iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL
FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 3 Issue: III Month of publication: March 2015

DOI:

Volume 3 Issue III, March 2015
ISSN: 2321-9653
International Journal for Research in Applied Science & Engineering Technology (IJRASET)

A Grid Interfaced Low Frequency Offshore Wind Power

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Abstract-OFFSHORE wind power plants are expected to represent a significant component of the future electric generation portfolio due to greater space availability and better wind energy potential in offshore locations. The integration of offshore wind power plants with the main power grid is a subject of ongoing research. Presently, high-voltage ac (HVAC) and high-voltage dc (HVDC) are well-established technologies for transmission. This project presents a low-frequency ac (LFAC) transmission system for offshore wind power including with grid. The LFAC system is interfaced with the main power grid with a cyclo-converter. The wind power plant collection system is dc based, and connects to the LFAC transmission line with a 12-pulse thyristor converter. A method to design the system's components and controls is set forth. Simulation results are provided to illustrate the system's performance.

I. INTRODUCTION

OFFSHORE wind power plants are expected to represent a significant component of the future electric generation portfolio due to greater space availability and better wind energy potential in offshore locations [1], [2]. The integration of offshore wind power plants with the main power grid is a subject of ongoing research [3]–[5]. Presently, high-voltage ac (HVAC) and high-voltage dc (HVDC) are well-established technologies for transmission [6]. HVAC transmission is advantageous because it is relatively straightforward to design the protection system and to change voltage levels using transformers. 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) [8]. The main advantage of HVDC technology is that it imposes essentially no limit on transmission distance due to the absence of reactive current in the transmission line [9]. LCC-HVDC systems are capable of handling power up to 1 GW with high reliability [7]. LCCs consume reactive power from the ac grid and introduce low-order harmonics, which inevitably results in the requirement for auxiliary equipment, such as capacitor banks, ac filters, and static synchronous compensators [4]. On the other hand, VSC-HVDC systems are able to independently regulate active and reactive power exchanged with the onshore grid and the offshore ac collection grid.

In this paper, a novel LFAC transmission topology is analyzed. The proposed system differs from previous work[11]–[13] in that the wind turbines are assumed to be interconnected with a medium-voltage (MV) dc grid, in contrast with current practice, where the use of MV ac collection grids is standard [14]. DC collection is becoming a feasible alternative with the development of cost-effective and reliable dc circuit breakers [15], and studies have shown that it might be advantageous with respect to ac collection in terms of efficiency and improved production costs [16]. The required dc voltage level can be built by using high-power dc–dc converters and/or by the series connection of wind turbines.

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 (e.g.,step-up transformers and generators). The design of the dc collection system is outside the scope of this paper. At the sending end of the proposed LFAC system, a dc/ac 12-pulse thyristor-based inverter is used to generate low-frequency (20- or 16 2/3-Hz) ac power, as shown in Fig. 1. At the onshore substation (the receiving end), a thyristor-based cyclo-converter is used as an interface between the low-frequency side and the 60- or 50-Hz onshore power grid. Thyristor-based converters can transmit more power with increased reliability and lower cost compared to VSC-HVDC systems. However, large filters are necessary at both ends to suppress low-order harmonics and to supply reactive power. Furthermore, the system can be vulnerable to main power grid disturbances. The proposed LFAC system could be built with commercially available power system components, such as the receiving-end transformers and submarine ac cables design for regular power frequency. The phase-shift transformer used at the sending end could be a 60-Hz transformer derated by a factor of three, with the same rated current but only one-third of the original rated voltage.

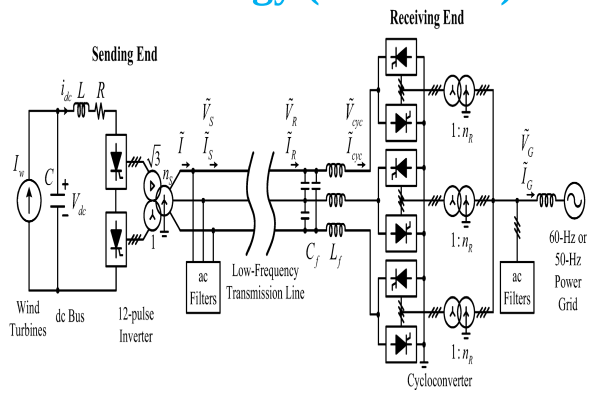

Fig. 1. Configuration of the proposed LFAC transmission system

II. SYSTEM CONFIGURATION AND CONTROL

The proposed LFAC transmission system is shown in Fig. 1, assuming a 60-Hz main grid. 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 current source represents the total power delivered from the 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 used to suppress the 11th, 13th, and higher-order (>23rd) current harmonics, and to supply reactive power to the converter. A smoothing reactor is connected at the dc terminals of the inverter. At the receiving end, a three-phase bridge (6-pulse) cyclo-converter is used to generate 20-Hz voltage. A filter is connected at the low-frequency side. At the grid side, ac filters are used to suppress odd current harmonics, and to supply reactive power to the cyclo-converter.

