Low-Frequency AC Transmission System for Offshore Wind Farms

M. Manohara, S. Sonia

Abstract— **In recent years the amount of electricity produced from wind has grown rapidly. Offshore wind farm is currently seen as a promising solution to satisfy the growing demand for renewable energy source. The main reasons for the rapid development of offshore wind farms includes much better wind resources and smaller environmental impact. However, the current state of the offshore wind farms presents economic challenges significantly greater than onshore. The integration of offshore wind farms with the main power grid is a major issue. 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. In this paper, simulations are performed using MATLAB to illustrate the system's performance.**

Index Terms— High voltage ac (HVAC),high voltage dc (HVDC) thyristor converters, underwater power cables, wind farms, permanent magnet synchronous generator(PMSG).

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[1-3]. 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 than 60km for offshore wind power transmission. Two classes of HVDC systems exist, depending on the types of power-electronic devices used: 1) line-commutated converter HVDC (LCC-HVDC) using thyristors and 2) voltage-source converter HVDC (VSC-HVDC) using self-commutated devices, for example, insulated-gate bipolar transistors (IGBTs)[4]. 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 1 GW with high reliability[3]. 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[6-7]. 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 than 100 km for offshore wind power transmission.

In addition HVAC and HVDC, high-voltage low-frequency ac (LFAC) transmission has been recently proposed[8-9]. In LFAC systems, an

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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[11], in contrast with current practice, where the use of MV ac 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 costs.

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[10]. By eliminating grid-side inverters, a medium-voltage dc 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, which 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 ac cables designed for regular power frequency. The phase-shift transformer used at the sending end could be a 60-Hz 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 multi terminal transmission, since the design of multi terminal 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 to 160km.

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. Section IV analyses the simulation results and finally section V concludes this paper.

II. Principle and configuration of lfac system

A. Principle of LFAC system

For AC transmission system, the active power(p) transmitting over the transmission lines, which should be cables for connecting offshore wind farms ,which can be expressed by

$$P = \frac{V_S V_R}{X_L} \quad (1)$$

Where V_S and are V_R the sending end voltage and receiving end voltages, respectively. X_L is the line reactance. δ is the transmitting angle. Equation (1) is valid when the cable is short that neglects the effect of the line angle, increasingthe transmitting power is either by increasing the voltagelevel or lowering the impedance of the cable. Furthermore,with the fixed sending end voltages, the only way to improve the transmission capability by reducing theimpedance of the cable. The reactance is proportional to power frequency f,

$$X = 2\pi f L \quad (2)$$

Where L is the total inductance over the line, decreasingthe electricity frequency can proportionally increase the transmission capability. The LFAC system uses low frequency to reduce the reactance of the transmission system thus, its transmission capacity can be increased several fold. For instance, when frequency is 50/3 Hz, the theoretically transmission capability can be raised three times. The LFAC system can also improve the voltage stability given the same amount of reactive power transmission as given in eq.3.

$$\%\Delta V = \frac{QX}{V^2} * 100 \quad (3)$$

Where ΔV is the voltage drop over the cable, V is the nominal voltage, Q is the reactive power flow of the cable.Because the impedance is reduced in the LFAC system dueto the power lower grid frequency, the voltage drop overthe cable is proportionally reduced accordingly.

B. Configuration of LFAC system

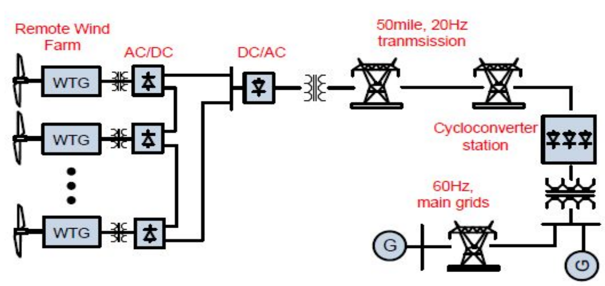

Fig.1. Configuration of the propoded LFAC transmission system

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 (L_f- C_f) is connected at the low-frequency side to decrease the amplitude of the harmonics generated by the cycloconverter. At the grid side, ac filters are used to suppress odd current harmonics, and to supply reactive 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 the 20-Hz 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. Components Of LFAC System and Its Control

For the LFAC-transmission systems, variable-speed wind turbine systems (Type-3 and Type-4 wind-generation units) are considered, since variable-speed wind generation systems are attractive for increasing energy capture and reducing mechanical-fatigue damage. The variable-speed wind turbine systems cannot be directly connected to grid systems and converters are used to connect systems with different frequencies. Power electronic devices have been used for the robust and reliable transmission and interconnection of renewable energy into central grid systems, since switching systems can easily permit excellent controllability of electrical signals; changing voltage and frequency levels, and power factors. Therefore at the sending end and receiving end thyristor based 12 pulse inverter and 6pulse bridge cycloconverter is used for conversion .

