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THERMAL AND ELECTROMAGNETIC MODELLING OF POWER UMBILICALS

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ABSTRACT

This paper describes the most important steps in the design of a 12 km umbilical feeding two subsea motors of about 2 MW. A specific umbilical design is evaluated in detail. The highest temperatures occur inside the platform's air filled J-tube. The temperature of the fibre optic and filler elements was close to the limit. The most favourable power conductor arrangement has been determined. The cross talk in the low voltage circuits is within acceptable limits. The only potential problem is air gap torque oscillation due to the currents in the other circuit. Based on results obtained, it was possible to optimise the umbilical design.

KEYWORDS

Umbilical, design, thermal rating, cross talk, single layer, motor drives, torque oscillation

INTRODUCTION

The development in oil and gas production is more subsea processing which requires electrical power supply from platform or onshore installations by umbilicals. The umbilical often includes power circuits, signal transmission circuits, fibre optic cables and steel pipes containing chemicals (hydraulic oil, methanol). There are various umbilical configurations depending of the field requirements. A single layer design is often preferable from a mechanical point of view but there is a potential problem due to the inductive coupling between conductive elements. The coupling can be reduced to an insignificant level by a suitable multilayer design.

Comprehensive electrical and thermal analyses are required to make sure that the operating temperature and electrical performance are within acceptable limits. The thermal analysis must assure that the maximum operating temperature of the various elements is within acceptable limits. A "worst case" configuration for the temperature conditions must be defined as a base for the analysis. The maximum temperature occurs often at "hang off" on the platform, where the umbilical may be located inside an air filled I- or J-tube. The submerged part of the umbilical may be covered by seabed sediments, rock dumped or trenched. These different boundary conditions along the umbilical must be considered in the thermal analyses.

Long umbilcals give considerable voltage drop and electrical analyses require accurate data for the series impedance and the capacitance of the electrical cables in the umbilical. The frequency dependence of the series resistance and inductance must in some applications be taken into account. The series impedance cannot be determined by analytical formulae due to the complex geometry of the umbilical. Finite element methods have during the last decades proven to be a suitable tool and the software, [1], is used in this work. The resistance depends on the temperature and the applied software is able to perform a combined thermal and electromagnetic analysis.

Cross talk between power cables and signal cables must be considered for elements in the same layer and to some degree between elements in different layers.

SYSTEM DESCRIPTION

The actual system has to be analyzed in detail when designing an umbilical and a particular system is therefore selected in this paper.

The actual system consists of two subsea motors that are operated independently. Each motor is fed by an individual VSD located at a platform 12 km away as shown in Fig.1. The main focus in this paper is on the common umbilical between the topside installation and the subsea installation. Some simplified introductory analysis showed that it reasonable to use 240 mm^2 power conductors as shown in Fig.1.

UMBILICAL DESIGN

Fig.2 shows an initially proposed umbilical configuration based on the required number of power conductors, fibre optic cables, quads for LV control and steel pipes. All cables and pipe lines are located in one layer, which implies that their relative position is not altered along the umbilical. The one layer design is favourable from a mechanical point of view but there is a potential problem regarding the inductive coupling between the conductive elements.

The particular umbilical design is based on a self-supporting elements principle. This means that the design, materials selection and fabrication ensure that fibre cables, quads, power cables, steel tubes (for fluid/hydraulic supply) and weight/strength elements (if required) are embedded in plastic profiles and twisted in a certain way, so that the overall strength capability and proper dynamic behaviour is ensured based on friction, twisting forces, and axial stiffness / weight. The basic idea is to use steel tubes as strength members, and this saves weight since external steel armouring is not required. The friction between the plastic profiles and the various elements ensures that cables in many cases will not require any kind of armouring, even at relatively deep waters. In cases where extra weight or strength is required, steel wires or carbon fibre rods can be added. Such power umbilicals are typically used for subsea flow line heating and subsea multiphase/water injection pumps and gas compression.

