Low Frequency High Voltage Offshore Grid for Transmission of Renewable Power

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Abstract-- **AC Power transmission using underground cables at 50 or 60 Hz is limited by the charging current and thus the distance. Often this is the reason to change to the DC technology. However, there is an intermediate solution of low frequency operation allowing longer distances from offshore platform to the onshore station. The railroad frequency of 16.7Hz at the voltage level of 145 kV is fully developed, field proven and in broad commercial use. A higher transmission voltage of 220 kV seems doable. Also 3 core AC submarine cables are commercially available, and can be used without any changes at reduced frequency. This paper presents a preliminary basic design of the low frequency offshore link and discusses the pros and cons in terms of technical feasibility for offshore installations as well as operational aspects.**

***Index Terms*—low frequency power transmission; offshore wind farm, HVDC, smart grid**

I. INTRODUCTION

THE limitation in fossil energy resources, the growing world population and the fast development of emerging industrialized countries are the basic motivations for a new approach in energy exploration, transportation, generation and consumption [1]. Germany has decided on energy transition for reducing CO2 emission and for avoiding potential nuclear disasters by replacing fossil and nuclear generation with renewable energies [2],[3]. Therefore Germany has to cope with two dramatic changes with regard to its electricity supply

1) large amount of renewable power remotely generated e.g. offshore
2) small power generation connected to low and medium voltage grids near load centers

Major wind farm parks will be installed offshore in the North and Baltic Seas. Currently the Transmission System Operators (TSOs) at the coast are legally obliged to take the offshore generated electricity from the platform near the wind farm. Typically renewable power has to be transmitted from offshore to onshore over a distance of 50 to 300 km with a capacity in the range of 50 to 900 MW.

On the basis of technical feasibility and economic viability, the transmission technology to be selected as of now is either alternating (50 Hz) or direct current (0 Hz).Since the commissioning of the different wind farm parks takes place in stages, each one is individually connected to the nearest onshore substation. There is no coordinated planning in place. An offshore DC grid is not possible due to the non-availability of DC circuit breakers (CB) and DC/DC converters which would be needed to connect DC links of different voltage levels.

In this paper the authors suggest using reduced frequency transmission, for example the railway frequency of 16.7 Hz, for the connection of offshore wind farms to the grid instead of the HVDC transmission [4]-[6]. Wind turbines would be able to generate power directly at this frequency. Traditional equipment like transformers, XLPE submarine cables, circuit breakers could be used and are available. Due to the reduced frequency the transmission distance at 16.7 Hz can reach 300-400 km. Thus all wind farms currently under consideration could be linked to the main grid without any offshore converter station. Besides, the AC/AC frequency converters which would be needed onshore to connect 16.7 Hz to the 50 Hz grid are well developed for the railway supply. The authors will discuss the main technical aspects of the proposed approach including the available components that could be used. Simulation results will show the performance of transmission system at 16.7 Hz in comparison to 50 Hz.

II. TECHNICAL SOLUTIONS FOR OFFSHORE POWER TRANSMISSION

The sea water obviously precludes transmission links using overhead line towers and air insulated conductor systems. Therefore the industry has developed reasonable and efficient submarine cable solutions. For instance the North African Continent and Europe are linked via an AC submarine cable of approximately 30 km length at 50 Hertz and 400 kV voltage level [7]. Another example for water crossing via AC sea cables is the interconnection within the Gulf Cooperation Council (GCC) Grid to supply 600 MW at 400 kV and 50 Hertz to Bahrain. The total length is less than 50 km [8]. Longer distances cannot be bridged by ac submarine cables since the charging reactive current reduces the amount of active current over the distance until it becomes technically impossible or economically not reasonable.

Due to the current opinion 50 Hz transmission via submarine cable is possible up to 100 km. Longer transmissions would result in considerably higher reactive

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currents at both ends of the cable which, on the other hand, would limit the available active power transmission capacity. Besides, the voltage increase along the cable and the transmission losses would be significant. Therefore in the past the only alternative to 50 Hz AC technology seemed to be the HVDC (High Voltage Direct Current) transmission. The HVDC technology is still very costly due in part to the expensive converters at each end as well as the need to place one of the converters including the associated sensitive equipment on an offshore platform which increases the capital and operational expenditures.