A. Inverter control

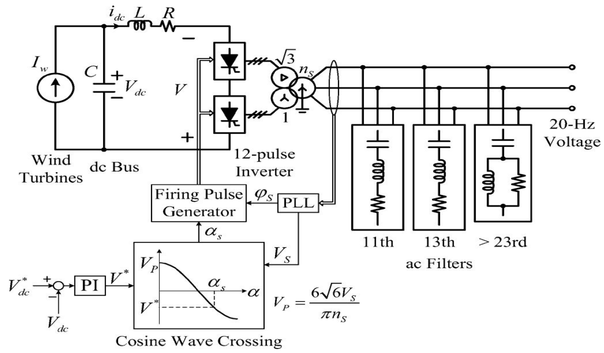

Fig .2. Sending-end inverter control.

The control structure for the sending-end inverter is shown in Fig. 2. The controller regulates the dc bus voltage V_{dc} 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 12 pulse inverter is given[12] by

$$\alpha_S = \cos^{-1}\left(\frac{V^*}{V_P}\right) \tag{4}$$

where V_p is the peak value of the cosine wave, V^* is the reference voltage and α_s 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 V_S (line-to-neutral, rms) are related by

$$V = \frac{6\sqrt{6}}{\pi n_S} V_S \cos(\alpha_S) \tag{5}$$

A 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 rms value of the fundamental component of the voltage, which is used in the firing-angle calculation.

B. Cycloconverter control

The structure of the cycloconverter controller at the receiving end is illustrated in Fig. 3. The control objective is to provide a constant 20-Hz voltage1 of a given rms value V_{cyc}^* (line-to-neutral).The fundamental component of the cycloconverter voltage is obtained with the signal conditioning logic depicted in Fig. 4.

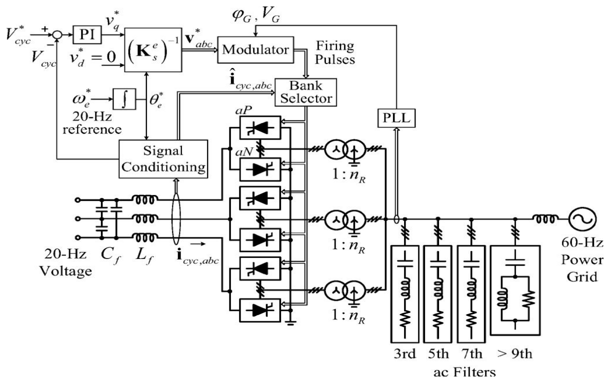

Fig. 3. Receiving-end cycloconverter control.

The basic control principle of the three-phase, six-pulse cycloconverter is to continuously modulate the firing angles of the individual converters (positive and negative converters), according to its control algorithms. Here, the cosine wave-crossing method with the circulating current free mode or blocking mode of operation is selected for its switching sequences, since the proposed control algorithm has demonstrated the following properties. The partial circulating current mode can prevent discontinuous operations during bank-exchange operations from the positive to negative bank, or conversely, with minimal circulating loss. Distortion of output-currents can be eliminated in this mode. Firing pulses are generated by the crossing points of both wanted and threshold voltages of reference voltages. Cosine wave crossing method is used to reduce the total harmonic distortion (THD) of output-voltages.

The control action for the three-phase, six-pulse cycloconverter can modulate the frequency, magnitude, and phase angle of output-voltages. 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-a positive and negative converters (denoted as "*aP*" and "*aN*" in Fig. 3) are α_{aP} and α_{aN}, respectively. For the positive converter, the average voltage at the 20-Hz terminals is given by[13]

$$V_{aP} = \frac{3\sqrt{6}}{\pi n_R} V_G \cos(\alpha_{aP}) \qquad (6)$$

Where V_G is the rms value of the line-to-neutral voltage at the grid side, and is the turns ratio of the transformers. The condition $\alpha_{aP} + \alpha_{aN} = \pi$ ensures that average voltages with the same polarity are generated from the positive and negative converter at the 20-Hz terminals.