Simply put, the operation of the LFAC transmission system can be understood to proceed as follows. First, the cyclo-converter 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. In reality, more sophisticated schemes for system startup would have to be devised, based nevertheless on this operating principle.

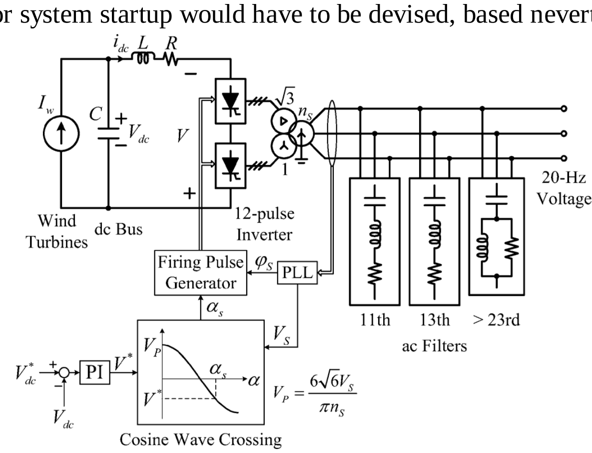

Fig 2: sending end control

The control structure for the sending-end inverter is shown in Fig. 2. The controller regulates the dc bus voltage by adjusting the voltage at the inverter terminals. The cosine wave crossing method is applied to determine the firing angle.

$$\alpha_S = \arccos\left(\frac{V^*}{V_P}\right)$$

Volume 3 Issue III, March 2015
ISSN: 2321-9653

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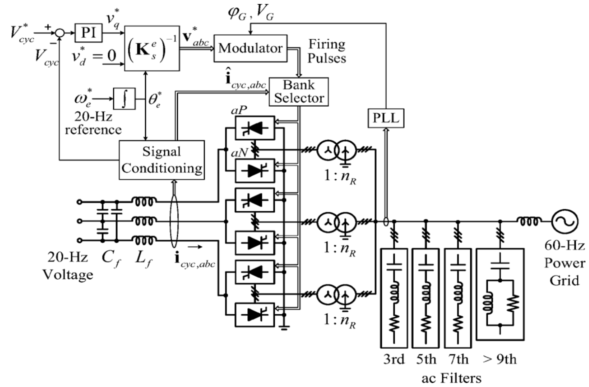


Fig 3: Receiving end cyclo converter control

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

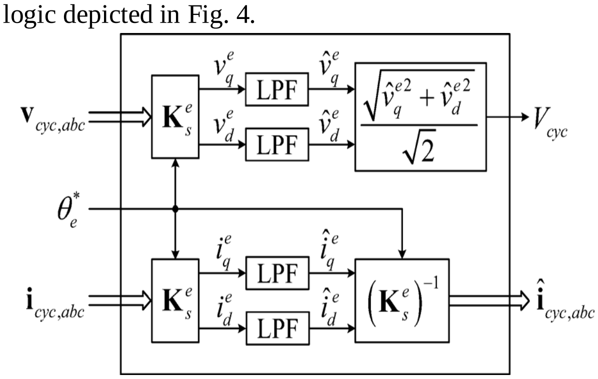
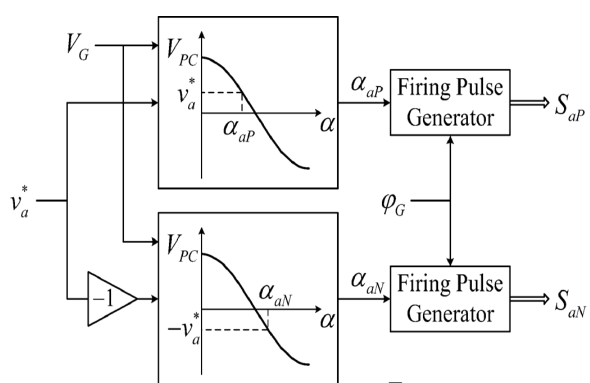


Fig. 4. Details of the signal conditioning block

The firing angles are determined with the cosine wave crossing method, as shown in Fig. 5, which uses phase as an example. The firing angles of the phase positive and negative converters (denoted as “oP”and“oN”inFig.3) are and, respectively. For the positive converter, the average voltage at the 20-Hz terminals is given by

