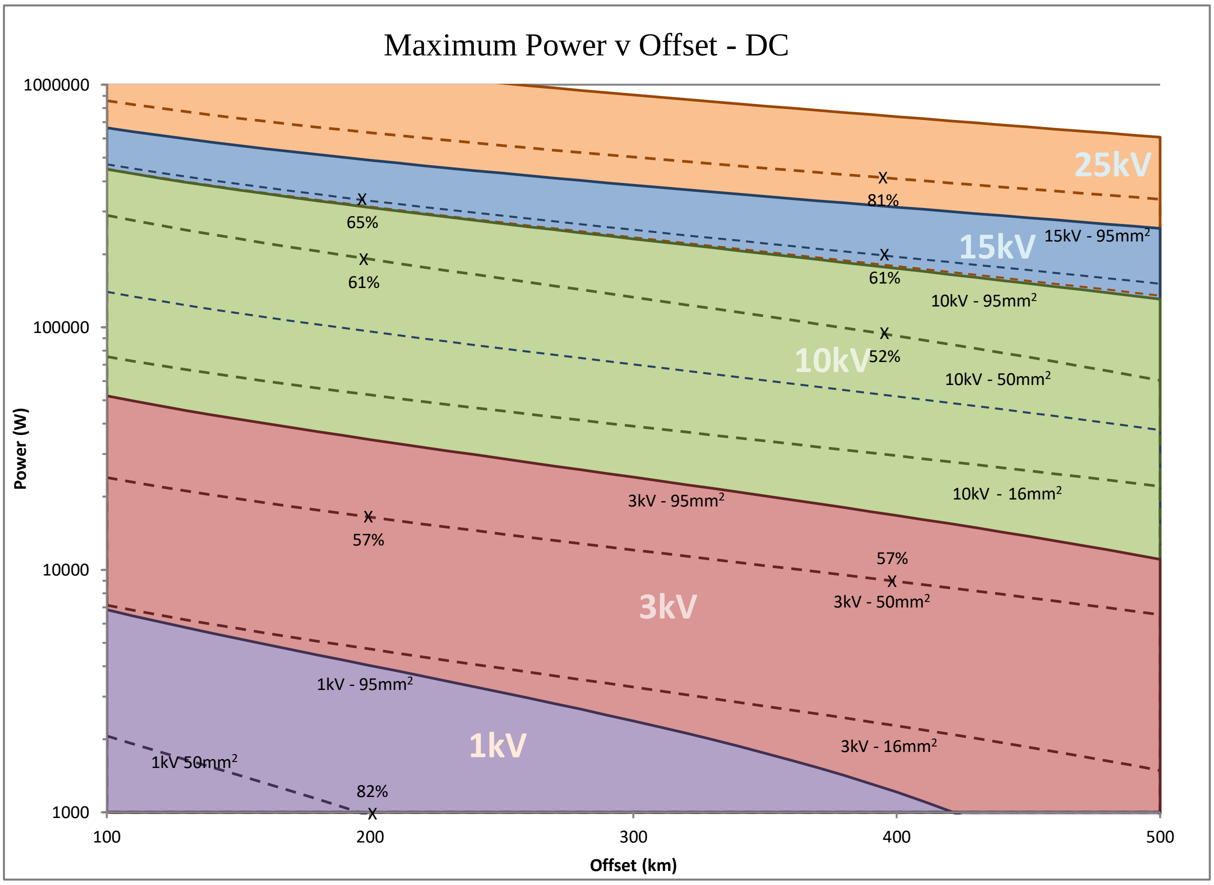

Fig. 8. Maximum Power Capability v Offset – DC

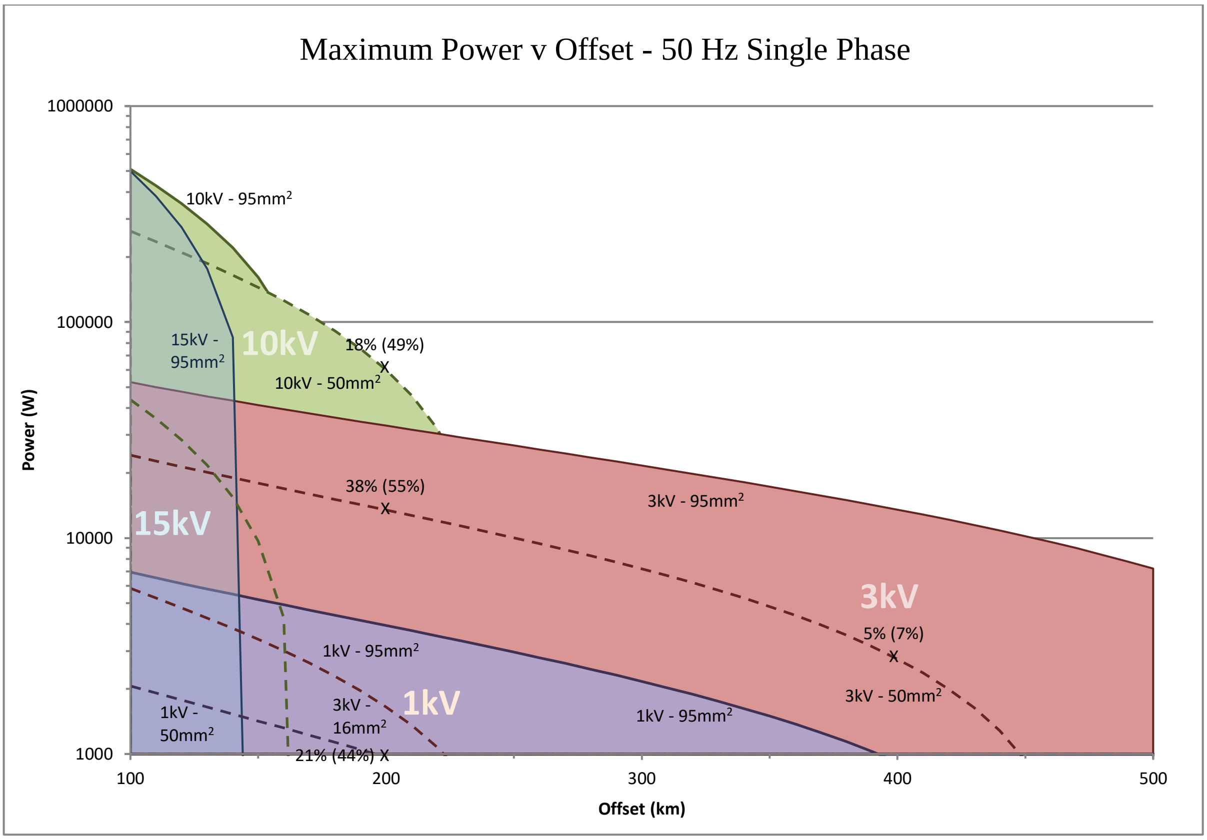

Fig. 9. Maximum Power Capability v Offset – 50Hz Single Phase

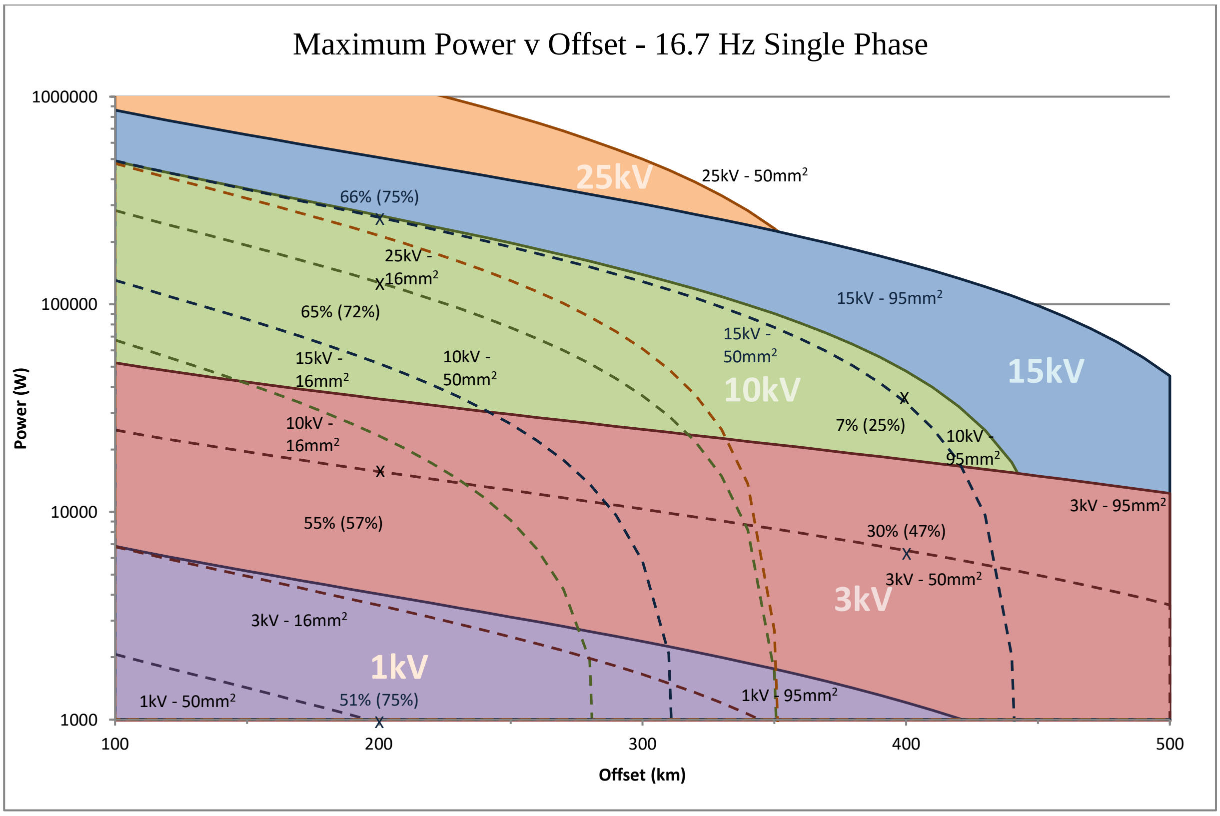

Fig. 10. Maximum Power Capability v Offset – 16.7Hz Single Phase

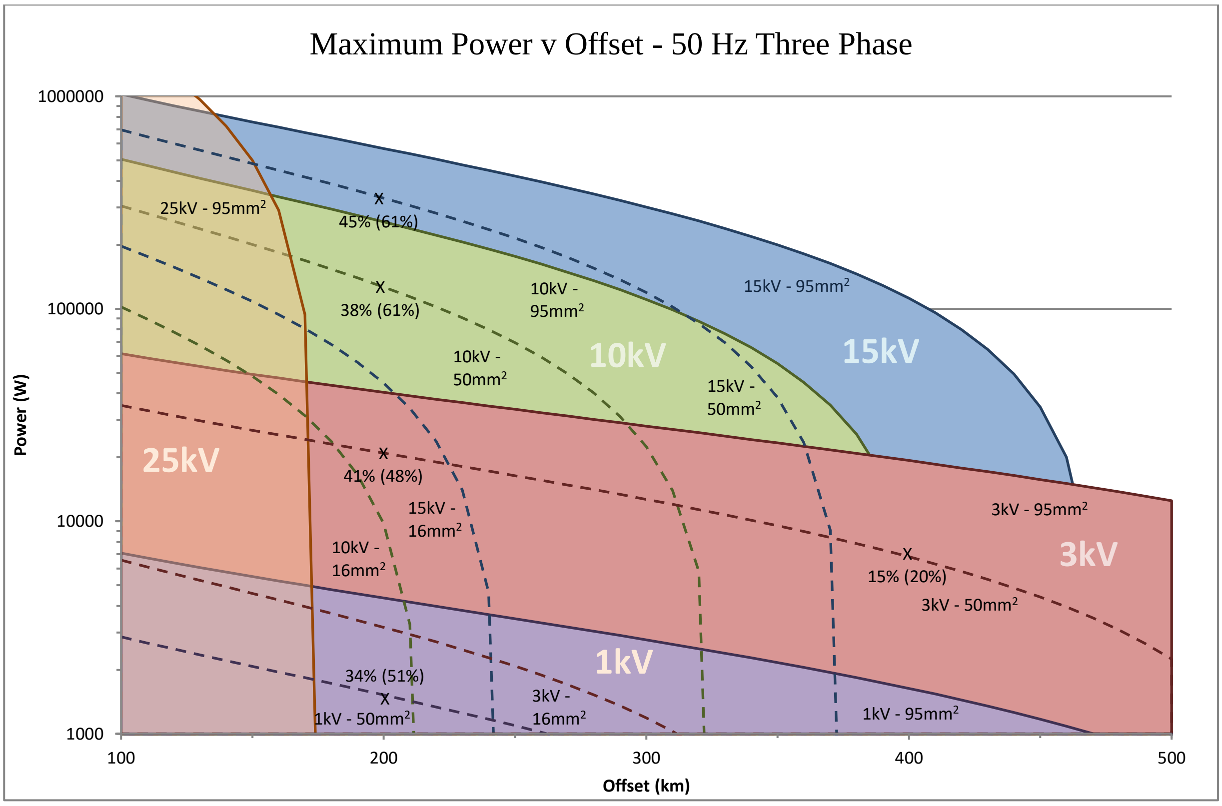

Fig. 11. Maximum Power Capability v Offset – 50Hz Three Phase

