Optimizing Electrical Heating System of Subsea Oil Production Pipelines

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ABSTRACT

Direct Electrical Heating (DEH) is a field-proven technology for hydrate and wax management of subsea production pipelines. DEH has been in use for nearly 20 years and is installed on approximately 30 pipelines/flowlines with length up to 43 km and on 1000 m depth, Studies indicate significant cost-reductions and improved utility by going from the present DEH-systems operating at normal power frequency of 50/60 Hz to a system operating at a frequency ranging between 100 and 200 Hz. Increased frequency reduces the size and weight of the cables, reduces electrical currents in seawater, reduces AC corrosion and is favourable regarding development of ultra-deep fields as well as continuous operation.

KEY WORDS: Direct Electrical Heating; Power frequency; Flowlines; Pipelines; Flow Assurance; Hydrate Management.

NOMENCLATURE

CTZ – Current Transfer Zone at the terminations at both pipeline ends
DEH – Direct Electrical Heating
FEA – Finite Element Analysis
RC – electrical Riser Cable
PBC – Piggy Back Cable
a_1, a_2, a_3, a_4, b_1, b_2, b_3, b_4 – constants used for simplification of equations
C – capacitance of the cable per length
f – frequency
k – propagation constant
I – current
j – imaginary operator
s – position
R, r – resistance, resistance pr. length
X, x – reactance, reactance pr. length
Z, z – impedance, impedance pr. length
U – voltage
Z_w – wave impedance
ω – angular velocity ($2\cdot \pi \cdot f$)

INTRODUCTION

In a DEH-system, electrical alternating current (AC) is conducted by the pipeline steel to generate heat in the pipeline. The heat generation in the pipeline depends on several parameters, like the magnetic properties of the pipeline and the pipeline resistivity. These parameters are greatly affected by the power frequency of the supply current. A higher power frequency increases the heat efficiency of the pipeline current.

All currently installed and planned DEH installations operate at a power frequency of 50 or 60 Hz. To fully understand how DEH will benefit from higher power frequencies (up to 200 Hz), a development program has been initiated. The partners, a power cable manufacturer, installation contractor, research institute and university, have extensive experience in development, manufacturing and installation of DEH systems from early 1990s and to present.

This article presents case studies for electrical rating DEH systems. The cases are equal to many of the DEH installations in operation, to give pragmatic results. Pipeline lengths from 5 to 60 km for water depths of 300 and 3000 m are considered. The electrical rating includes evaluation on required topside power system and power cables size. Evaluation of installation issues and cost studies are carried out to find the optimized solution. The case studies are supported by data from the development program partners. The results in this paper considers a part of the development programme limited to one pipe dimension for a pipeline supplied with a thermal coating applicable for deep waters.

Separately, a laboratory test programme and finite element computations have been carried out to study how the geometry, thermal, steel pipe electrical and magnetic properties influence the heat development in the pipeline and rating of DEH for the power frequency range from 50 to 200 Hz. The tests are performed on steel grades of carbon steel and 13% Cr. These results are not yet available, and are therefore not included in this paper. This means that the magnetic properties at 50 Hz are also used for rating the system at 100 and 200 Hz.

The topside power system design is not considered in the paper. However, the main challenge for a frequency converter is the single-phase load with low power factor and high supply voltage.

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BASIS FOR DEH RATING

Fig. 1 shows the principle sketch of the DEH system (Lervik, 1993) considered in the study. Rating of the DEH considers the riser cable, RC in the figure (routed from power system topside and connected to the DEH cables subsea) and the DEH pipeline supplied with piggyback cable (PBC). For deep waters the length of the riser cable may be of the same length as the DEH pipeline and influences the rating of the supply system.

