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Offshore Wind Farm with DC/AC/AC Converter for Low Frequency AC Transmission System

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Abstract**—** *The possible solutions for transmitting power from wind farms are HVAC, Line commutated HVDC and voltage source based HVDC (VSC-HVDC). In this paper Low Frequency AC (LFAC) transmission system is used for interconnecting the offshore wind farms for improving the transmission capability and also the dc collecting system with series connected wind turbines are used at the offshore to reduce the cabling requirement. A method to design the systems components and control is set forth. Simulation results are provided to illustrate the systems performance*.

Keywords**—** *Power transmission, thyristor converters, under water power cables, wind energy.*

I. INTRODUCTION

The increasing interest and gradual necessity of using Renewable resources, such as wind, solar and hydro energy, have brought about strong demands for economic and technical innovation and development. Especially offshore wind farms are expected to represent a significant component of the future electric generation selection due to larger space availability and better wind energy potential in offshore locations. In particular, both the interconnection and transmission of renewable resources into synchronous grid systems have become promising topics to power engineers. For robust and reliable transmission and interconnection of renewable energy into central grid system Switching systems have been used, Since switching systems can easily permit excellent controllability of electrical signals such as changing voltage and frequency levels, and power factors. At present, high-voltage ac (HVAC) and high-voltage dc (HVDC) are well-known technologies for transmission HVAC transmission is advantageous because it is somewhat simple to design the protection system and to change voltage levels using transformers. However, the substantial charging current due to the high capacitance of submarine ac power cables reduces the active power transmission capacity and limits the transmission distance. Therefore HVAC is adopted for relatively short underwater transmission distances. HVAC is applied for distances less than 60km for offshore wind power transmission.

Two classes of HVDC systems exist, depending on the types of power-electronic devices used line-commutated converter HVDC (LCC-HVDC) using thyristors and voltage-source converter HVDC (VSC-HVDC) using self commutated Devices, for example, insulated-gate bipolar Transistors (IGBTs)[The major advantage of HVDC technology is that it imposes effectively no limit on transmission distance due to the absence of reactive current in the transmission line. LCC-HVDC systems can transmit power up to 1GW with high reliability LCCs consume reactive power from the ac grid and introduce low-order harmonics, which results in the requirement for auxiliary equipment, such as, ac filters, static synchronous compensators and capacitor banks. In contrast, VSC-HVDC Systems are able to independently regulate active and reactive power exchanged with the onshore grid and the offshore ac collection grid the reduced efficiency and cost of the converters are the drawbacks of VSC-HVDC systems. Power levels and reliability are lower than those of

LCC-HVDC. HVDC is applied for distances greater than100 km for offshore wind power transmission. In addition HVAC and HVDC, high-voltage low frequency (LFAC) transmission has been recently proposed InLFAC systems, an intermediate frequency level 16.66 or 20Hz is used, which is created by using a cycloconverter, that lowers the grid frequency to a smaller value, normally to one-third its value. In general, the main advantage of the LFAC technology is the increase of power capacity and Transmission distance for a given submarine cable compared to 50-Hz or 60-Hz HVAC This leads to substantial cost savings due to the reduction in cabling requirements (i.e. fewer lines in parallel for a required power level) and the use of normal ac breakers for protection. In this paper, a novel LFAC transmission topology is analyzed. The proposed system differs from previous work. Here the wind turbines are assumed to be

Interconnected with a medium-voltage (MV) dc grid, in contrast with current practice, where the use of MVac collection grids is standard DC collection is becoming a feasible alternative with the development of cost-effective and reliable dc circuit breakers, and studies have shown that it might be advantageous with respect to ac collection in terms of efficiency and reduced production cost The required dc voltage level can be built by Using the series connection of wind turbines For example, multi MW permanent-magnet Synchronous generator (PMSG) with fully Rated power converters (Type-4 turbines) are Commonly used in offshore wind plants eliminating grid-side inverters, a medium-voltage collection system can be formed by interconnecting the rectified output of the generators. The main reason for using a dc collection system with LFAC transmission is that the wind turbines would not need to be redesigned to output low-frequency ac power, This would lead to larger, heavier, and costlier magnetic components such as step-up transformers and generators. The proposed LFAC system could be built with commercially available power system components, such as the receiving-end transformers and submarine cables designed for regular power frequency. The phase-shift transformer used at the sending end could be a 60-Hz