In contrast, an economic as well as reliable and technically proven technology is offered by 16.7 Hz (≈50/3Hz) which has been developed for the railway grid and is in use since several decades. There are comprehensive experiences and knowledge available from the 110 resp. 132 kV single phase 16.7 Hz high voltage transmission systems operated in Austria, Switzerland. Based on these operational experiences and the familiarity with the components, installing and operating a low frequency offshore grid safely and in a secure mode seems to be easy. At one-third of the grid frequency the charging reactive current is also one-third of the corresponding 50 Hz value only. Therefore the reach of the cable could be approximately three times longer until the reactive current occupies the cross section of the cable to such an extent that any transmission of active current becomes impossible or economically unattractive. Fig. 1 shows a comparison of the suggested 16.7 Hz and the HVDC offshore links.

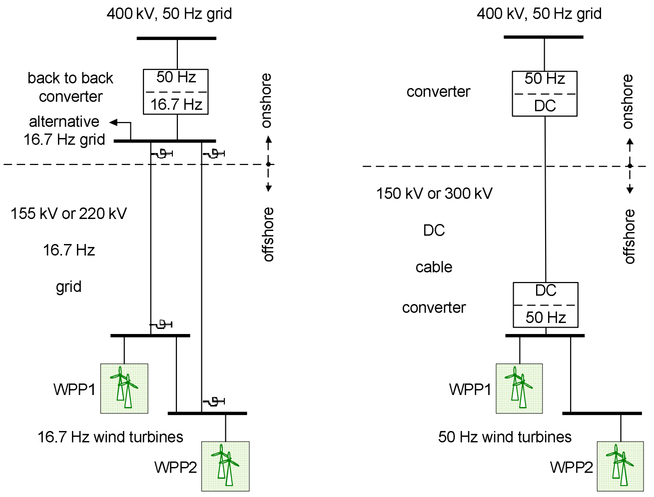

Fig. 1 Comparison of AC 16.7 Hz and DC offshore links

For the suggested low frequency grid at 16.7 Hz only one back-to-back frequency converter is needed which will be located onshore with easy access for maintenance and operation. However it has to be mentioned that the transformers and shunt reactors will be larger in volume and thus heavier due to the larger core cross-section at the same allowable flux density. In case of full converter technology, adapting the converter to the 16.7 Hz frequency is the only change from the current practice. For DFIG based wind turbines a considerably larger and heavier doubly-fed induction generator is required, which makes this kind of wind turbines for 16.7 Hz application unattractive. However, one of the key points of the approach suggested is using reduced frequency throughout the whole offshore grid. Therefore, adaptation of existing full rated converter based wind turbines for 16.7 Hz is one of the preconditions.

An overwhelming advantage of the proposed concept of low frequency offshore grid is that submarine cable links of different voltage levels originally planned and installed as separate projects could be interconnected with one another to an offshore grid similar to the commonly used practice in onshore grids. The availability of the AC breakers and proven protection systems will allow the detection and clearance of faults with the required speed to ensure the security of the supply. In general establishing a meshed 16.7 Hz AC offshore grid seems to be, in contrast to meshed DC grid, much less challenging and realistic by using largely existing equipment.

The converter in the suggested approach is located onshore. Therefore, it is not exposed to environmental stresses as it is with the HVDC converters located on the offshore platform. Both components of the converter, the inverter on the 50-Hz and the rectifier at the 16.7-Hz g sides, are at the same location so that operation and control as well as maintenance become easier. The converters are already being developed for single phase railway supply. The extension to three-phase system on the 16.7 Hz side is not substantial and would allow even some simplifications concerning the required filter. Also the application of new sophisticated technologies like direct AC/AC multilevel converters would be possible.

It should be also mentioned that the 16.7 Hz grid could be extended to onshore leading to an onshore overlay transmission grid. 50/16.7 Hz converters would in this case be shifted to the connection points of both grids, and this may be located in distant location from the shore.