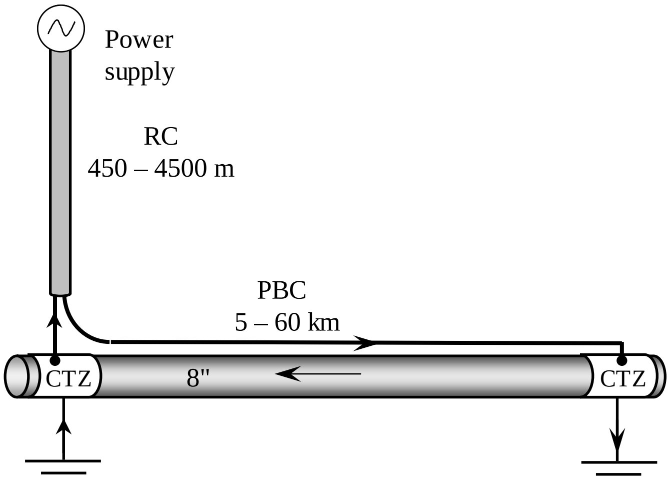

Fig.1. Sketch of the DEH system. CTZ is the Current Transfer Zones supplied with anodes required for grounding of the pipeline.

Heating Scenarios and Required Current

The selected case considers two heating cases at a seawater temperature of 4^{o}C:

- To keep the pipe content at 32^{o}C during shut down.
- Reheating from 4^{o}C to 32^{o}C within 48 hours assuming no hydrate formation and with the pipe filled with water.

The DEH system calculations are based on two worst case scenarios:

- Maximum required DEH current
- Thermal limit of piggyback cable

The maximum required DEH system current is calculated when the pipeline is located on the seabed surrounded by minimum seawater temperature (4^{o}C), see Fig. 2.

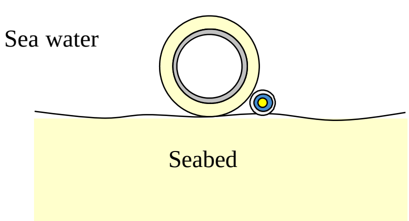

Fig. 2. The thermal model used in the calculations to determine the pipe steel required heat input and the corresponding current. The pipe is located on the seabed and surrounded by seawater at a minimum seawater temperature of 4^{o}C.

The thermally worst location for the PBC is when located beneath a buried pipeline, at maximum seawater temperature (4^{o}C). Fig. 3 shows a rocked dumped DEH pipeline. This location dictates the PBC cross section. A case where the pipeline has penetrated the seabed and the PBC is located at 6 o'clock is considered. Data from DEH installations show that the PBC is normally located in the 4 to 5 o'clock position. The rating is carried out to select the PBC cross section, which gives a core temperature as close to the 90^{o}C limit as possible. The equivalent thermal model of the rocked dumped case in Fig. 3 is shown in Fig. 4. Seabed sediments may fill up part of the rock dump and studies have concluded that typical height of the filled part may be up to 0.3 m.

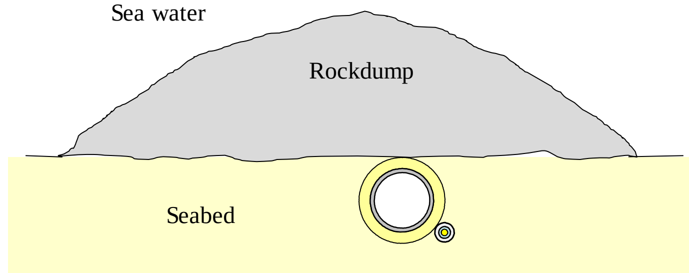

Fig. 3. Location of a DEH pipeline covered by rock dump.

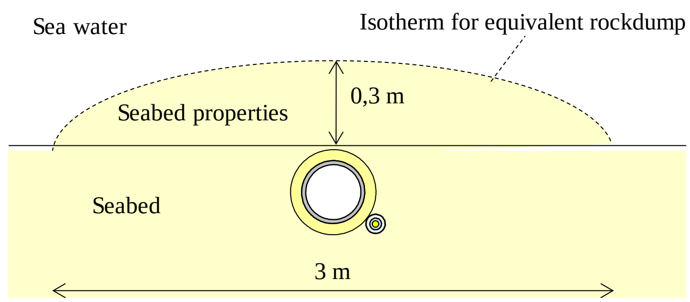

Fig. 4. Thermal model for the rock dumped DEH pipeline. This case determines the maximum piggyback cable temperature. An isotherm equal to the maximum seawater temperature of 4^{o}C is applied on the surfaces of the seabed and the rock dump.