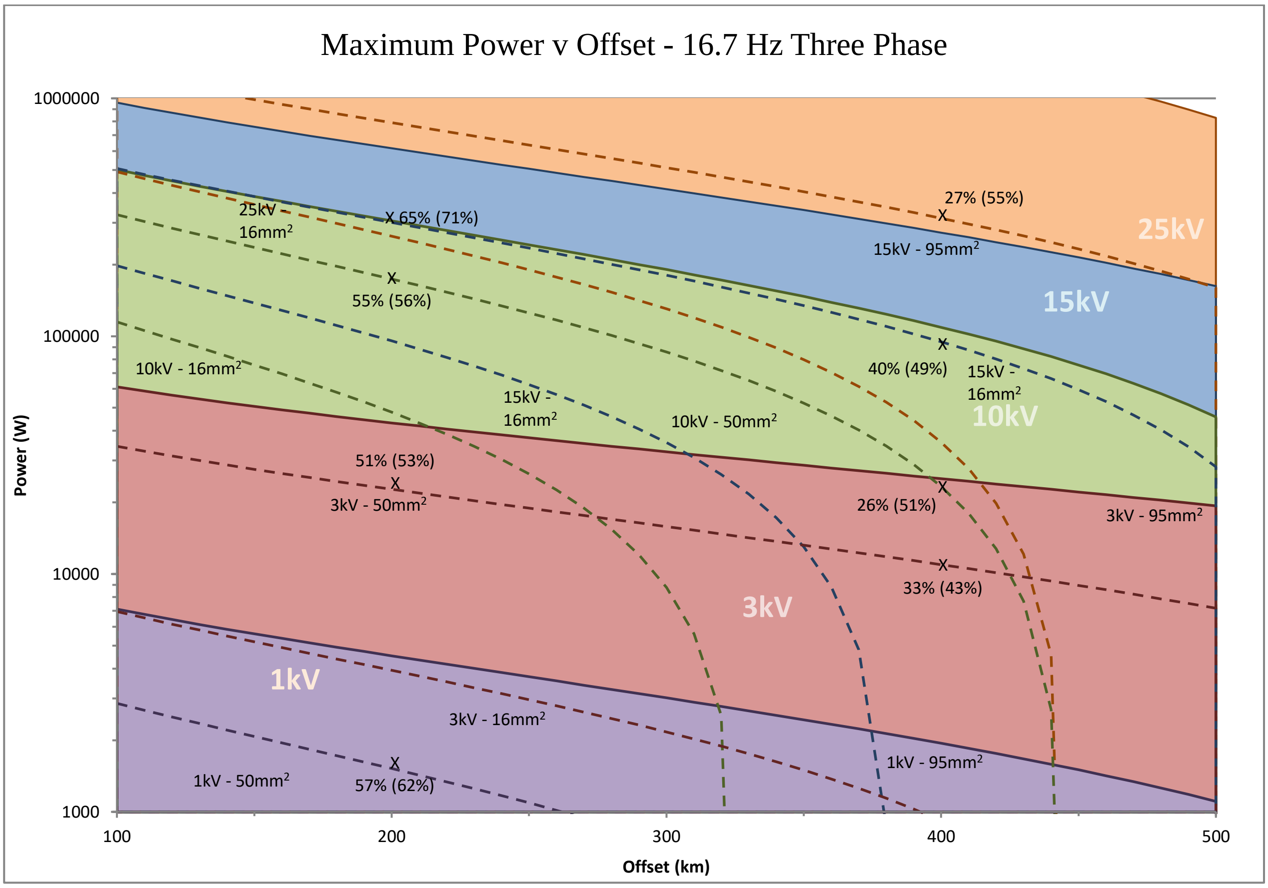

Fig. 12. Maximum Power Capability v Offset – 16.7Hz Three Phase

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

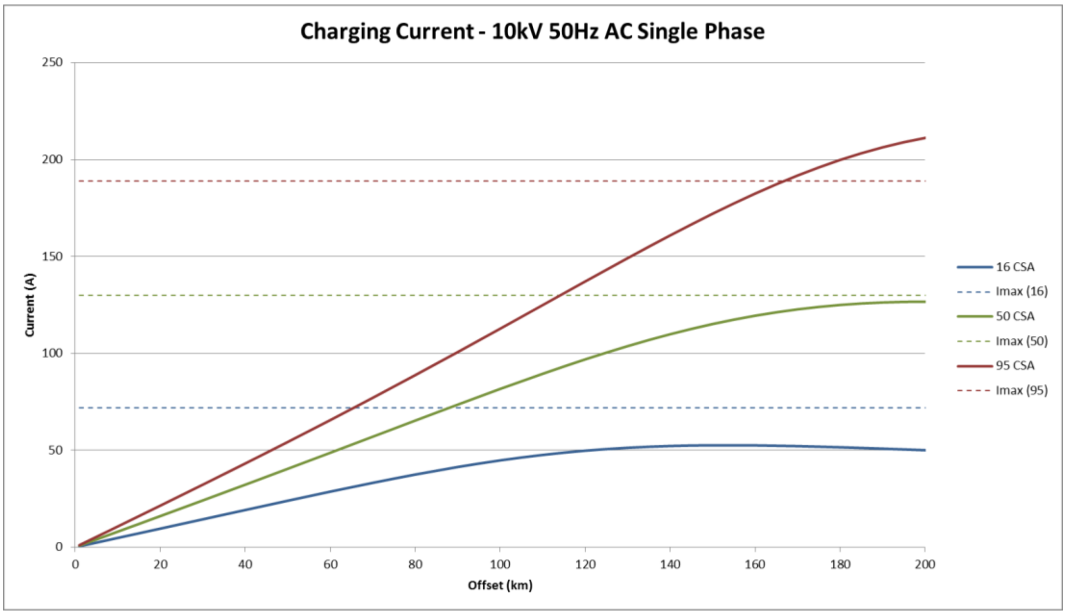

Fig. 13. No Load Cable Charging Current – 10kV 50Hz AC Single Phase

It is also clear that the linear relationship between cable charging current, line voltage