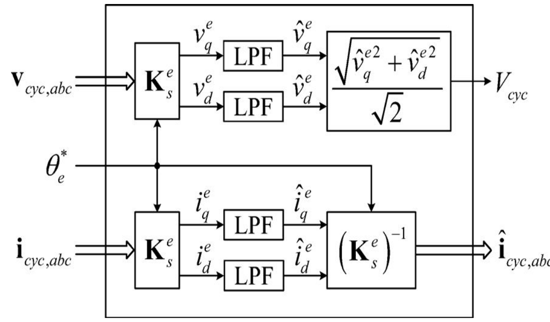

Fig. 3. Details of the signal conditioning block.

The firing pulses S_{aP} and S_{aP} 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 Fig. 3, 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

$$V_{cyc}^{\max} = \frac{3\sqrt{3}}{\pi n_R} V_G \qquad (7)$$

and that a voltage ratio is defined as

$$r = \frac{V^{cyc}}{V_{cyc}^{\max}} \qquad (8)$$

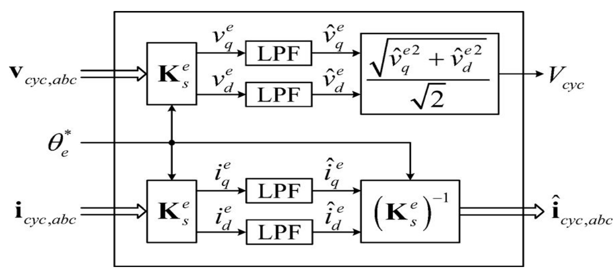

Fig. 4. Details of the signal conditioning block.

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

IV. SIMULATION AND RESULTS

To demonstrate the validity of the proposed LFAC system, test system is modeled in MATLAB/ SIMULINK. Software.The Fig.1. is considerd as the test system for the simulation. The Fig.7.shows the simulink model of LFAC transmission system for offshore wind farms. Control methods of Figs.2 and 3 were applied to control the sending end inverter and receiving end cycloconverter

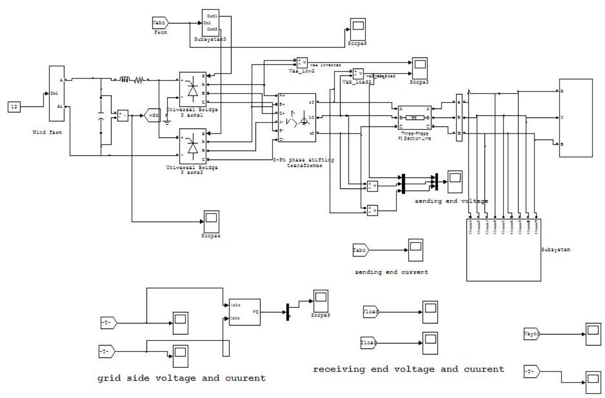

Fig.5. SIMULINK model of LFAC transmission system for offshore wind power

This section presents the simulation results of wind-farm with an LFAC-transmission system connected to a power grid, as shown in Fig.. The wind farm consists of many wind turbine systems - the example system includes three of them. The wind turbine systems are connected in series after the wind-generated power is rectified to DC, and the DC power is converted to 20-Hz AC power using an inverter. A transformer boosts the voltage to 46-kV. An LFAC line operated at 46-kV transmits the power over a distance of 160-Km to the nearest power grid substation. At that point, a cycloconverter converts the LFAC power into 60-Hz AC power for the interconnection, and another transformer boosts the voltage to 115-kV. The transformer is connected to the power grid, which is a 115-kV, 60 Hz-transmission at that point.

The results illustrate the operation of a wind farm transmission system by using a three-phase, six-pulse cycloconverter. The three-phase, six-pulse cycloconverter operates in a partial circulating-current mode and the control algorithm used to generate switching pulses is the cosine-wave crossing method.