DEH Cables

The main two cables are the RC and the PBC. The principle designs of these cables are shown in Figs. 5-6. A RC of coaxial design is considered in this work. This design has some advantages related to reduced voltage drop and heat loss compared to a design with two single core cables with common steel reinforcement. Furthermore, in a dynamic application, a two-core design is less suited. The PBC is supplied with IPS (integrated protection system) for mechanical protection. The RC length needed is approximately 1.5 times the water depth. For 300 m and 3000 m depths the required lengths are 450 m and 4500 m respectively. The PBC is strapped to the pipeline. A DEH system uses XLPE insulated cables of wet design (no metallic water barrier can be used). Reference is made to (Lervik, 2015).

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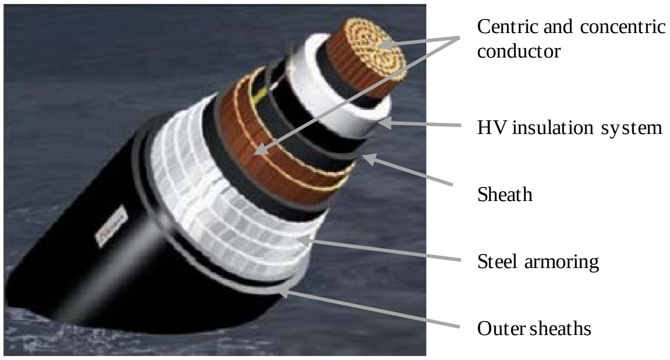

Fig. 5. Riser cable of coaxial design (patented).

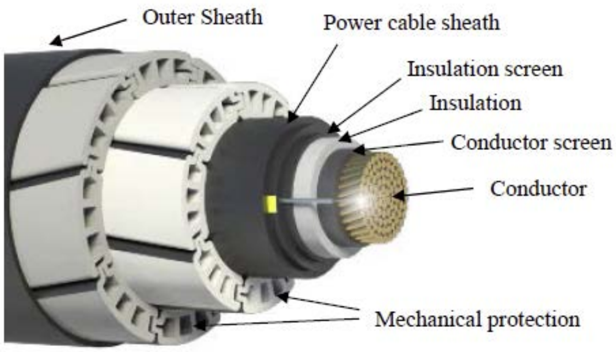

Fig. 6. Piggyback cable with Integrated Protection System (IPS) (patented). The thickness of the IPS used in the analyses is 25 mm.

COMPUTATION METHOD

Based on the theoretical modelling of the DEH system considered in (Nysveen, 2007: Lervik, 2007), an electrical model for the DEH system in Fig.1 is established. Fig. 7 shows the simplified circuit equivalent representing the feeder cables and the DEH pipeline. The impedance terms, Z_{RC} and Z_{DEH} consist of resistive and reactive parts and are determined by FEA tools (www.Comsol.com; www.Altair.com). The cable capacitances, C_{RC} and C_{DEH}, for the studied cases are given by cable manufacturer and are in the range from 0,2 – 0,8 μF/km depending of voltage level and cross section as shown in Fig 8. Typical voltage level is in the range of 12 – 52 kV.

Due to the cable capacitances there will be a current exchange to ground. This results in a current increase in the cable conductor along the length and hence, increased heat development in the cable and pipe along the length.

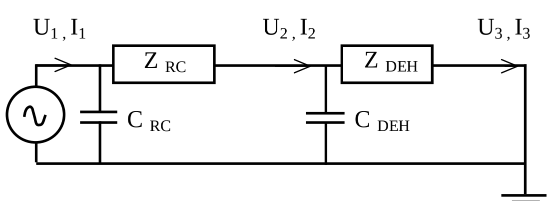

Fig. 7. Principal electrical circuit. Index "1" indicates topside, "2" connection to the DEH cables at the near pipe end and "3" the grounded connection at the far end.

When rating DEH the required supply current in the PBC is determined based on the configuration shown in Fig. 2. This defines the current I_2 in Fig. 7 since the current and the heat input to the pipeline is minimum at this position and increases along the length.