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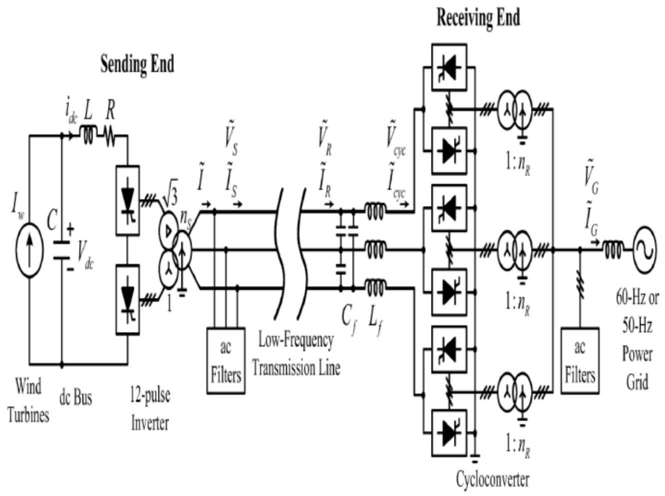
transformer de rated by a factor of three, with the same rated current but only one-third of the original rated voltage. Another advantage of the proposed LFAC scheme is its feasibility for multiterminal transmission, since the design of multiterminal HVDC is complicated, but the analysis of such an application is not undertaken herein.

In summary, LFAC transmission could be an attractive technical solution for medium-distance transmission i.e., 50 to160km.The structure of this paper is as follows. The principle and configuration of the system is briefly explained in section II. The control strategies of converters are discussed in section III. The selection of the major system components and filter design are discussed in Section IV. Simulation results are presented in section V and finally section VI concludes this paper.

II. SYSTEM CONFIGURATION AND CONTROL

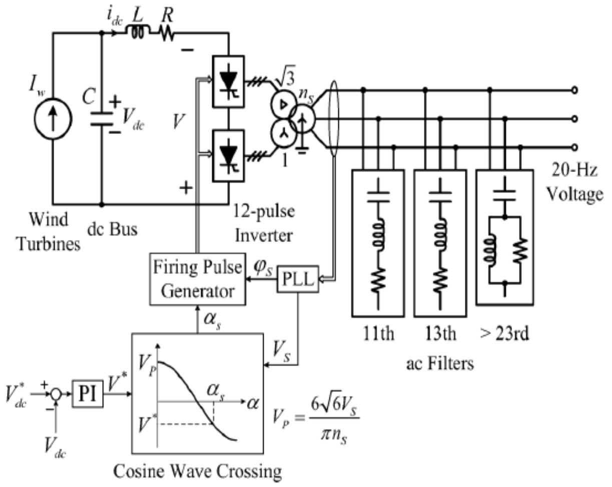


Configuration of the proposed LFAC transmission system

The proposed LFAC transmission system is shown in Fig.1, assuming a 60-Hz main grid at the receiving end. At the sending end, a medium-voltage dc collection bus is formed by rectifying the ac output power of series-connected wind turbines. A DC/AC 12-pulse thyristor-based inverter is used to convert dc power to low-frequency (20-Hz) ac power. It is connected to a three-winding transformer that raises the voltage to a higher level for transmission. AC filters are connected at the inverter side to suppress the 11th, 13th, and higher-order (23rd) current harmonics, and to supply reactive power to the converter.

At the receiving end, a three-phase (6-pulse) bridge cycloconverter is used to generate 20-Hz voltage. A filter (Lf -Cf) is connected at the low-frequency side to decrease the amplitude of the harmonics α side, ac filters are used to suppress odd power to the cycloconverter. Simply put, the operation of the LFAC transmission system can be understood to proceed as follows. First, the cycloconverter at the receiving end is activated, and the submarine power cables are energized by a 20-Hz voltage. In the meantime, the dc collection bus at the sending end is charged using power from the wind turbines. After the20Hz voltage and the dc bus voltage are established, the 12-pulse inverter at the sending end can synchronize with the 20-Hz voltage, and starts the transmission of power.

III. CONTROL OF LFAC SYSTEM



Sending end inverter control.