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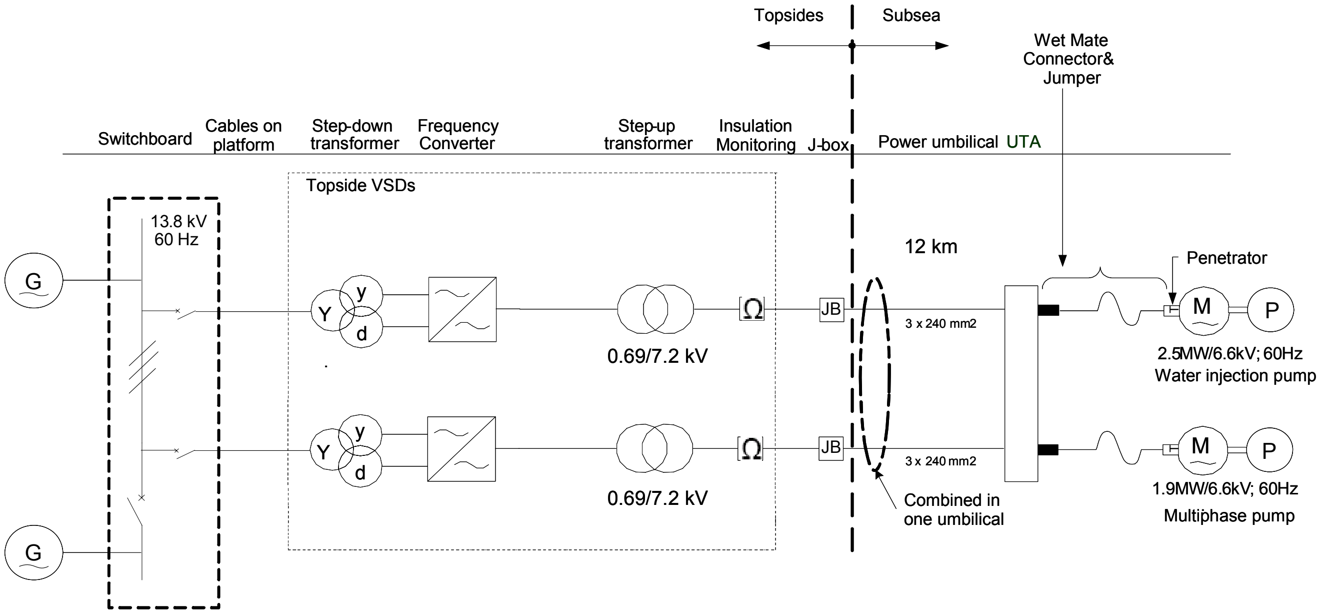
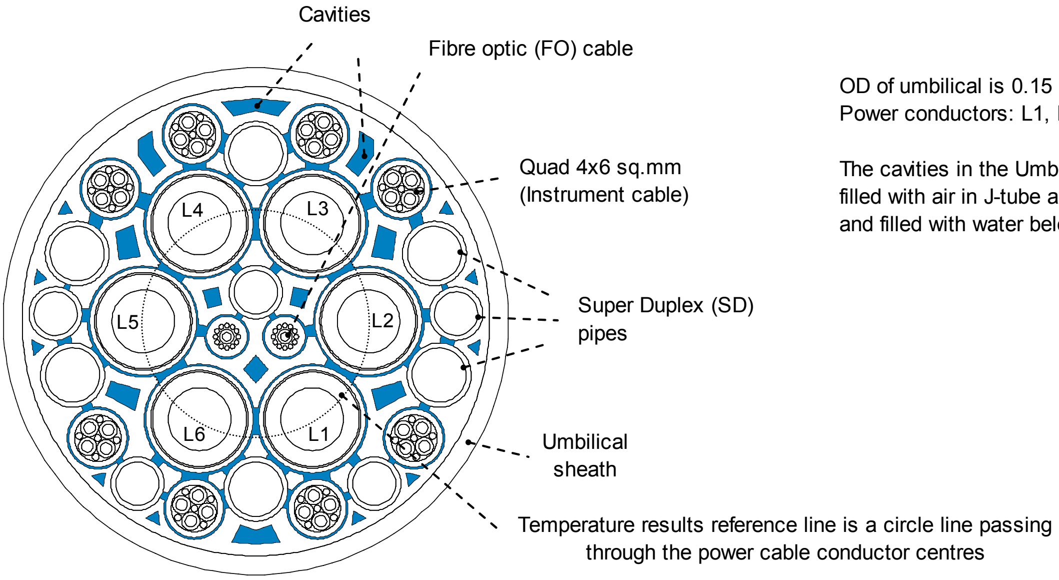