III. COMPONENTS FOR TRANSMISSION AT 16.7 HZ

A. Submarine Cables

AC submarine cables for 50/60 Hz and voltages up to 400 kV are in commercial operation for several decades now and there is no difference in design between cables with a frequency of 16.7 Hz or 50/60 Hz. At 16.7 Hz the thermal rating under the same environmental conditions is even higher, as sheath and dielectricity losses are lower. Also, the resistance of the cable is lower due to lower skin effect. Table I and II show the loadability and typical parameters of 155 kV and 220 kV 1200 mm^2 Cu wire submarine cables for both 50 Hz and 16.7 Hz. As can be seen, there is a considerable increase in loadability at 16.7 Hz frequency.

TABLE I

CAPACITY AND PARAMETERS OF AVAILABLE 155 KV (MAX. 170 KV) 1200 MM^2 CU SUBMARINE CABLE

Parameter	50 Hz	16.7 Hz
I_{max}	1012 A	1230.4 A
S_n	271.7 MVA	330.3 MVA
R’	25 mOhm/km *)	16.6 mOhm/km
L’	0.426 mH/km	0.426 mH/km
X’	133.8 mOhm/km	44.6 mOhm/km
C’	236 nF/km	236 nF/km

TABLE II

CAPACITY AND PARAMETERS OF AVAILABLE 220 KV (MAX. 245 KV) 1200 MM^2 CU SUBMARINE CABLE

Parameter	50 Hz	16.7 Hz
I_{max}	1262 A	1534.3 A
S_n	480.9 MVA	584.7 MVA
R’	25 mOhm/km	16.6 mOhm/km
L’	0.3661 mH/km	0.3661 mH/km
X’	115 mOhm/km	38.333 mOhm/km
C’	183 nF/km	183 nF/km

B. Gas Insulated Switchgear (GIS)

Hermetically sealed GIS switchgear with SF6 circuit breakers (CB) for 16.7 Hz are already in commercial operation for several years in the railway grids of Deutsche Bahn (DB) Energie and Swiss Federal Railways (Schweizerische Bundesbahn (SBB)). Development for higher voltages, in the opinion of the authors, could be accomplished within approximately one year. CBs for the next higher insulation level of 245 kV and 16.7 Hz would be based for instance on CBs for 300 kV rating and 50 Hz. It is important to mention that compared with the operational conditions in single phase railway networks the short circuit level within offshore grids are much lower, making the operational challenges in 16.7 Hz offshore grid in terms of short-circuit interruption easier.

C. Power Transformers and Shunt Reactors

Single phase power transformers for 16.7 Hz currently in operation have ratings of up to 187.50 MVA a weight of about 200 tons and primary voltages up to 145 kV. For hermetically sealed transformers – recommended for offshore operation - on-load tap-changers are technically available but not yet in common use. For design and manufacturing of three phase 16.7 Hz transformers no significant R&D costs are to be expected. However, the design should focus on weight optimisation. Three phase transformers for 16.7 Hz will weigh at least twice that compared to 50 Hz transformers of the same rating. Noise and loss optimisation may be neglected. The same applies to shunt reactors.

D. Protective Systems

For the cable systems and power transformers the differential protection is the same as that used for 50 Hz systems. Note that the three core submarine cables have in-built fibre optic wire suitable for fast acting protective systems. With the fibre optic elements the thermal loading of the submarine cables can be monitored, to help avoid overload and accelerated aging.

E . 3phase 50/16.7 Hz Frequency Converter

Standard back to back stations already in operation for connecting 50 Hz with 60 Hz networks need to be modified for 16.7/50 Hz operation. A 3 phase frequency converter could be equipped with thyristors operating as line commutated converters or with IGBTs (insulated gate bipolar transistor) operating as voltage sourced converters for the commutation process. For the supply of railway grids fully developed 50/16.7 Hz converters are available which can be easily extended to three phase operation on the 16.7 Hz side. The technology to be chosen is the optional decision of the planner. Appropriate modifications in control and for suppression of harmonics should be considered. All in all a fundamental change in system and component design which might necessitate additional research cannot be anticipated.

For the proposed transmission scheme with 16.7 Hz no converters need to be installed offshore. This will lead to considerable cost savings on both investment as well as operation and maintenance costs. It will also reduce downtime and thus will increase the availability of the offshore wind power. Further savings can be achieved by installing both parts of the converter, in contrast to HVDC transmission, in the same location. If only unidirectional power transmission is to be considered, even standard thyristor type converters can be used.