The control structure for the sending-end inverter is shown in figure 2. The controller regulates the dc bus voltage Vdc by adjusting the voltage V at the inverter terminals. The cosine wave crossing method is applied to determine the firing angle. Firing pulses are generated by the crossing points of both wanted and threshold voltages of reference voltages. This method demonstrates superior properties, such as minimum total harmonic distortion of output voltages, and simplicity of implementation. The firing angle for the 12pulse inverter is given

$$\alpha\, s = across\ \{ V^* / Vp \} \tag{1}$$

Where VP is the peak value of the cosine wave, V* is the reference voltage and αs is sending end inverter firing angle. Note that V<0 and 90<α<180 (using common notation), since the converter is in the inverter mode of operation. V and VS (line-to-neutral, r m s) are related by

$$V=6\sqrt{6}\ v_{S.}\ /\pi\ n_{s\ (COS}\ \alpha\ _{S)} \tag{2}$$

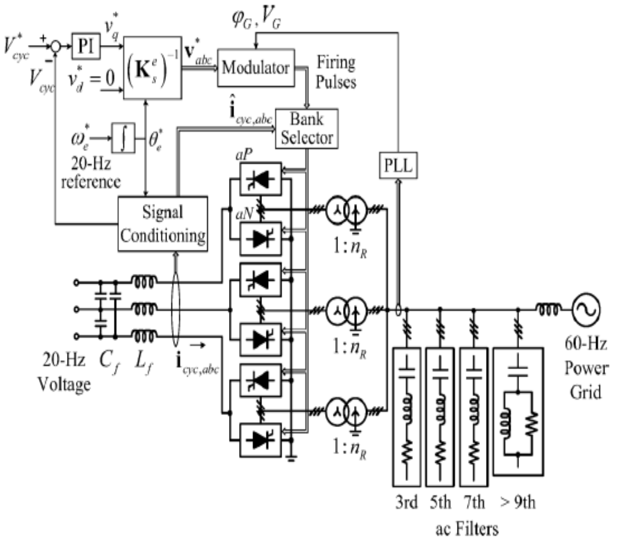
VA phase-locked loop (PLL) provides the angular position of the ac-side voltage, which is necessary for generating the firing pulses of the thyristors. It also outputs the r m s value of the fundamental of the voltage, which is used in the firing-angle calculation

The operating-frequency level in this work is limited to 20-Hz, since frequencies higher than 20Hz can cause high THD (Total Harmonic Distortion). The voltage level and phase angle are also controlled by the application of the cosine wave-crossing method, since electrical power (capacity) can be regulated by the voltage level and phase angle. The firing angles of the phase-positive and negative converters

$$Vap=3\sqrt{6}V_G\ /\pi\ n\ R\ COS\ (\alpha\ a\ p) \tag{3}$$

Where VG is the rms value of the line-to-neutral voltage at the grid side, and is the turn’s ratio of the transformers. The condition αaP+αaN=Π ensures that average voltages with the same polarity are generated from the positive and negative converter at the 20-Hz terminals. The firing pulses SaP and

SaN are not simultaneously applied to both converters, in order to obtain a non circulating current mode of operation. This functionality is embedded in the Bank Selector block of figure 5, which operates based on the filtered current. Note (for later use) that the maximum line-to-neutral rms value of the 20-Hz cycloconverter voltage is



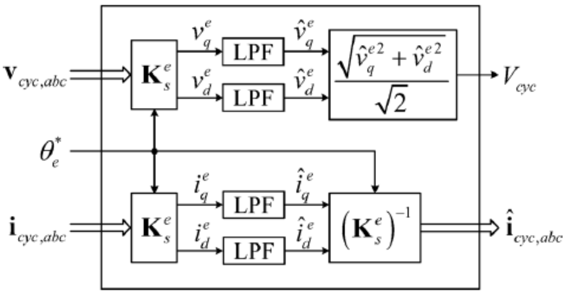
Receiving end cycloconverter control.

$V_{CYC}\ MAX = 3\sqrt{6}V_G\ /\pi\ n\ R$ (4)

The voltage ratio is defined as

$R = v_{cyc}/\ v_{cyc}^{max}$ (5)

In practice, the theoretical maximum value r=1cannot be achieved, due to the leakage inductance of the transformers, which was ignored in the analysis.

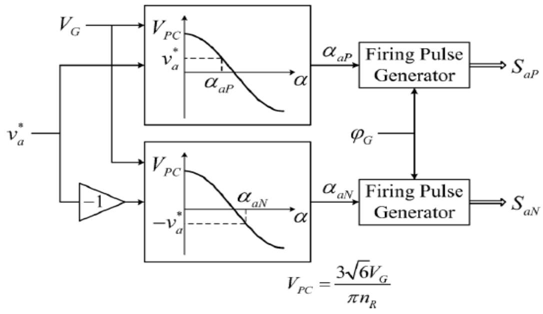


Details of signal conditioning block.