Fig.1 Single line diagram



OD of umbilical is 0.15 m
Power conductors: L1, L2, L3, L4, L5, L6.

The cavities in the Umbilical are assumed filled with air in J-tube above seawater level and filled with water below seawater level.

Fig.2 Umbilical cross section

THERMAL ANALYSES

The following two cases have been analysed concerning the “worst case” temperature conditions:

- At “hang off” on the platform, where the umbilical is located inside an air filled J-tube with OD of 0.4 m. The J-tube is approximately 10 m long above seawater level and is not subjected to solar radiation and the ambient maximum air temperature is 20°C.
- For the submerged case with the umbilical embedded in seabed of clay at maximum 1 m depth. The seawater temperature is 4°C.

The maximum permissible temperature is 90°C for the power conductors and 60°C for the fibre optic cables and filler elements.

The six power cables can be connected to the two circuits in different ways and Table 1 shows the alternative layouts that were analyzed in detail.

Table 1 Alternative circuit layouts

Configuration	Conductors circuit # 1	Conductors circuit #2
Flat	L1,L2,L3	L4,L5,L6
Trefoil	L1,L3,L5	L2,L4,L6

The thermal analysis was carried out at 60 Hz with rated current in both circuits (220 A in circuit # 1 supplying the multiphase pump and 310 A in circuit # 2 supplying the water injection pump). The current was for both circuits assumed symmetrical with positive sequence in counter clockwise direction.

Cable screens and armouring (power cables armouring, fibre optical cable armouring and super duplex tubes) are assumed grounded at both ends. The cross section of the copper screen of the power cables is 6 mm^2.

The other input data used in the analyses are given in Tables 2 and 3. Above seawater level the cavities inside the umbilical will be air filled and for this case there are uncertainties concerning the thermal properties. For the submerged part the cavities are water filled and more reliable data are available.

For the thermal analyses inside the 10 m long air filled J-tube, the boundary conditions of the umbilical surface (temperature) was determined by analytical formulae for free air convection and heat radiation. This calculation was carried out based on total generated heat in the umbilical determined by finite element calculations at relevant temperature.

Table 2 Thermal data

Material	Specific thermal conductivity [W/mK]
Fibres, insulation and sheath, aramid reinforcement, LDPE fillers	0.3
Gel fill in Quad	0.2
PVC fillers	0.22
Copper conductors and screens	385
FO armour wires	50
Super Duplex tubes	17
Content of Super Duplex pipes	0.5
Cavities inside umbilical (air)	0.01 – 0.1
Cavities inside umbilical (water)	0.56
Clay (seabed)	1.3

Table 3 Electrical data at 20°C

Material	Resistivity [Ωmm^2/m]	Temp. coeff. [1/°C]	Relative permeability
Cu	0.0178	0.004	1
Super Duplex	0.82	0.0008	32
Carbon steel	0.20	0.004	1000

The results from the thermal computations show:

- The maximum temperature of 65°C occurs in the power cable conductor for the part inside the air filled J-tube for the trefoil configuration. For this case the temperature of the fibre optic cables and the filler elements in the center of the umbilical (inside the power cables) was approximately 60°C, which is at the temperature limit.
- The maximum temperature for the flat configuration was approximately 1°C lower and the maximum temperature of the fibre optic cables and the filler elements in the center of the umbilical (inside the power cables) was approximately 58°C.
- For the main part of the umbilical, which is buried at a depth of 1 m in clay, the maximum temperature was approximately 36°C at a seawater temperature of 4°C for the trefoil configuration.