F. Outlook

It can be concluded that except for on-load tap changer for hermetically sealed transformers/shunt reactors and for circuit breakers with nominal voltages above 170 kV, no major R&D effort are to be borne. Time required to develop new equipment is well within the typical time span for planning, installation and construction time needed to implement the overall offshore generation platform und transmission grid. For the 16.7 Hz three phase submarine cable transmission basic research is not required for any of the components.

IV. COMPARISON OF TRANSMISSION CHARACTERISTIC AT 50 HZ AND 16.7 HZ

Power transmission via AC underground cable is considerably limited by the capacitive charging current I_C which is about 15 - 25 times higher than that of overhead lines.

$$I_C = \frac{U_n}{\sqrt{3}} \cdot 2\pi f_n \cdot C_1 \cdot l \qquad (1)$$

Where U_n , f_n are nominal voltage and grid frequency, respectively, C_1 positive sequence capacitance per km and l the length of the cable. Due to the large charging current for the operation of long cables - such as those required for offshore wind farm links - it is necessary to connect shunt reactors in both ends of the cable which are usually switched together with the cable so that the capacitive switching capability of the circuit breakers are never exceeded. The capacity of reactors is calculated usually with the nominal voltage and frequency according to (2).

$$Q_C = \frac{1}{2} \cdot U_n^2 \cdot 2\pi f_n \cdot C_1 \cdot l \qquad (2)$$

In practical operation the frequency may differ from the nominal value and also the voltage along the cable doesn't correspond exactly with the nominal voltage. Therefore, a small mismatch in compensation is always a possibility. Sometimes the cable is intentionally undercompensated to keep capacitive power available for the grid, which typically has to supply reactive load.

The maximum distance between two reactors is a tradeoff between utilization of the cable capacity for power transmission and the additional cost for installing several reactors. As can be seen in Fig. 2 the charging current of the cable reaches the full loading capacity of the cable already at distances of up to 140 km for 155 kV cables without compensation of charging current and 270 km if shunt reactors are installed in both ends. However, in this case the reactive charging current occupies the transmission capacity entirely so that no active power transmission is possible anymore. In onshore applications the distribution of compensation devices along the cable and thus extension of the transmission capability usually does not represent a challenging problem. However, offshore the connection of shunt reactors is possible only in both ends; otherwise additional offshore platforms would be needed. As a general principle nowadays the practical limit for 50 Hz AC submarine cable is considered to be about 100-140 km using compensation in both ends. For longer distances it was assumed that DC transmission is the only alternative.

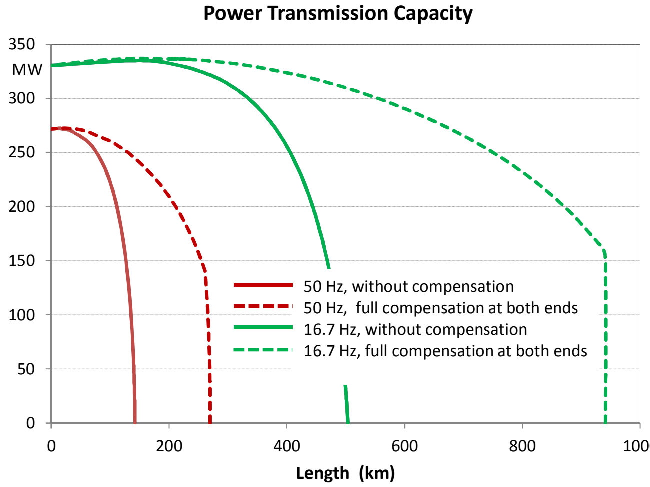

Fig. 2 Power transmission capacity of 155 kV 1200 mm^2 Cu submarine cable by 50 Hz and 16.7 Hz (Cable parameters from Table I and II)

However, as can be seen from Fig. 2 the possible distance at 16.7 Hz is much longer, even more than three times the available distance at 50 Hz, against expectations from the ratio of frequencies. This is partly due to the fact that the current loadability using 16.7 Hz is higher, due to the reduced resistance as a result of lower skin-effect. Besides, the transmission characteristic along the cable is better as reflected by improved voltage profile and more uniform current distribution. To get results closer to the reality, for the diagrams shown in Fig. 2 the cable was modeled using 100 Pi-sections. It is interesting to note that at the sending-end section of the cable, the loadability increases slightly with increasing distance. The effect is observable for both frequencies but at 16.7 Hz it is more pronounced. In practical applications, transmission over the distance of about 400 km seems to be possible. Fig. 3 shows the transmitted power and the corresponding losses (I^2R-losses) over the length of up to 400 km. Under no load conditions the charging current will cause transmission losses in 400 km 155 kV cable which is less than the converter losses in using the alternative HVDC approach.