(LPF = Low Pass Filter)

Details of the signal conditioning block. (LPF= First-order low-pass filters, with time constants equal to 0.05 s and 0.01 s for the voltage and Current respectively.)

Voltage is fixed. Varying the transmitting angle from 0 to 180 degree, e.g. in figure 5, the transmitting power of the 50/3 Hz system is approximately 3 times of the conventional 50 Hz AC system at any transmission angle over e.g. 100 km length cable. Using a load with a constant power factor (0.8 lag) to replace the voltage source at the receiving end and increasing the cable length and the transmission angle, the PV curve with no compensation are plotted in figure 6. The PV curves of the both 50 and 50/3 Hz systems are moving left when increasing the cable length, meaning that the transmitting power is reduced accordingly. The red line represents the PV curve of the conventional 50 Hz AC system with the length of125 km whilst the solid and the dash blue lines represent the PV curves of the 50/3 Hz LFAC system in the length of 125 km and 375 km, respectively. It is observed that the Maximum power transmission occurs at the break pointing each system. The 50/3 Hz system can transmit much more power than the conventional 50 Hz system over the same distance. It also shows



Modulator for phase.

IV. FIXED SPEED WIND TURBINE BASED WIND FARM GIRD INTEGRATION

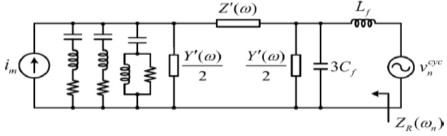
The wind turbines generally have 3 types: fixed-speed wind turbines with a capacitor compensator, induction generators with full size back-to-back converters and wind turbines with doubly-fed induction generators the induction generator with the full-size converter can be integrated to the LFAC system without any Difficulty, because the converter isolates the generator from the grid by the DC connection. The grid-side inverter has a Phase Lock Loop (PLL) to synchronize the frequency, for instance, the 50 Hz or 50/3 Hz. The wind turbine with a doubly-fed induction generator has two tracks: the stator connects directly to the grid and the rotor connects to the grid though the partial size converter. The doubly-fed generator is excited by the converter through the rotor circuit. The active power output is controlled according to the wind speed and the control strategy, e.g. the maximum power tracking strategy. Due to the lower grid frequency in the LFAC system, to produce the same amount of power without damage generators may require modified design to the wind turbine system e.g. increased rotating mass and number of poles and winding design for the induction generators

V. MAIN POWER COMPONENTS

The main power components are selected based on a steady-state analysis of the LFAC transmission system only fundamental components of voltages and currents are considered. The receiving end is modeled as a 20-Hz voltage source of nominal Magnitude. The power losses of the reactor, thyristors, filters, and transformers are ignored. The resistances and leakage inductances of transformers are neglected. The ac filters are represented by an equivalent capacitance corresponding to the fundamental frequency. The design is based on rated operating conditions (i.e., maximum power output).At the steady state, the average value of the current is Idc equal to Iw, so the power delivered from the wind turbines is system e.g. increased rotating mass and number of poles and winding design for the induction generators.

VI. FILTER DESIGN

At the sending end, the 12-pulse inverter Produces harmonics of order m=12k±1, k =1, 2,.., and can be represented as a source of harmonic currents. These current harmonics are filtered by two single-tuned filters for the 11th and 13thharmonic, and one damped filter for higher-order harmonics (≥23rd). Generally, the filter design is dependent on the reactive power supplied at fundamental frequency (also known as the filter size) and the required quality factor (QF). The total reactive power requirement of these filters can be estimated based on eq. (18). Here, it is assumed that the total reactive power requirement is divided equally among the three filters. A high quality factor (QF =100) is used for the single-tuned filters, and a low quality factor (QF = 1) is used for the high-pass damped filter. Finally, with the capacitance and quality factor known, the inductance and resistance of each filter can be determined. With such filter design, the 12-pulse-related current harmonics originating at the sending end are essentially absent from the transmission line. At the receiving end, there are two groups of filters, namely, the ac filters at the 60-Hzside and the *LC* filter at the 20-Hz side. At the 60-Hz side, if the cycloconverter generates exactly one-third of the grid frequency, that the line current has only odd harmonic components (3rd, 5th, 7th, etc). Sub harmonic and interharmonic components are not generated. Here, three single-tuned filters and one damped filter are used to prevent these harmonic currents from being injected into the 60-Hz Power grid. These filters are designed with a procedure similar to that for the ac filters at the sending end. At the 20-Hz side, the line-to-neutral voltage has harmonics of order 3, 5, 7without sub harmonic andinter harmonic components. However, the harmonic components of order equal to integer multiples of three are absent in the line-to-line voltage. Therefore, as seen from the 20-Hz side, the cycloconverter acts as a source of harmonic voltages of order n=6k±1,k=1,2,..., . The design of the *LC* filter has two objectives 1) To decrease the amplitudes of the voltage harmonics generated by the cycloconverter 2) To increase the equivalent harmonic impedance magnitudes seen from the receiving end, indicated by