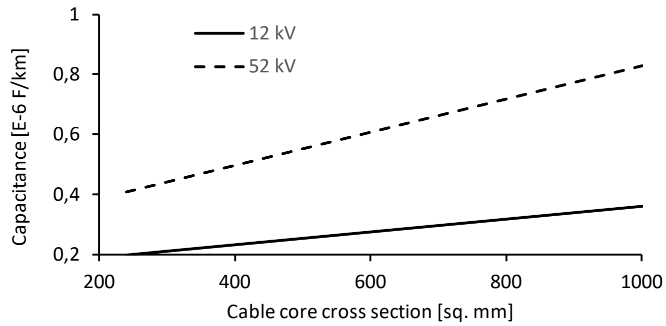

Fig 8. Cable capacitances versus core cross section.

The general equations for determining voltage and current for the circuit shown in Fig. 7 are given in Eqs. 1 – 4.

$$U_1 = U(s) \cdot \cosh(k \cdot s) + I(s) \cdot Z_w \cdot \sinh(k \cdot s) \quad (1)$$
$$I_1 = U(s) \cdot (1/Z_w) \cdot \sinh(k \cdot s) + I(s) \cdot \cosh(k \cdot s) \quad (2)$$

Where:

$$k = ((r + j \cdot x) \cdot j \cdot \omega \cdot c)^{0,5} \quad (3)$$
$$Z_w = ((r + j \cdot x) / j \cdot \omega \cdot c)^{0,5}) \quad (4)$$

The equations can be simplified to:

$$U_1 = U_2 \cdot a_1 + I_2 \cdot a_2 \quad (5)$$
$$I_1 = U_2 \cdot a_3 + I_2 \cdot a_4 \quad (6)$$
$$U_2 = U_3 \cdot b_1 + I_3 \cdot b_2 \quad (7)$$
$$I_2 = U_3 \cdot b_3 + I_3 \cdot b_4 \quad (8)$$

By inserting $U_3 = 0$ and using the required current, I_2, determined by the computations FEA tool for the configuration in Fig. 2, the equations, Eqs. 5 –8, are solved.

The total apparent power, S_1, can then be determined by the general equation:

$$S_1 = U_1 \cdot I_1^* = P_{1+j} \cdot Q_1$$

Where I_1^* is the complex conjugate of I_1, P_1 is the power demand and Q_1 is the total reactive power.

DATA FOR THE ANALYSES

Power frequencies of 50, 100 and 200 Hz and pipe lengths of 5, 10, 30 and 60 km are considered for 300 m and 3000 m water depths, see Fig. 1. The rating includes required current, voltage and power for the DEH systems, in addition to piggyback conductor cross section. The paper considers one pipe dimensions of 8" only with a 40 mm thermal coating and a U-value of 6 W/m^{2}K referred to steel pipe inner diameter. The existing DEH pipelines have U-values from 3 to 8 W/m^{2}K. The pipe is of carbon steel (X65), which is magnetic steel. It is assumed that the relative permeability is 400 and the resistivity is 0,22 μΩm for the steel material at 4ºC with a temperature coefficient of 0,003 1/K. The effect of increased frequency on the steel material parameters are covered in another working package in the research programme and will be updated when these data are available.

The heating scenarios and configuration are defined in the previous sections of the paper.

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RESULTS FROM THE ANALYSES

The rating data of the 5, 10, 30 and 60 km pipeline cases at 50, 100 and 200 Hz are given in Tables 1 - 6 for the 8" pipeline for water depths of 300 m and 3000 m. Required PBC current is summarized in Table 7. The corresponding required PBC conductor cross section (both required and nominal values) for pipe length up to 10 km is given in Table 8. The correlation between PBC conductor cross section versus power frequency are shown in Fig. 9.

From the results given in the Tables 1 – 4, the terminal voltage, power demand and PBC cross section for 300 m water depths are illustrated in Figs. 10 - 12. The results for 3000 m gives somewhat increased voltage and power demand for 5 and 10 km for all frequencies due to the longer supply cable.