and cable length ($I_c = j\omega C_u V l$) 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 95mm^2 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 50mm^2 cable and is reflected in Fig. 9 by an increase in the offset capability over that of the equivalent system based on 95mm^2 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.

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 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 16mm^2, 50mm^2 and 95mm^2 cables with characteristics as defined previously. These specific parameters have been selected in order to investigate the apparent peculiarity that a system utilising 50mm^2 cable has greater capacity above 160km than an equivalent system based on 95mm^2 cable, as shown on Fig. 9 however the theory is applicable to all AC systems.

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 (50mm^2 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.

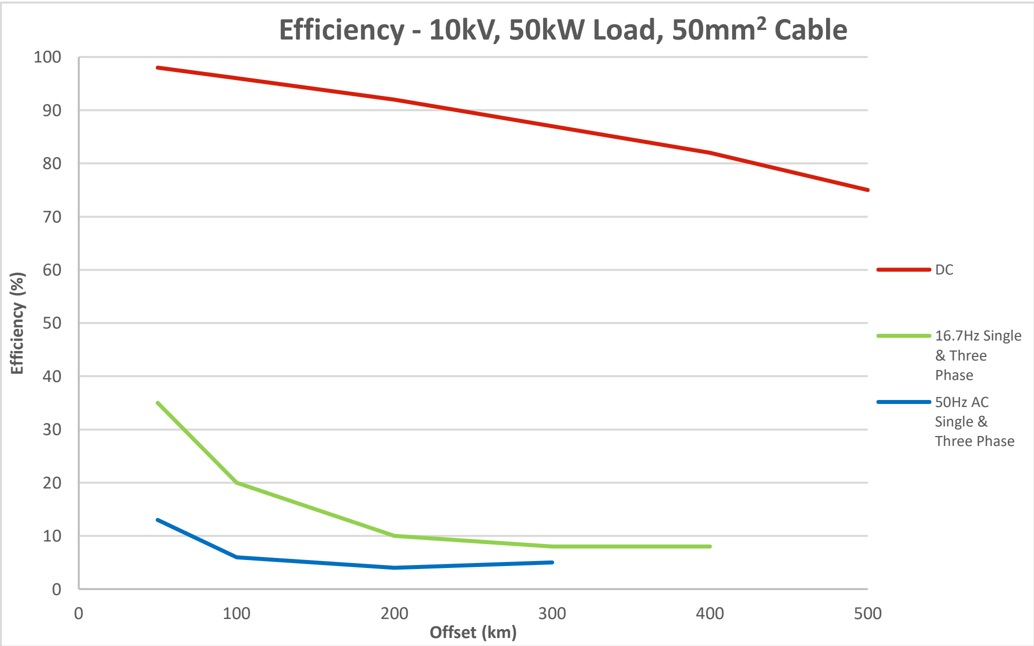

Fig. 14. Comparison of AC and DC System Efficiencies

It is apparent that power transmission systems capable of operating at long 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.