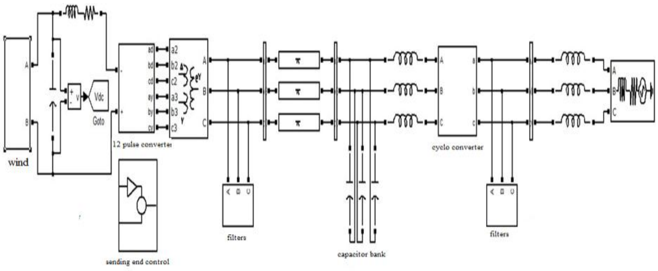


ZR (ωn) Equivalent circuit of the LFAC transmission system for harmonic analysis.

The 20-Hz LFAC system is designed to transmit 180MW over 160 km.

At the sending end, the dc bus voltage level is chosen as 30 kV and a 214-MVA, 132/13.2-kV, (ns=10), 20-Hz phase-shift transformer issued. Due to the lower frequency, this transformer would be larger compared to a 60-Hz transformer. This is a drawback of the proposed LFAC system. The total size of the ac filters at the sending end is 115MVAr. For the cycloconverter, the voltage generated at

VII. SIMULATION DESIGN OF PROPOSED SYSTEM

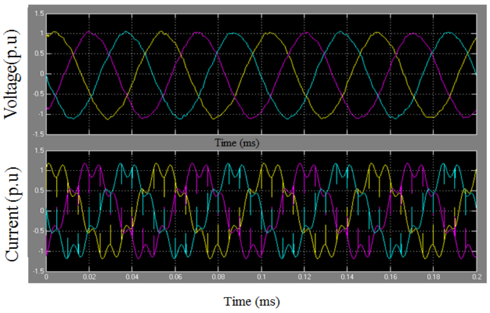


MATLab design model of proposed system.

To demonstrate the validity of the proposed LFAC system, simulations have been carried out using Mat lab/Simlink and the Piecewise Linear Electrical Circuit Simulation (PLECS) toolbox. The wind power plant is rated at 180 MW, and the transmission distance is 160 km. The transmission power cable is modeled by cascading 20 identical sections. The ABB 5 STP 42U6500 and the ABB 5STP 08F6500 thyristors are selected to construct the sending-end inverter and the receiving-end cycloconverter, respectively. Multiple series-connected thyristors (5 thyristors at the sending end and 30 thyristors at the receiving end) are used such that the rated voltage of a switch is 150% of the rated blocking voltage Shows the steady-state line-to-line voltage and current waveforms at the sending end, the receiving end, the 20-Hz side of the cycloconverter, and the 60-Hz power grid side under rated power conditions. The 20-Hz voltage generated from the cycloconverter has significant harmonic distortion (THD is 14.8%).Due to the *LC* filter, the voltages at the receiving and sending ends have reduced THD values (3.9% and 2.2%, respectively).

