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Low Frequency AC Transmission System

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Abstract

Presently, High Voltage AC transmission and High Voltage DC transmission systems are well established technologies for transmission of power. A new Low Frequency AC transmission system employs transmission at an intermediate frequency and thus, establishes itself in between these two alternatives. Low Frequency AC transmission system can transmit bulk power over long distance with low investment cost. This system is based on generation at low frequency and AC to AC conversion from nominal to low frequency using power electronic devices. This technology is more reliable and provides a cost effective solution for power transmission. This paper presents the feasibility of applying low frequency AC transmission technology to interface the wind farm to grid, which is a major issue. The wind power plant collection is DC based and connects transmission line with 12-pulse converter. This system is interfaced with main power grid with cycloconverter. Low Frequency AC transmission system is implemented with a suitable controller. The system design and control strategies are discussed. System performances are verified using MATLAB/SIMULINK.

Keywords: *power transmission, wind energy, thyristor converters, low frequency AC (LFAC), cycloconverter*

1. Introduction

The electrical power system consists of generation, transmission and distribution system. Remote electrical power generation and interconnection of system lead to invention of transmission system at different power levels. Electrical power generated is transmitted over long distance to substations by using transmission cables.

Conventionally, High Voltage AC (HVAC) and High Voltage DC (HVDC) are well established technologies for transmission [1]. HVAC system can able to design the protection system and change voltage levels using transformers. However, the high capacitance of submarine AC power cables lead to significant charging current, which reduces the active power transmission capacity and limits the transmission distance. It is used for short distance transmission for 50-70km. To overcome the disadvantage of HVAC system, High Voltage DC transmission system is developed. Depending on types of power electronic devices used, HVDC system are classified in to two classes. There are Line Commutated Converter HVDC (LCC-HVDC) using thyristor and Voltage Source Converter HVDC (VSC-HVDC) using self commutated devices like insulated gate bipolar transistors (IGBT). The main advantage of HVDC technology is that it imposes no limit on transmission distance due to absence of reactive current in transmission line. LCC-HVDC systems are capable to transmit high power up to 1GW with high reliability but it consumes reactive power from the grid and introduces lower order harmonics, which results in the requirement for auxiliary equipment such as capacitor banks, ac filters and static synchronous compensators. On the other hand, VSC-HVDC systems are able to regulate active and reactive power exchange with onshore grid and offshore ac collection grid. Also, space charge accumulation is caused by the DC currents. The

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reduced efficiency and cost of the converters are drawbacks of VSC-HVDC systems. HVDC is used for transmission of power for the distance greater than 100km.

Due to the limitations of both HVAC and AVDC transmission system, a High Voltage Low Frequency AC (LFAC) transmission has been proposed as anew alternative technology for transmission of power [2-5]. The low frequency AC transmission system utilizes an intermediate frequency for transmission of power. The main advantage of LFAC transmission technology is increase in power transmission capacity over long distance for a given submarine power cable. This lead to considerable cost saving due to reduction in cabling requirement, decline in cable charging current and also losses are reduced compared to traditional transmission systems. Thus, investment cost and maintenance cost is reduced as well, since the frequency converter that synchronizes the frequency between LFAC system and power grid. Other benefits of LFAC system include improved voltage stability and no space charge accumulation due to the use of lower frequency range. .

2. Description of LFAC Transmission System

An alternative topology of transmission is used, operating at low frequency for purpose of bulk power transmission. The general approach for defining this topology is illustrated and benefits by using this transmission system are presented in this section

2.1. Principle of the LFAC System

As For AC transmission system, the active power (P) transmitting over transmission lines are expressed as

$$P= (V_S V_R / X_L) \quad (1)$$

Where V_S and V_R are sending end and receiving end voltage respectively. X_L is the line reactance. According to the equation, transmitting power increases either by increasing the voltage level or by lowering the impedance of the cable. Furthermore, with fixed sending end and receiving end voltages, the only way to improve the transmission capability is by reducing the impedance of cable.

The reactance dominates the line impedance which is proportional to the power frequency f.

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

Where L is the total inductance over the line, decreasing the electrical frequency can proportionally increase transmission capability. Figure 1 shows the power transmission capability at 50Hz and 20Hz frequency at different cable length. This LFAC system not only increases the transmitting power, but also improves the voltage stability, as illustrated in below equation.