The most important results are illustrated in Fig. 3, which shows the temperature along the circle line through the power conductors defined in Figure 2. Fig.3 applies to the trefoil configuration and the temperature is somewhat lower for the flat configuration.

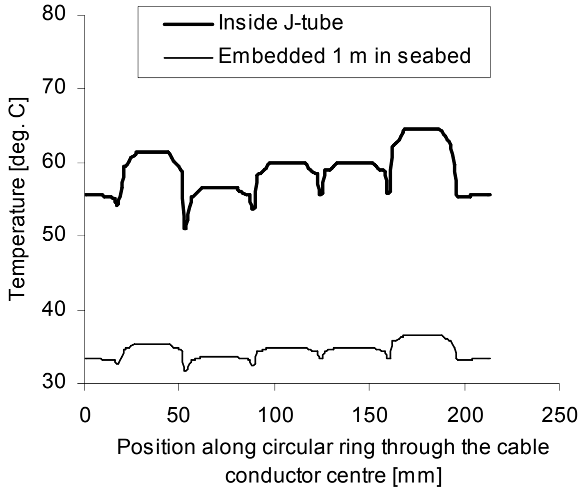


Fig. 3 The temperature along the circle line defined in Fig. 2 for the Umbilical inside the J-tube and for the Umbilical buried at a depth of 1 m in clay. The "flat areas" indicate the copper conductors.

The generated heat in the trefoil configuration is approx. 6% higher than for flat configuration. Table 4 shows the generated heat in all conductors in the umbilical when it is located inside the J-tube.

Table 4 Generated heat in conductive elements

Element	Generated heat [W/m]	
	Flat configuration	Trefoil configuration
Power cables (6 cables)	36.8	37.4
Power cable screens (6 screens)	2.81	3.9
Super Duplex 1/2" (5 tubes)	0.19	0.40
Super Duplex 5/8" (6 tubes)	0.49	0.75
FO cable screen (2 tubes)	0.09	0.39
FO armouring (2 armourings)	0.02	0.08
Total	**40.4**	**42.92**

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ELECTRICAL ANALYSES

Cross talk between power circuits

The six power conductors are located in one layer and the relative positions of the conductors do not vary along the umbilical. This implies that there is a significant inductive coupling between the conductors. The coupling causes a cross talk between the two circuits and it may also cause a non-symmetrical voltage drop within each circuit. The coupling is different for the flat and the trefoil configuration. The applied positive sequence voltage may for each circuit be connected clockwise or counter clockwise. These choices have an impact on the cross talk too.

The series impedance was for each configuration determined by two computations where a 1 A / 60 Hz positive sequence current was applied in counter clockwise direction either to circuit # 1 or to circuit # 2. The result from the computation was the per unit length voltage drop for each of the six conductors and the voltage drops in each circuit was converted into symmetrical components. The zero sequence component was disregarded since it does not influence the voltage between the motor terminals. The positive sequence voltage drop due to the applied positive sequence current in the same circuit gives the positive sequence impedance that is the impedance used when neglecting non-symmetrical effects.

The other voltage drops are used to determine transfer impedances. Three transfer impedances are considered in this paper: The impedance giving the negative sequence voltage drop in the circuit where the positive sequence current is applied and two impedances giving the positive and the negative sequence induced voltage in the neighbour circuit. It is normally sufficient to consider the magnitude of the transfer impedances.

Table 5 shows the obtained values for the positive sequence impedance

Table 5 Positive sequence impedance [Ω/km]

Configuration	Circuit # 1	Circuit # 2
Flat	0.0879+j·0.1408	0.0888+j·0.1408
Trefoil	0.0937+j·0.1744	0.0940+j·0.1744

It is seen that the impedance is practically the same for both circuits. This result is as expected since the power conductors are symmetrical.