Table 1. Power requirements for 50 Hz and 300 m water depth.

Frequency	50 Hz			
Water depth	300 m			
Pipeline length	5 km	10 km	30 km	60 km
Supply current	1195 A	1195 A	1194 A	1194 A
Current at far end	1196 A	1200 A	1221 A	1293 A
Supply voltage	2,2 kV	4,4 kV	13,3 kV	27,6 kV
Power demand	0,8 MW	1,6 MW	4,7 MW	10,1 MW
Power factor	0,30	0,30	0,30	0,31
PBC cross section	630 mm^2	630 mm^2	630 mm^2	800 mm^2

Table 2. Power requirements for 100 Hz and 300 m water depth.

Frequency	100 Hz			
Water depth	300 m			
Pipeline length	5 km	10 km	30 km	60 km
Supply current	920 A	919 A	919 A	916 A
Current at far end	923 A	931 A	970 A	1201 A
Supply voltage	3,2 kV	6,4 kV	19,6 kV	45,4 kV
Power demand	0,8 MW	1,6 MW	5,1 MW	13,7 MW
Power factor	0,28	0,28	0,28	0,33
PBC cross section	500 mm^2	500 mm^2	500 mm^2	800 mm^2

Table 3. Power requirements for 200 Hz and 300 m water depth.

Frequency	200 Hz			
Water depth	300 m			
Pipeline length	5 km	10 km	30 km	60 km
Supply current	699 A	698 A	694 A	NA
Current at far end	704 A	717 A	900 A	
Supply voltage	4,6 kV	9,2 kV	32,0 kV	
Power demand	0,8 MW	1,6 MW	6,3 MW	
Power factor	0,24	0,24	0,28	
PBC cross section	300 mm^2	300 mm^2	630 mm^2	

Table 4. Power requirements for 50 Hz and 3000 m water depth.

Frequency	50 Hz			
Water depth	3000 m			
Pipeline length	5 km	10 km	30 km	60 km
Supply current	1193 A	1191 A	1187 A	1180 A
Current at far end	1196 A	1200 A	1221 A	1293 A
Supply voltage	2,5 kV	4,7 kV	13,6 kV	27,9 kV
Power demand	1,2 MW	1,9 MW	5,1 MW	10,4 MW
Power factor	0,39	0,34	0,31	0,32
PBC cross section	630 mm^2	630 mm^2	630 mm^2	800 mm^2

Table 5. Power requirements for 100 Hz and 3000 m water depth.

Frequency	100 Hz			
Water depth	3000 m			
Pipeline length	5 km	10 km	30 km	60 km
Supply current	915 A	910 A	905 A	880 A
Current at far end	923 A	931 A	970 A	1201 A
Supply voltage	3,7 kV	6,8 kV	20,1 kV	45,8 kV
Power demand	1,1 MW	1,9 MW	5,4 MW	13,9 MW
Power factor	0,33	0,31	0,30	0,34
PBC cross section	500 mm^2	500 mm^2	500 mm^2	800 mm^2

Table 6. Power requirements for 200 Hz and 3000 m water depth.

Frequency	200 Hz			
Water depth	3000 m			
Pipeline length	5 km	10 km	30 km	60 km
Supply current	692 A	684 A	643 A	NA
Current at far end	704 A	717 A	900 A	
Supply voltage	5,3 kV	9,9 kV	32,5 kV	
Power demand	1,1 MW	1,8 MW	6,5 MW	
Power factor	0,29	0,27	0,31	
PBC cross section	300 mm^2	300 mm^2	630 mm^2	

Table 7. Required PBC currents.

Frequency	Required currents (I_2)	
	Keep warm case of content at 32°C	Reheating case of content from 4°C to 32°C within 48 hours
50 Hz	1170 A	1195 A
100 Hz	895 A	920 A
200 Hz	675 A	700 A

Table 8: Required PBC cross section for 10 km pipeline.