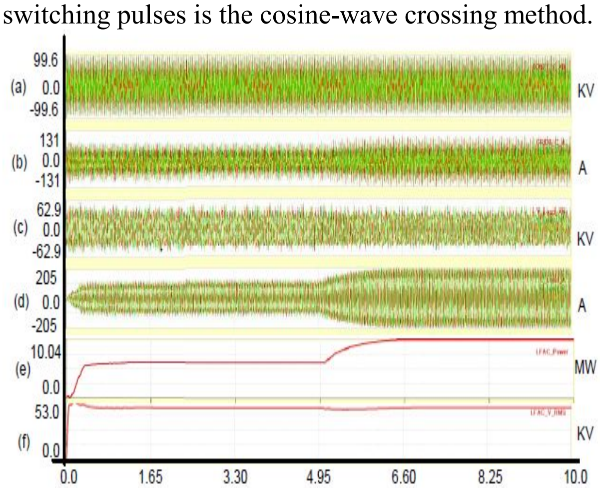

Fig.6. (a) Three-Phase Line-to-Line Voltages and (b) Three-Phase Currents at 60Hz AC Transmission Connected to the Cycloconverter; Three-Phase (c) Voltages and (b) Currents at LFAC Transmission Connected to the Cycloconverter; and (e) Real Power from the Wind Farm and (f) the RMS Voltage at the LFAC from 0.0 to 8.0 Seconds.

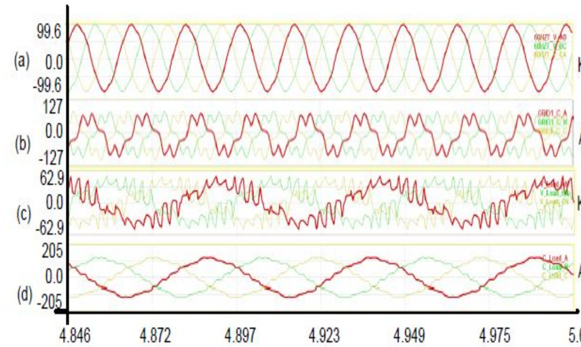

Fig.7. (a) Three-Phase Line-to-Line Voltages and (b) Three-Phase Currents at 60Hz AC Transmission Connected to the Cycloconverter; and Three-Phase (c) Voltages and (b) Currents at LFAC Transmission Connected to the Cycloconverter during Steady-State from 4.846 to 5.0 Seconds.

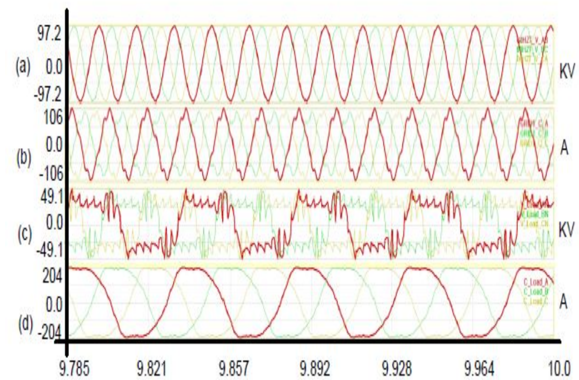

Fig.8. (a) Three-Phase Line-to-Line Voltages and (b) Three-Phase Currents at 60Hz AC Transmission Connected to the Cycloconverter; Three-Phase (c) Voltages and (b) Currents at LFAC Transmission Connected to the Cycloconverter during Steady-State from 9.785 to 8.0 Seconds.

Fig..6. and Fig.8. represent three-phase (a) line-to-line voltages and (b) currents at the 60Hz AC transmission system connected to the three-phase, six-pulse cycloconverter, and three-phase (c) voltages and (d) currents at the LFAC transmission system connected to the three-phase, six-pulse cycloconverter. In Fig.7, the power demand is 6-MW and the operation mode is a partial circulating-current mode of 0.7-pu of the phase currents at the LFAC side. Fig.8. shows the results with the following conditions: the power demand is 10MW, and the operation mode is a partial circulating-current mode of 0.4-pu of the phase current at the LFAC side.

V.CONCLUSION

Alternative transmission systems from offshore wind farms to the main power grid using low-frequency AC

(LFAC) technology are evaluated in this paper. In this project, LFAC system as a new and alternative solution to the conventional HVAC and HVDC systems which are so far deemed as the only solution for large offshore wind farms connection. With the cycloconverter that converts the 50 Hz to the lower frequency, for instance 50/3 Hz, the transmission capability is greatly improved. A method to design the system's components and control strategies has been discussed. The use of low frequency can improve the transmission capability of submarine power cables due to lower cable charging current. The LFAC system appears to be a feasible solution for the integration of offshore wind power plants for medium distances.

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