Transmission of electrical power through subsea-cables over long distances

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1 Introduction

Crude oil is the basis for almost all products of our modern life. However, the sources where crude oil can be exploited easily are limited. Therefore, in addition to existing oilfields, sources which require more technical effort must be exploited in future. Many of such oil-wells are subsea. Some of them are nearby the coast, but others are some 10 to 100 km away from the coast and in a depth of up to 2000 m.

For the exploitation of subsea oil-wells multiphase twin screw pumps are used. Such pumps are driven by oil-cooled asynchron-squiral-cage motors with ratings of some MW. Now the question arises how to energize this motor.

Basically, the AC motor must be fed by an AC voltage and current. There are different possibilities to provide an AC power supply under consideration of the mentioned circumstances (depth up to 2000 m, in between 10 km and 100 km away from the coast).

2 Basic AC supply concepts

2.1 Basic requirements

Basic requirements for the AC supply for asynchrony-squiral-cage motors are a variable frequency and voltage level within a certain range. Otherwise, if the motor is directly switched to the AC supply, the starting current would be extremely high, besides of problems with system stability.

2.2 Supply concepts

The individual AC power supply concepts have to be evaluated using a variety of criteria. According to our opinion the following criteria are relevant:

- feasibility
- power losses
- experience of components related to availability and life-time
- dynamic system behaviour
- financial effort for components and the entire system

2.3 Concept 1: AC power transmission with frequency converter subsea

Figure 1 illustrates the concept. The connection to the power grid is made by a circuit breaker and a matching transformer. The matching transformer is required for the adaption of the grid voltage level to the voltage level of the frequency converter. The frequency converter is connected to the matching transformer by a cable. The frequency converter consists of both parts, the DC converter, the DC voltage intermediate circuit and the AC converter. The asynchronous machine is directly connected to the frequency converter.

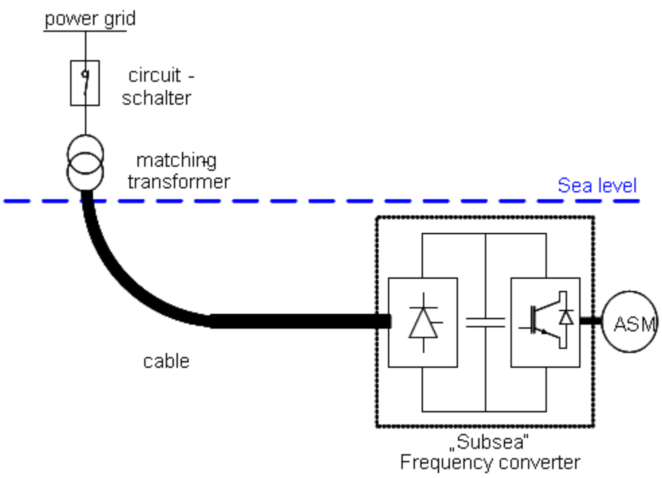

Figure 1: AC power transmission with frequency converter subsea

Advantages of this concept are the following:

- the power losses are moderate
- a subsea AC power grid could be realized
- the power transmission characteristic of the connecting cable is well-known

Howerver, there are some disadvantages which have to be mentioned. These disadvantages concern mainly the reliability of the system. The entire frequency converter is located on the ground of the sea. In case of a malfunction of the frequency converter any kind of repair or exchange is cost-intensive. There is limited experience with frequency converters which are operated subsea. Therefore, the reliability of the system is not known. Furthermore, it is not possible to use a standard frequency converter. A special frequency converter has to be designed and manufactured for the subsea application.

2.4 Concept 2: DC power transmission with DC motor subsea

The next concept is shown in Figure 2. Thereby, a DC motor is used for driving the multiphase pump. This concept is very easy, because all electronic components like the DC converter are ashore. Again, the power grid feds via a circuit breaker and a matching transformer a DC converter and the DC current is transmitted via a subsea cable to the DC motor.