Frequency	PBC cross section	
	Required	Nominal
50 Hz	600 mm^2	**630 mm^2**
100 Hz	440 mm^2	**500 mm^2**
200 Hz	260 mm^2	**300 mm^2**

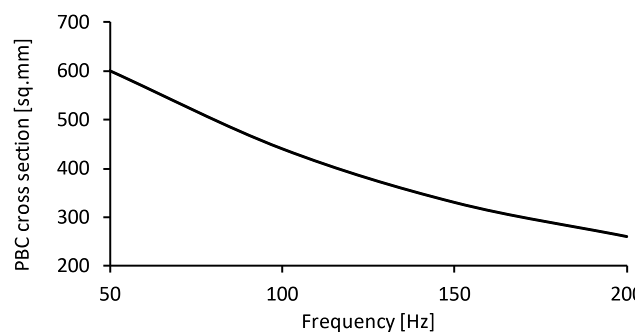

Fig. 9. Required PBC conductor (copper) cross section versus frequency.

The PBC charging current (capacitive current) in the PBC increases when increasing the frequency, pipeline length and cable capacitance. When the current increases, the heat generation in the cable also increases. This effect is visible for length above 10 km for 200 Hz and length above 30 km for 100 Hz. By choosing a higher insulation level for the cables, and hence reducing the capacitive current the effect of increasing currents along the length will be reduced. The feasibility of this need to be evaluated on a case to case basis.

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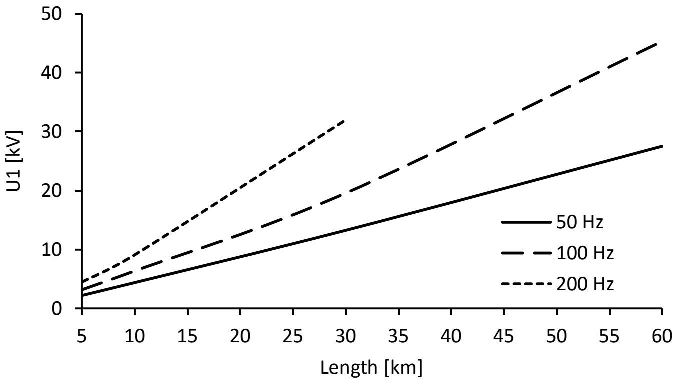

Fig. 10. Supply voltage at hang-off (U_1) versus pipeline length for 300 m water depth.

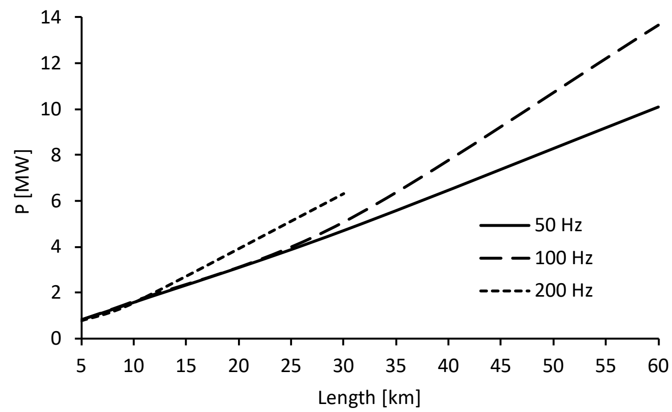

Fig. 11. Power demand ref. hang-off (P_1) versus pipeline length for 300 m water depth.

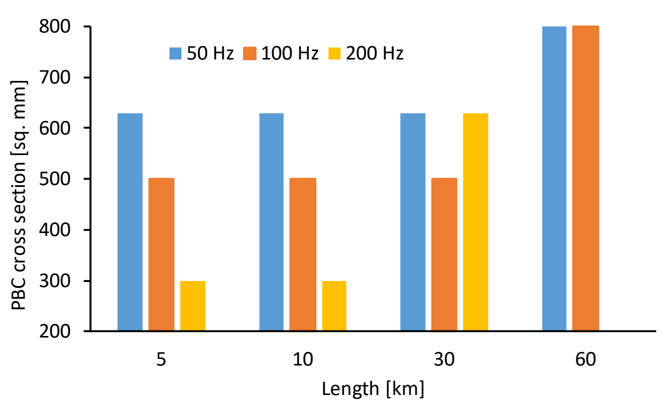

Fig. 12. PBC cross section versus pipeline length for 8" pipeline. This is valid independent of water depth (300 m and 3000 m).