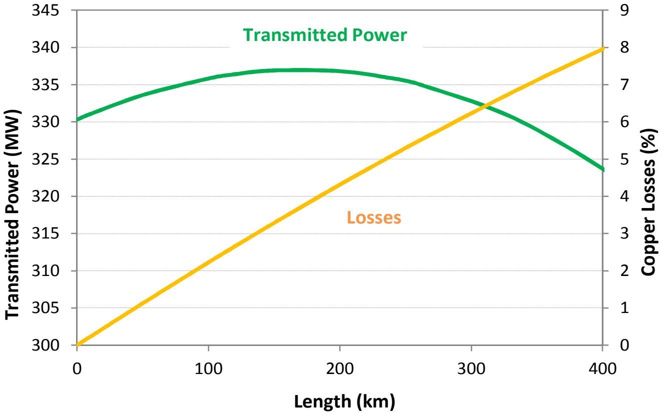

Fig. 3 Maximum power transmission through 155 kV 1200 mm^2 Cu submarine cable and corresponding I^2R losses by operating with 16.7 Hz

The Fig. 4 shows a comparison of transmission I^2R-losses for 50

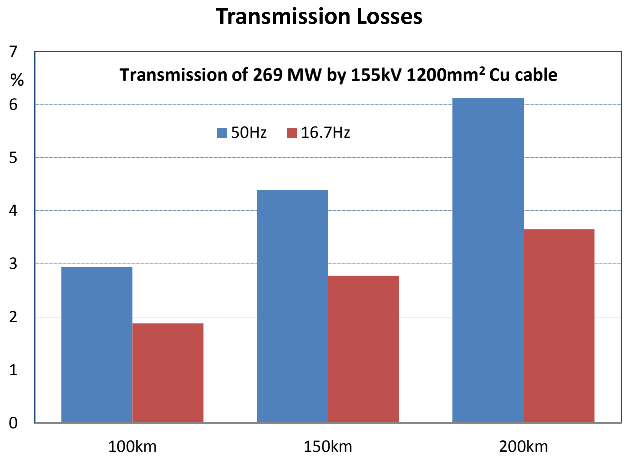

Fig. 4 Comparison of transmission I2R-losses at 50 Hz and 16.7 Hz

Figs. 5 to 8 show the current distribution and the voltage profile along the AC cable in a transmission system with 50 Hz and 16.7 Hz, respectively. Common to both frequencies is that the maximum current appears at the ends of the cable. However, the minimum current in the middle is lower for 50 Hz. In other words the current is more uniformly distributed along the cable for 16.7 Hz which is more favorable. Due to this characteristic the loading at both ends decreases with increasing distance in 16.7 Hz operation. In contrast, at 50 Hz the current in the ends increases for longer distances which will limit the transmission capability. The voltage profile along the cable is more flat at 16.7 Hz. The voltage increase is less even though the transmission distance considered in this example for 16.7 Hz is longer than that of 50 Hz.