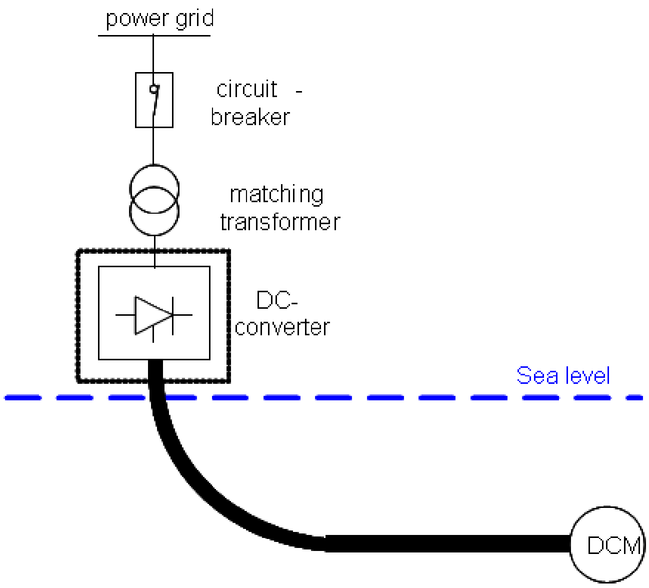

Figure 2: DC power transmission with DC motor subsea

The concept is quite easy. The transmission losses are low and the system control is very easy. Another aspect is that there are no travelling waves due to switching operations of the DC converter. The big capacitance of the cable cares for a very smooth DC voltage. However, there are some hints of this concept. DC motors with the required rating of some MW are not technical state-of-the-art. Today DC drives have been almost completely replaced by frequency converters and asynchronous machines. Therefore, a manufacturer for oil-cooled DC motors in the MW range could not be found. Furthermore, DC machine are less reliable than asynchronous machines due to the brushes. Another principal disadvantage is, that a subsea grid is not possible or would not make much sense because all motors would be fed by the same voltage.

2.5 Concept 3: Use of the subsea cable as DC intermediate circuit

Concept 3 is an interesting combination of concept 1 and concept 2. As shown in Figure 3 the power grid is connected to the system by the circuit breaker and the matching transformer. Then the AC output voltage of the matching transformer is converter into a DC voltage. The subsea cable acts as a DC intermediate circuit. Such a system realization is possible because a capacitance of the cable is in the range of some 100 nF per km. If the capacitance of the DC circuit would not be high enough an additional capacitance can be located ashore. Subsea an AC converter converts the DC voltage into an appropriate AC voltage for the asynchronous machine which drives the multiphase pump.

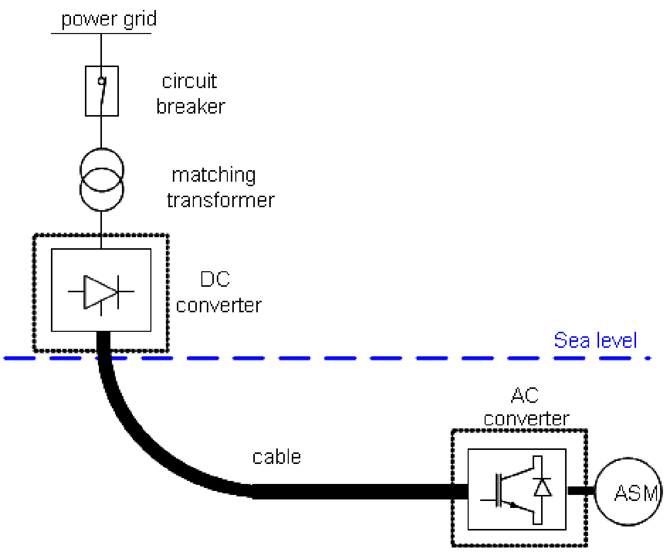

Figure 3: Use of the subsea cable as DC intermediate circuit

The system according to concept 3 seems to be the best technical solution. It combines the advantages of concept 1 and concept 2. Travelling waves cannot occur or only with extremely low amplitude. Furthermore, an asynchronous machine can be used for driving the multiphase pump. Controlling of the system is also quite easy. A subsea DC grid is possible because the AC converter allows an adjustment of the voltage level for each individual asynchronous machine. Due to the DC grid, the power losses are low. Thus, this concept can be regarded as “solution created by engineers”.

However, even this solution has some disadvantages. It has to be mentioned that there is not experience with the operations of such split systems. An active component, the AC converter must be operated subsea. Therefore, the reliability of such a system is unknown. Furthermore, no standard frequency converter can be used. The split frequency converter requires a new design. Maybe, there are some effects which are not known yet.

2.6 Concept 4: Combination of standard components

Figure 4 shows a very easy concept for power transmission over long distances using standard components. The system is connected to the power grid via the circuit breaker and the matching transformer. The output of the matching transformer is connected to a standard frequency converter which is completely operated ashore. The power transmission is made by an AC subsea cable. The cable is connected to the asynchronous motor which drives the multiphase pump.

The system consists of standard components. This makes it reliable and reduces costs. Service activities on active components like the frequency converter are easy because this component is located ashore.