INSTALLATION

Installation of DEH systems is carried out by piggybacking the cable (hence piggyback cable) to the pipeline during installation. A lighter and smaller cable is favourable since it needs to be transported from production facility and finally strapped piggyback to the pipeline during laying. Utilizing increased power frequency introduces installation benefits such as:

- Reduced cross section area of PBC (lighter and smaller cable). This will result in easier logistics. For cross sections as presented in Fig. 12, a weight reduction of approx. 30% can be achieved and a reduction in size of approx. 10%. Consequently, this will ease installation and logistics as dry cable weight in a 50Hz system typically can be in the order of 15 kg/m for the PBC. Logistics typically involve purchase of reel (or basket), spooling as well as lifting to transport vessel. Later lifting to installation vessel (or trans-spooling) also involves heavy lift cranes and requirement to deck space. It is consequently a substantial benefit if the number of reels and weight can be decreased.
- The same benefits do also apply for the RC, but in addition the benefit of reduced weight to the platform is especially interesting for deep water applications. Wet weight may reduce from approx. 50 kg/m down to 35 kg/m. The large dry weight is also a logistical and cost driver for 50 Hz projects.

There are approximately 30 pipelines installed with DEH and approximately 10 are under development. The length varies from approximately 3 – 43 km and the water depth from approximately 30 – 1050 m. The distribution of the pipeline lengths is shown in Fig. 13. As seen the majority is from 3 – 10 km length and there are 4 pipelines with lengths above 20 km. All these pipelines use 50/60 Hz power frequency and the PBC cross section is 1000 or 1200 mm^2 except one smaller pipeline having 630 mm^2 cross section (60 Hz). As seen from the results in Fig.13, there could be considerably cost savings by using higher frequencies, especially for the shortest pipelines.

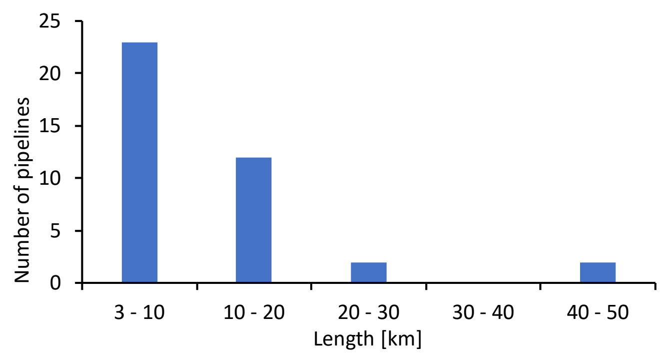

Fig. 13. Number of DEH pipelines versus length (installed and under development/installation).

CONCLUSION

The results from computations show:

- Required supply current is reduced up to 40% at 200 Hz, compared to 50 Hz.
- The conductor cross section is reduced up to 25% at 100 Hz, 50% at 200 Hz, compared to 50 Hz
- Power input to the DEH system is unchanged at 50, 100 and 200 Hz, for pipeline lengths up to 10 km.
- The benefits of higher frequencies are reduced when increasing the pipeline length. At lengths above approx. 30 km, 200 Hz is not attractive due to high system voltage and power demand due to capacitive charging currents.
- Design of Piggyback Cable is independent of water depth from a DEH functionality point of view.
- The cost of DEH projects can be considerably reduced when using higher frequency. Actual benefit is dependent on project,

but up to 10-20 km there is a clear cost saving compared to a 50 Hz system.

- For lengths longer than 30 km, the cost savings is not as prominent when using higher frequency. For some projects it will still be an enabler due to less current needed in the cable and hence less heat development.
- Higher frequency and less currents is favourable regarding risk for AC corrosion.

Recommended power frequency vs. pipeline length is given in the table below:

Pipeline length	Power frequency		
	50 Hz	100 Hz	200 Hz
5 km	Good	Very good	Excellent
10 km	Good	Very good	Excellent
30 km	Excellent		Possible
60 km	Excellent	Good	Not feasible

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