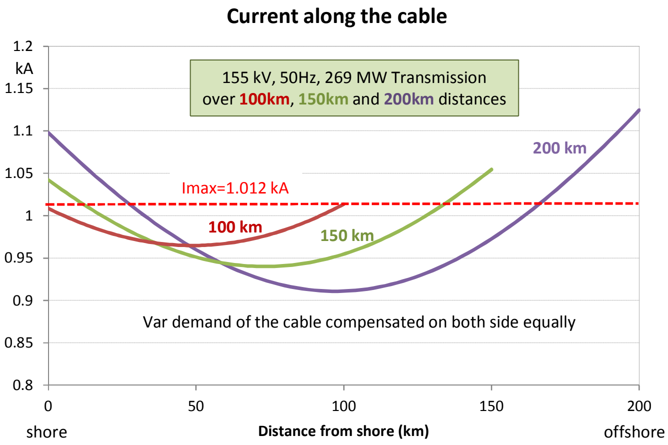

Fig. 5 Current profile along the cable operated with 50 Hz

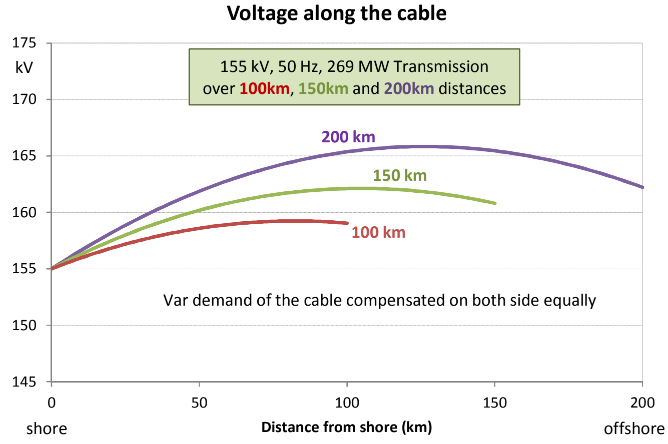

Fig. 6 Voltage profile along the cable operated with 50 Hz

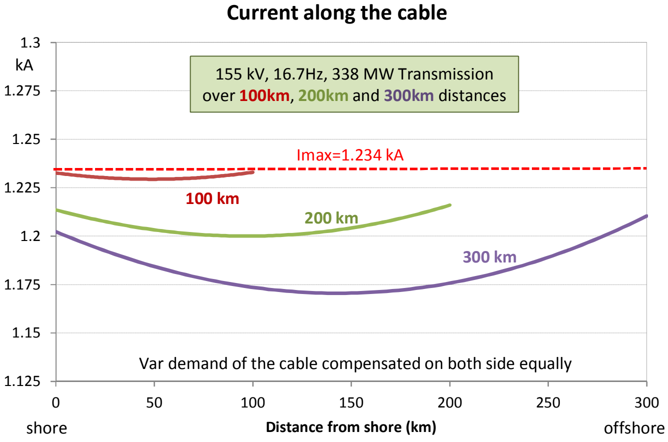

Fig. 7 Current profile along the cable operated with 16.7 Hz

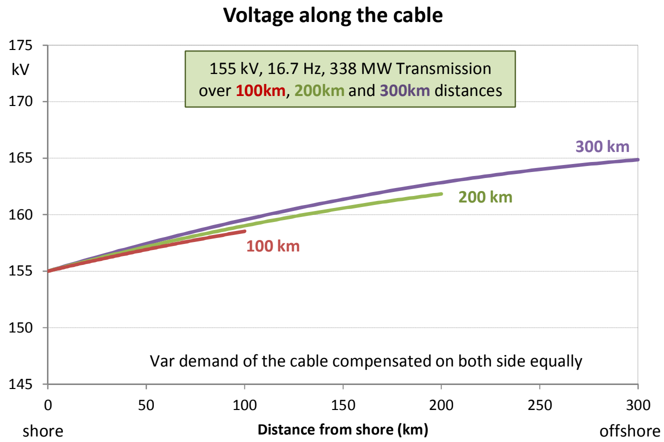

Fig. 8 Voltage profile along the cable operated with 16.7 Hz

For both frequencies the best transmission characteristic can be achieved if the required reactive power is provided from both sides of the cable equally. This includes not only the shunt reactors installed for the compensation of capacitive charging current but also the inductive power absorbed by the cable inductance ($3I^2X$).

In this section the authors have shown simulation results only for 155 kV submarine cables due to the fact that this is the cable currently considered in most AC applications. However, 220 kV cables are also available nowadays. The discussions and conclusions deduced for 155 kV are applicable to the 220-kV cable as well.

V. CONCLUSIONS

The offshore grid at a frequency of 16.7 Hz offers several benefits in comparison to 50 Hz or even 0 Hz .Fig. 9 highlights the major advantages.