However, some disadvantages are also present for this concept. Travelling waves due to switching operations of the IGBT’s inside the frequency converter can result in high overvoltages on the motor side of the cable. This has to be evaluated in detail. A subsea power grid is not reasonable because the output voltage of the frequency converter would be the same for all asynchronous motors. The power losses are high. The motor has to be fed with active power and reactive power. The sum of them, the apparent power has to be transmitted.

Main problem is that the dynamic behaviour of the entire system as well as the limits of power transmission via the AC cable.

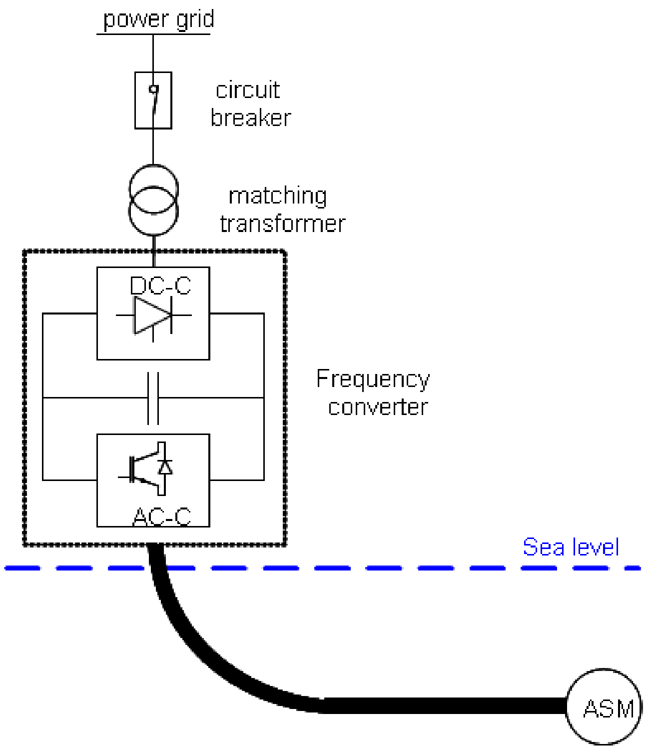

Figure 4: combination of standard components

3 Dynamic behaviour of the system

3.1 Time ranges

The dynamic behaviour of the entire system must be evaluated within three time ranges:

- steady state condition: constant load torque, no acceleration or deceleration of the asynchronous motor, relevant for a time range > 10 s.
- dynamic condition: variation of the load (multiphase pump), changes of mechanical characteristics of the asynchronous motor, dynamic of the electrical components are relevant for a time range in between 100 ms and 10 s.
- transient condition: constant mechanical characteristic, travelling waves are active, relevant for a time range < 100 ms.

3.2 Models for the electrical components

Models for the asynchronous machine and the cable are well known for the steady state condition as well as for the dynamic condition. Figure 5 shows a simplified circuit consisting of the AC supply, the cable and the asynchronous machine. The cable can be described by the following equations:

$$\underline{U}_1(x) = \underline{U}_2 \cdot \cosh(\underline{\gamma} x) + \underline{Z}_W \cdot \underline{I}_2 \cdot \sinh(\underline{\gamma} x)$$

$$\underline{I}_1(x) = \underline{I}_2 \cdot \cosh(\underline{\gamma} x) + \frac{\underline{U}_2}{\underline{Z}_W} \cdot \sinh(\underline{\gamma} x)$$

with

$$\underline{Z}_W = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}} \qquad \underline{\gamma} = \sqrt{(R' + j\omega L') \cdot (G' + j\omega C')}$$

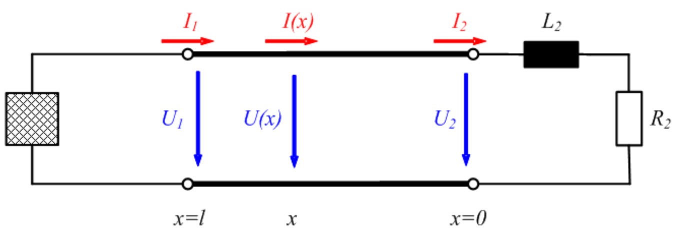

Figure 5: simplified system model consisting of the AC supply, the cable and the asynchronous motor

The asynchronous motor is simulated according to its typical steady state circuit according to the literature as shown in Figure 6. Together with the cable the entire system can be simulated. In a first step, the frequency converter is replaced by an ideal AC source. If the system works well, the frequency converter can be simulated in more detail as a next step.