The measured fundamental power factor angle at the 20-Hzside of the cycloconverter is 34.9, which is close to the design requirement

Simulated Results of Proposed System Voltage and Current Waveforms at Sending End



(a) Sending end

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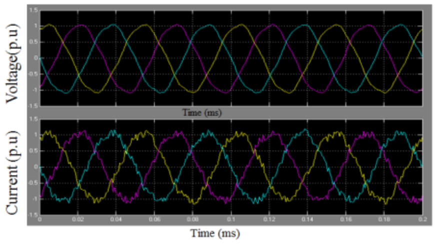
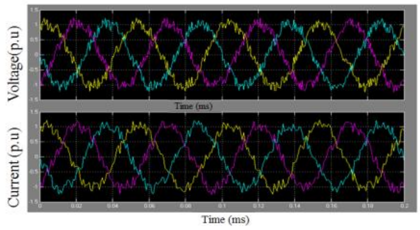
VIII. VOLTAGE AND CURRENT WAVEFORMS AT RECEIVING END



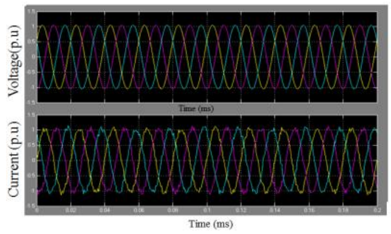
(b) Receiving end

IX. VOLTAGE AND CURRENT WAVEFORMS AT CYCLOCONVERTER 20HZ SIDE



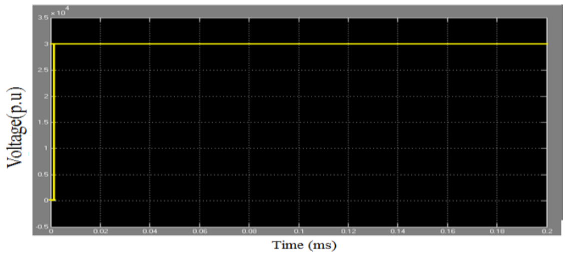
(c) Cycloconverter 20Hz side

X. VOLTAGE AND CURRENT WAVEFORMS AT 60HZ POWER GRID SIDE



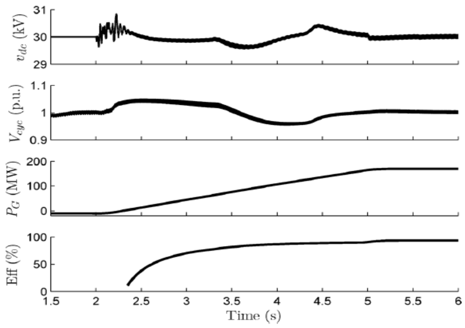
(d) 60Hz Power grid side

XI. VOLTAGE AND CURRENT WAVEFORMS OF DC VOLTAGE

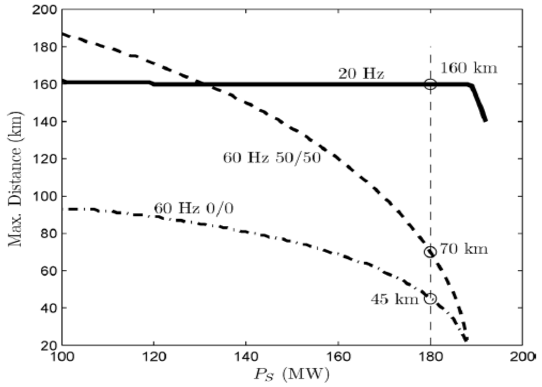


(e) Dc voltage

Simulated voltage and current waveforms



Transient waveforms during a wind power ramp event



Sending-end active power VS maximum transmission distance

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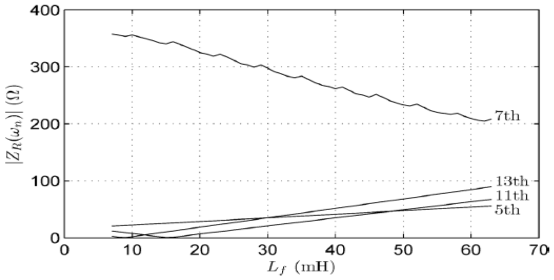
LC filter design characteristics



Equivalent impedance magnitude seen from the receiving end (n=5, 7, 11, 13)

XII. CONCLUSION

A low-frequency ac transmission system for offshore wind power has been proposed. A method to design the system's components and control strategies has been discussed. The use of a low frequency can improve the transmission capability of submarine power cables due to lower cable charging current. The proposed LFAC system appears to be a feasible solution for the integration of offshore wind power plants over long distances, and it might be a suitable alternative over HVDC systems in certain cases. Furthermore, it might be easier to establish an interconnected low-frequency ac network to transmit bulk power from multiple plants. In order to make better-informed decisions, it is necessary to perform a complete technical and economic comparison among HVAC, HVDC, and LFAC, evaluating factors, such as the transmission efficiency, investment and operating costs, and the performance under system transients

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