For the traditional electrohydraulic systems, both 16.7Hz and 50Hz technologies utilised in either single phase or three phase configurations also provide potential solutions up to 500km, 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 500km 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 500km, 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.

6 Conclusions

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 do not address the increased complexity associated with converter stations required to replace the well proven and simple AC transformer, nor has the analysis addressed the commercial comparisons of different technologies, cable sizes and subsea installation. A full assessment for the preferred technology would also include for reliability and ability of different systems to operate in different failure modes.

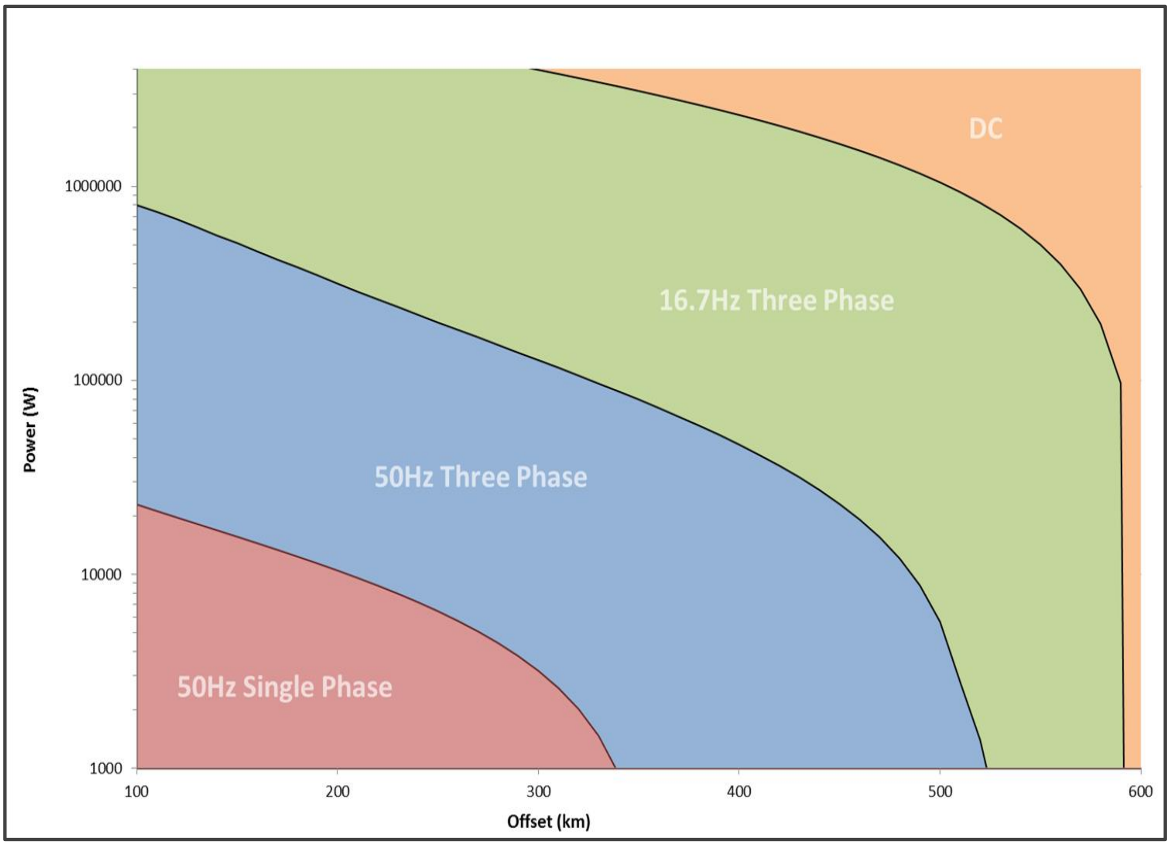

Fig. 15. Load versus Offset Limitations

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