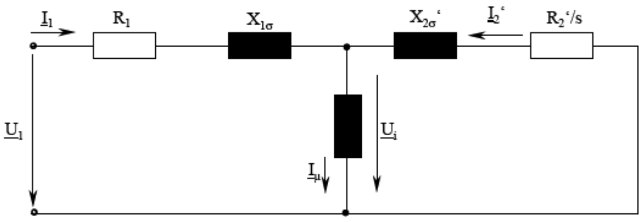

Figure 6: electrical model of the asynchronous motor for steady state condition according to the literature

3.3 Results of a simple system model

The simulation of the simplified system was performed using Simplorer. The machine was energized using a voltage-to-frequency ratio of:

$$\frac{U_1}{f_1} = \text{konstant}$$

With a linear increase of the frequency.

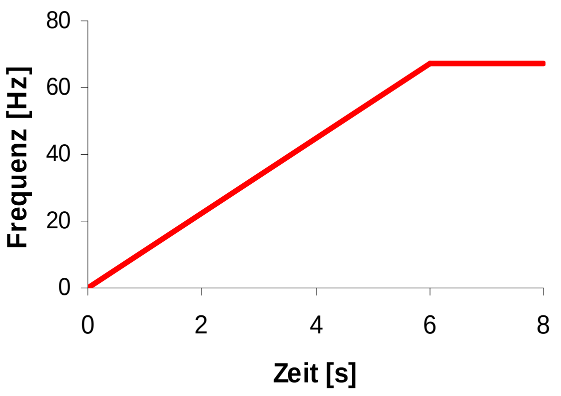

Figure 7: linear increase of the frequency with time

The voltages are adjusted according to the requirements of the transmission line equations. There are no problems with the start of the machine as long as the cable connection is short. However, with a long cable in the range of some km the machine does not start even if the voltages at the land side of the cable are adjusted. Especially, load changes at constant voltages cause instabilities. The voltages at the machine change and the rotation speed collapses down to zero.

3.3 Closed-loop control

According to the results mentioned above a pure governing of the asynchronous machine is not possible. Thus, a closed-loop controlled system is required in order to overcome the limitations of a pure governed system. The voltage at the machine terminals are adjusted according to the required stator currents.

Figure 8 shows the structure of the control system. A so-called rotation speed controller uses the actual machine current and rotation speed and compares it with the desired value. The results of this controller are the voltage and current of the machine. This is the input for the transmission line equation block. This block provides the input voltage for the cable at its output in that way that the desired voltage u2 is achieved at the terminals of the asynchronous motor. Using this system provides perfectly stable results for different cable lengths and load conditions as well as for load changes. However, the system requires information about the actual values of stator current and rotation speed of the asynchronous motor. This can be regarded as a disadvantage of that system design.

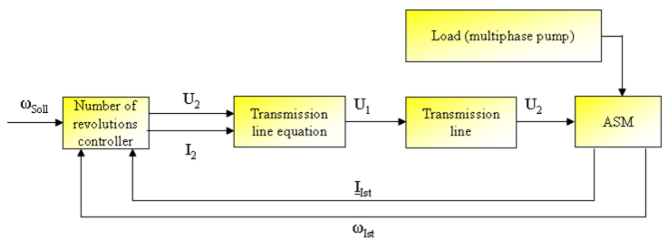

Figure 8: closed-loop control system the operation of the asynchronous machine

3.3.1 System characteristics without cable

In Figure 9 the rotary speed over the time is shown for a load change from rated load down to idling. At the beginning, the machine comes up to rated rotations speed and at t = 20 s the load is shedded. As shown in Figure 9, the rotation speed increases but finally come into a stable condition.

Figure 9 shows also the voltage during the run-up and the load shedding process. The voltage remains within a certain level around the rated voltage. During load shedding of the maximum level from rated load down to idling, the system remains in a stable condition.