The obtained transfer impedances are presented in Table 6.

The impedances in Tables 5 and 6 were obtained with the positive sequence in counter clockwise direction in both circuits. Changing the direction on one or both circuits did not have any significant influence except for a possible interchange of transfer impedances corresponding to the negative and the positive sequence induced voltage in the neighbour circuit. The values in Table 6 apply to the same direction in both circuits and the interchange takes place when the directions are opposite.

Table 6 Transfer impedance [Ω/km]

Configuration	Flat		Trefoil	
Current applied to circuit	# 1	# 2	#1	# 2
Neg. seq. ind. voltage same circuit	0.0309	0.0308	0.0043	0.0030
Negative seq. ind. voltage other circuit	0.0309	0.0309	0.0031	0.0031
Positive seq. ind. voltage other circuit	0.0283	0.0282	0.0624	0.0620

The rated current of the two motors is respectively 220 A (circuit # 1) and 310 A (circuit # 2). The rated voltage is 6.6 kV for both motors and the length of the umbilical is 12 km. Combining this information with the transfer impedances gives at rated current the induced voltages shown in Table 7.

Table 7 Induced voltage [% of rated voltage]

Configuration	Flat		Trefoil	
Induced voltage in circuit	# 1	# 2	#1	# 2
Negative seq. volt. from same circuit	2.14	3.00	0.30	0.29
Negative seq. volt. from other circuit	3.02	2.14	0.30	0.21
Positive seq. volt. from other circuit	2.75	1.96	6.05	4.32

The two motors are operated independently. The power frequency may be equal to the rated frequency (60 Hz) in both circuits but without any phase correlation. The two contributions to the negative sequence voltage in Table 7 may thus have the same phase. Table 7 assumes that the positive sequence corresponds to a counter clockwise arrangement for the conductors in both circuits. It may be better to use a clockwise arrangement in one of the circuits. Table 8 shows the induced voltage for the four alternative conductor arrangements when assuming that the two contributions to the negative sequence have the same phase. The positive sequence induced voltage in Table 8 is due to the neighbour circuit.

Table 8 Induced voltage at 60 Hz for alternative configurations

Con-figuration	Conductor sequence	Induced voltage [%]			
		Circuit # 1		Circuit # 2	
		Neg. seq.	Pos. seq.	Neg seq.	Pos. seq.
Flat	Same	5.16	2.75	5.14	1.96
Flat	Opposite	4.89	3.02	4.96	2.14
Trefoil	Same	0.60	6.05	0.50	4.32
Trefoil	Opposite	6.30	0.30	4.61	0.21

A small deviation between the power frequencies in the two circuits gives an induced voltage that varies from being in phase with the applied voltage at the motor to having the opposite sign. A 5 % positive sequence induced voltage would as an example give a motor voltage variation between

95% and 105 %. This gives for a constant motor speed ± 10 % variation in the air gap torque.

The induced voltage can be considered a distributed source along the umbilical and the voltage appearing at the motor terminals is somewhat lower due to a voltage drop along the umbilical. The voltage drop in circuit # 1 is 7 % for the positive sequence voltage and 15 % of the negative sequence voltage when both circuits are operating at 60 Hz.

The trefoil configuration with the conductors of the two circuits in opposite arrangement gives the lowest positive sequence induced voltage but the highest negative sequence induced voltage. The flat configuration with the conductors of the two circuits in opposite arrangement seems to be best compromise when considering both the positive and the negative sequence induced voltage. Table 5 shows further that a flat arrangement gives a lower positive sequence impedance compared to a trefoil arrangement.

The induced negative sequence voltage at the motor for the flat configuration with the positive sequence in opposite directions is about 4.2 % in circuit # 2 when taking the voltage drop into account. That value is higher than the normally acceptable limit but it is reason to believe that it may tolerated based on a more detailed analysis of the motor stresses. The induced positive sequence voltage in circuit # 1 causes an air gap torque variation of about ± 6 % when the two power frequencies is close to 60 Hz but not equal. The variation becomes higher when the frequency in the neighbour circuit increases. Fig.4 shows the result from a time domain simulation performed by ATP [2] when the frequency is the neighbour circuit is 65 Hz and the induced voltage is assumed proportional to the frequency. The induced voltage is applied after 0.1 s and the torque variation approaches a steady state 5 Hz oscillation with 10 % amplitude.