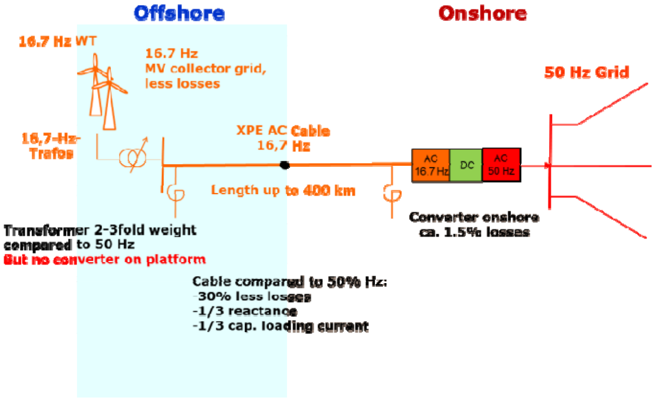

Fig. 9 Current profile along the cable by operating with 16.7 Hz

The most salient observations can be summarized as follows:

- In general the offshore grid will consists of field proven components for which suppliers are already available in global market.
- The charging current for the submarine cable will be only a third of a 50-Hz installation of equal rating, which allows using the cable link for more than triple the length.

- The transmission losses are lower at 16.7 Hz.
- Connection of existing submarine cable links, even of different voltage levels to a meshed AC grid can easily be performed.
- Stagewise installation of large wind parks can be managed much more economically with the added advantage of using field proven AC components.
- Using redundant grid design and operation the security of supply can be as good as that of the onshore AC grids at 50 Hz. It could meet the transmission code of ENTSO-E.
- For fault clearing there are AC breakers available for safe and fast fault clearance. The protection systems for reliable fault detection are in the market as well.
- The electronic converters will be located onshore, off the coast line with easy access and independent of any weather condition.
- Optionally the 16.7 Hz grid can be extended to an onshore high voltage overlay grid.
- All components on the platform will be encapsulated and hermetically enclosed .So the salty and humid atmosphere of the sea cannot harm the availability of the electrical equipment.

However it should be mentioned that the transformers and shunt reactors operated at that low frequency will be larger and heavier because of the bigger iron core needed for the transformation.

However, the concept of a low frequency high voltage offshore grid for transmission of renewable power is technically feasible. The economic advantages are to be elaborated in a separate feasibility study. But by knowing and weighing the pros and conts the authors are sure that a secure AC offshore grid exceeds any other offshore transmission especially if the interruption time i.e. loss of the power supply to the electricity consumers is economically considered.

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VII. BIOGRAPHIES

Wilfried Fischer (1948) received his Dipl.-Ing. degree in electrical engineering from the Technical University of Darmstadt in 1976. After his studies, he worked on ac transmission projects especially in Middle East. Mid of 80s he changed to the HVDC business field within Siemens. He managed several HVDC projects in Europe and US. Since 2004 he is in charge of the AC grid extension with the TSO 50 Hertz Transmission GmbH. He is a member of VDE and member of IEEE PES.

Rainer Braun (1950) received his Dipl.-Ing degree in Electrical Engineering from the Technical University Berlin in 1979. After his studies he work until 1999 for the Consulting Company Lahmeyer International in the field of Electrical Power Transmission. He was involved in a large number of power system studies for utilities worldwide. His studies included load flow, short circuit und stability studies for large power networks.

During this time he was also working 2 years for Siemens AG in the field of HVDC power transmission. Since 1999 he is working in various positions as Department/Division Head for DB Energie GmbH the Power Supply Company for the Deutsche Bahn. He was responsible for the technical development of 16,7 Hz components for both transmission and distribution grid.

István Erlich (1953) received his Dipl.-Ing. degree in electrical engineering from the University of Dresden/Germany in 1976. After his studies, he worked in Hungary in the field of electrical distribution networks. From 1979 to 1991, he joined the Department of Electrical Power Systems of the University of Dresden again, where he received his PhD degree in 1983. In the period of 1991 to 1998, he worked with the consulting company EAB in Berlin and the Fraunhofer Institute IITB Dresden respectively. During this time, he also had a teaching assignment at the University of Dresden. Since 1998, he has been Professor and head of the Institute of Electrical Power Systems at the University of Duisburg-Essen/Germany. His major scientific interest is focused on power system stability and control, modeling and simulation of power system dynamics including intelligent system applications. He is a member of VDE and senior member of IEEE. He is also chairing the IFAC Technical Committee on Power and Energy Systems.