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



$$V_{PC} = \frac{3\sqrt{6}V_G}{\pi n_R}$$

Fig. 5. Modulator for phase

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III. SYSTEM DESIGN

A. Main Power Components

The main power components are selected based on a steady state analysis of the LFAC transmission system shown in Fig. 1, under the following assumptions:

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 acfilters 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 dc current is equal to, so the power delivered from the wind turbines is

$$P_w = V_{dc} I_w.$$

IV. SIMULATION RESULTS

This section presents an example of the design process for a 20-Hz LFAC transmission system. To demonstrate the validity of the proposed LFAC system, simulations have been carried out using Matlab/Simulink and the Piecewise Linear Electrical Circuit Simulation (PLECS) toolbox. The simulation is done based on the fig 1. Fig. 6 shows the steady-state line-to-line voltage and current waveforms at the sending end, the receiving end, the 20-Hz side of the cyclo-converter, and the 60-Hz power grid side under rated power conditions. The 20-Hz voltage generated from the cyclo-converter has significant harmonic distortion (THD is 14.8%).

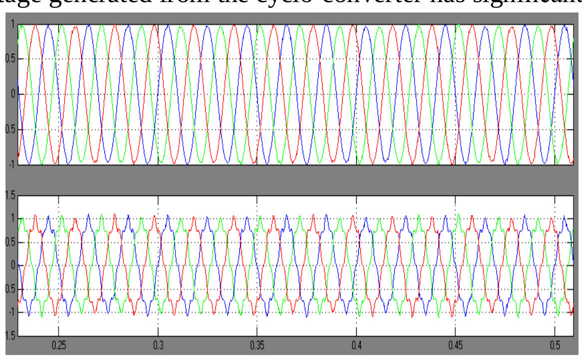

Fig 6: simulation result for L.F voltage and current

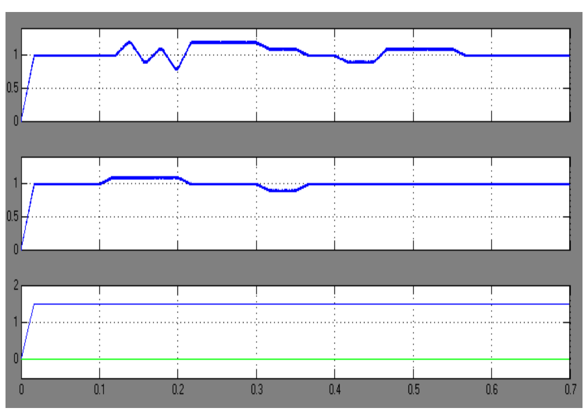

Fig 7: Transient waveforms during a wind power ramp event

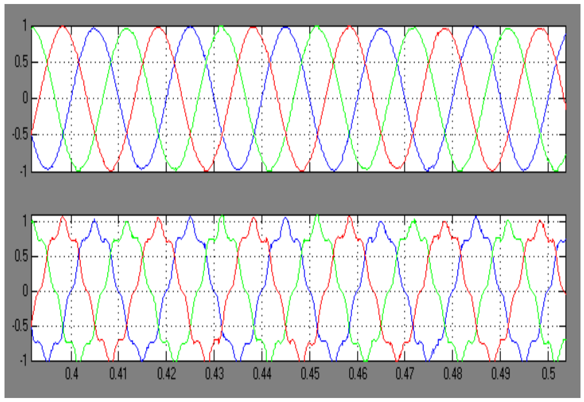

Fig 8: simulation result for receiving voltage and current

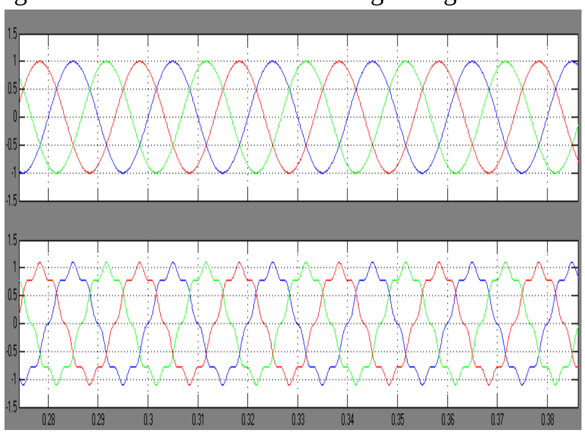

Fig 9: simulation result for grid voltage and current

V. CONCLUSION

A low-frequency ac transmission system for offshore grid connected 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. 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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