A closer examination revealed that the frequency of the air gap variation due to a positive sequence induced voltage from the neighbour circuit is equal to the absolute value of the difference between the two power frequencies. The air gap oscillation may be critical if its frequency is close to a natural frequency of the mechanical system.

It has been shown that a single layer design of the power conductor in the umbilical gives a significant coupling between the two motor circuits. There is a possibility that the coupling can not be accepted. The coupling can be reduced by increasing the system voltage since an increased voltage reduces the current and thus the induced voltage. Another solution is to introduce a multilayer design.

Induced voltage in signal circuits

The umbilical contains both power cables and quads each with two pairs of LV cables. The power cables cause some cross talk in the signal system. The differential mode cross talk becomes insignificant because the signal cables are twisted independently of the power cables and with a much smaller lay length. A detailed computation for the flat configuration gave for rated current at 60 Hz in both power circuits **0.37 mV**.

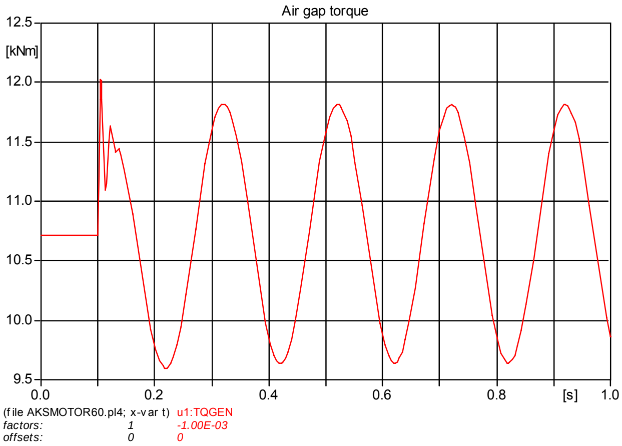

Fig. 4 Air gap torque variation (motor in circuit # 1) due to an induced 65 Hz positive sequence voltage

The twisting of the signal cables has only a minor influence on the common mode induced voltage. A detailed analysis assuming rated current at 60 Hz in both power circuits gave an induced voltage equal **550 V.** This voltage is the difference in the (common mode) voltage to ground at both ends of the umbilical. The voltage is harmless for the signal cable, but it may be critical for the signal transmitter/receiver. Such a problem can be solved by introducing an isolating transformer between the signal cables and the transmitter/receiver.

Motor start-up

The start-up takes place at a low frequency (e.g. 2 Hz). The main effect of the umbilical is then the resistive voltage drop. The flux in the motor is normally limited to its rated value during the start-up. This means that the motor voltage is limited to a value proportional to the frequency. The motor current is typically in the range of the rated value or less even when the rotor is locked. This means that the voltage along the umbilical does not represent any problem as it is well below the rated voltage. The current may be somewhat above the rated value when the rotor is locked or when the motor speed is very low but the current does not cause any thermal problem due to the limited duration of the start-up. Keeping the motor flux at rated value during start-up implies a much higher flux at the top side end of the umbilical. The increased flux is not important if the inverter is connected directly to the umbilical, but it has a strong impact if there is a step-up transformer between the inverter and the umbilical as in Fig.1. The flux may well be twice the rated value and the cross section of the transformer core must be increased accordingly. The transformer flux can be kept at its rated value by reducing the voltage. This gives a reduction in the breakaway torque of the motor. Reducing the voltage by a factor two implies as an example a torque reduction by a factor four. The required load torque is for most applications very low once the motor is rotating and it is then sufficient to keep the top side flux at its rated value. One alternative way to obtain a high breakaway torque is to bypass the

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transformer during the first part of the start-up.