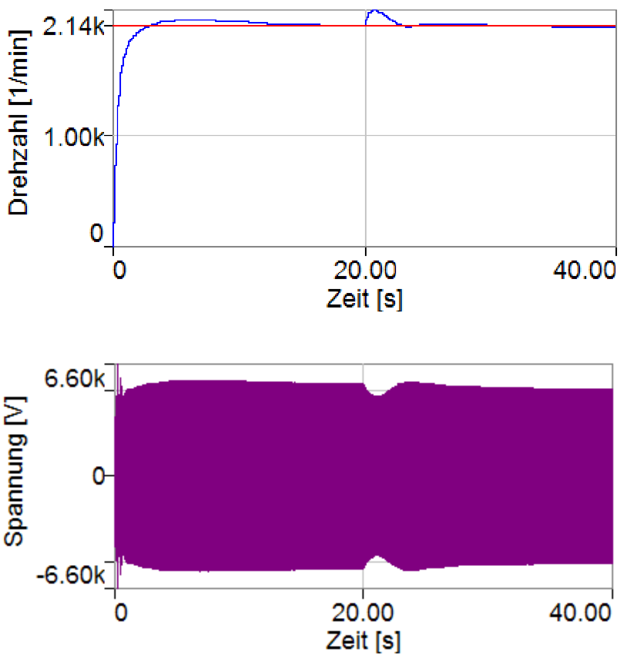

Figure 9: Rotation speed and voltage at the terminals of the asynchronous machine during run-up of the machine and during load shedding from rated load down to idling **without cable**

3.3.2 System characteristics with cable

The characteristic with a cable of 100 km length results in worse system characteristics. Figure 10 shows rotation speed and voltage at the input (u1) and output (u2) of the cable during run-up. The system needs more time to accelerate up to nominal speed. The voltage at the cable input needs to be much higher than at the output. The power losses are remarkable. Using a 1200 kW machine, the input power into the cable is 2060 kW and the output is 1240 kW. Thus, the efficiency is about 60%.

Another problem is the operation under various load conditions. Simulations showed that there could occur unstable conditions if the load shedding is too high or the rotation speed is far away from the nominal value when the load shedding happens. Thus, load shedding can not be the maximum level of rated load at each rotation speed.

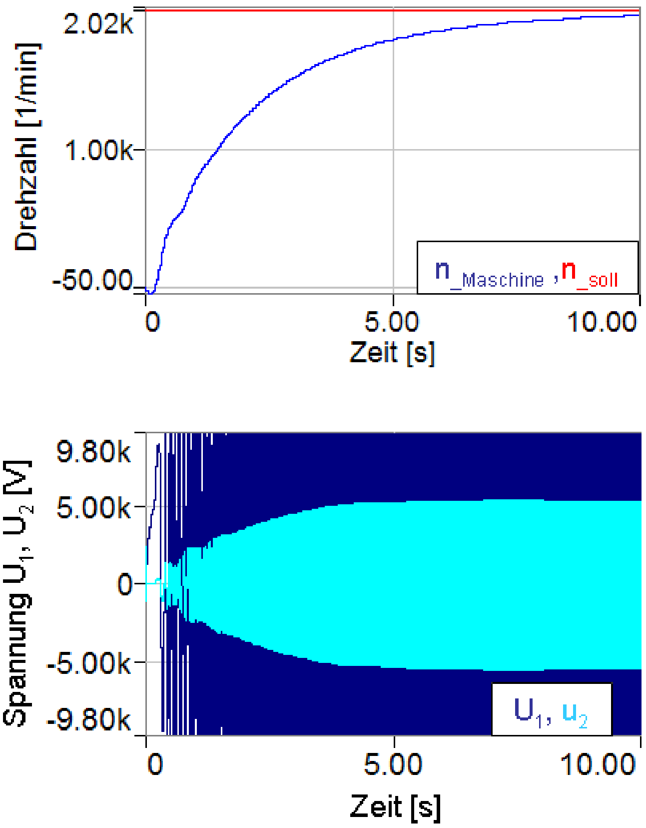

Figure 10: Rotation speed and voltage at the terminals of the asynchronous machine during run-up of the machine and during load shedding from rated load down to idling **with cable (length 100 km)**

4 Limitations and future work

Problematic for the system stability is load shedding or a step-like increase of load by the multiphase pump. In order to investigate if there is really a problem in practise, the load characteristics of the multiphase pump have to be included into the model and simulation in more detail. It is well known that torque pulses can occur. Further the range of load change must be defined in more detail. Using this information, the control system can be optimized.

Another area for future investigations is the question which quantities are really required for system control. The current design requires the currents of all three phases into the machine as well as the rotation speed. However, the system gets more simple if some of these quantities need not to be measured.

5 Literature

[1] Dierk Schröder: "Elektrische Antriebe – Grundlagen", Springer Fachbuch, Springer Verlag, 4. Auflage 2009, ISBN 978-3-642-02989-9

[2] Dierk Schröder: "Elektrische Antriebe – Regelung von Antriebsmaschinen", Springer Fachbuch, Springer Verlag, 3. Auflage 2009, ISBN 978-3-540-89612-8