A specific computation of the locked rotor torque was made for the actual umbilical and the actual motor in circuit # 1. Fig. 5 shows the result that was obtained by ATP. The air gap torque is presented relative to the rated torque that is the torque in Fig. 5 prior to the application of the induced voltage from the neighbour circuit.

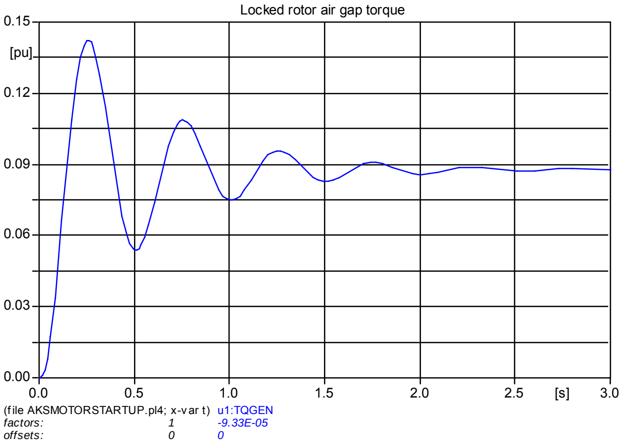

Fig. 5 Locked rotor torque during start-up

The frequency of the applied voltage was 2 Hz and the amplitude was reduced by a factor 30 compared to the voltage that gives the rated motor voltage at rated conditions. The steady state value of the motor flux relative to the rated value became 0.353 and the steady state torque in Fig. 5 is 9 %. This means that the top side flux would be 2.83 times the rated value if the source voltage was increased to give the rated motor flux. However, 9% breakaway torque is in most applications sufficient.

The influence on the locked rotor torque from the induced voltage from the neighbour circuit was investigated too. That voltage caused an additional oscillating torque that does not influence the acceleration of the motor in a negative way.

CONCLUSION

This paper describes the most important steps in the design of a 12 km umbilical feeding two subsea motors of about 2 MW. A specific single layer design with self-supporting elements was selected for the umbilical design. One important aspect is the maximum operating temperature and it has been shown how to determine the worst case condition. The maximum temperature occurred inside the air filled J-tube where the temperature of the fibre optic cables and the filler elements in the center of the umbilical was approximately 60°C, which is at the temperature limit. The power cable temperature was well below the limit (90°C). The temperature margin is low for the fibre optic cables and the fillers. A better margin can be obtained by increasing the cross sections of the power cables.

The single layer layout is favourable from a mechanical point of view. A potential drawback is the inductive coupling between the conductive elements. The flat power conductor configuration with opposite phase sequence in the two circuits seems to be the best choice regarding cross talk as well as thermal conditions.

The cross talk from the power cables to LV circuits does not seem to be a problem. The two motors are operated independently and it has been shown that the coupling cases an oscillation in the air gap torque. The oscillation may cause problems if its frequency is close to a natural frequency of the mechanical system. The oscillation level can be reduced by increasing the voltage or by introducing a multilayer power umbilical design.

The torque oscillation does not have a negative influence on the start-up of a motor. The start-up of the motor takes place at a very low frequency and the resistive voltage drop along the umbilical may cause some additional requirements if a high breakaway torque is needed. The required voltage is not a problem, but the required flux of a topside transformer may be several times the rated value.

Based on this study, which touches into the most important design challenges, it is possible to obtain an overall power umbilical and power system design strategy which ensures:

- Enough start-up torque for the motors
- Temperatures below acceptable limits
- Induced voltages to control cables are at sufficiently low level
- No problematic torque oscillations in any operational mode by optimized umbilical cross-section design

REFERENCES

[1] Flux2D, version 9.2.2, Cedrat France. (Computer software for 2D FEM analyses).

[2] H. Dommel,, ”Electro Magnetic Transient Program (EMTP) Theory Book”, Branch of System Engineering, Bonneville Power Administration, Portland Oregon USA , June 1987