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

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 due to the lower frequency, the voltage drop over the cable is proportionally reduced consequently

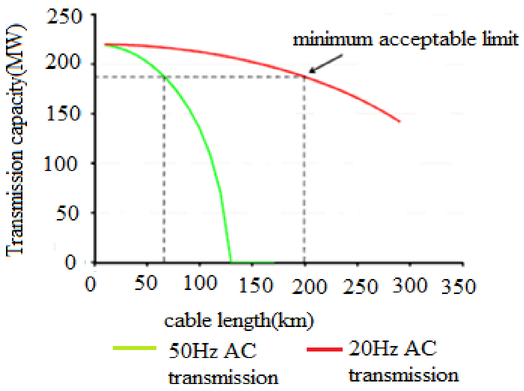


Figure 1. Power Transmission Capability

2.2. Configuration and Operation of Proposed System

2.1.1. Configuration of LFAC System:

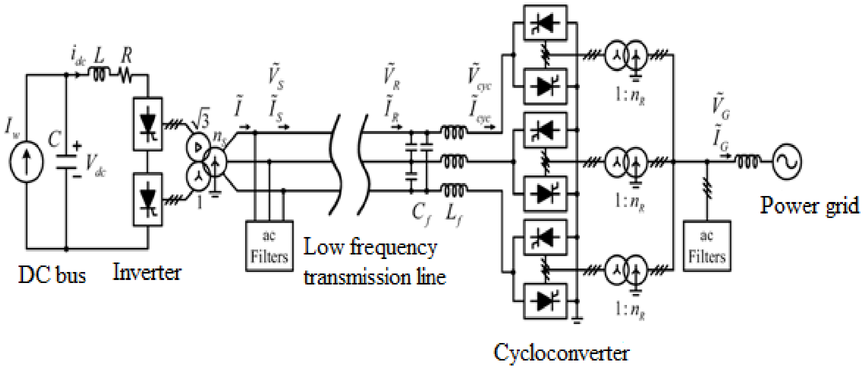


Figure 2. Configuration of Proposed LFAC Transmission System

The proposed configuration of LFAC system could be built with commercially available power system components. Figure2 represents interconnection of the wind power plant to the main power grid through LFAC transmission system. The main reason for using DC collection system with LFAC transmission system is that wind turbine would not need to be redesigned to output low frequency AC power which would leads to heavier and costlier components [9]. At the sending end of the proposed LFAC system, a DC/AC 12-pulse inverter is used to generate low frequency (20Hz or 16 2/3 Hz) ac power. The phase shift transformer used at the sending end could be a 60Hz transformer decreased by a factor of three, with same rated current but only one third of original rated voltage. At the receiving end, a thyristor based cycloconverter is used as an interface between the low frequency side and 60Hz or 50Hz power grid. Thyristor based converters can transmit more power with increased reliability and low cost. However, filters are necessary at both ends to suppress lower order harmonics and to supply reactive power. In summary, LFAC transmission could be an attractive technical solution for medium distance transmission.

2.1.2. Operation of LFAC System:

At the sending end, a medium voltage DC collection bus is formed by rectifying the AC output power of wind turbine [10]. A DC/AC 12-pulse thyristor based inverter is used to convert DC to low frequency (20Hz) 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 harmonics and to supply reactive power to the converter. At the receiving end, a three phase six pulse cycloconverter is used to generate 20Hz voltage. A filter L_f-C_f is connected at the low frequency side to decrease the amplitude of harmonics generated by the cycloconverter. At the grid side, AC filter are used to suppress odd current harmonics and to supply reactive power to the cycloconverter.

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 20Hz voltage. In meantime, the DC collection bus at the sending end is charged using power from the wind turbines. After the 20Hz voltage and the DC bus voltage are established, the 12-pulse inverter at the sending end can synchronize with the 20Hz voltage, and initiates the power transmission.

2.1.3. Technical Benefits and Cost Comparison:

In remote land locations and offshore locations, the transmission of wind energy to main grid is complex. In HVAC systems, interconnecting wind farms with long submarine cables suffers from reactive power requirement due to capacitance of cable and need for inductive compensation, which are not economically feasible, since HVAC cable does not exceed breakeven distance of 50km. In HVDC system, cables do not affect from capacitance and technically feasible for long distance transmission of electrical energy, but this system is more expensive for short and medium distances because of converters cost. Space charge accumulation is present HVDC system, which can be neutralized by increase in frequency higher than 1Hz. Using LFAC transmission, the transmission capability increases by reducing capacitance in the cable, since the impedance is decreases to one third of nominal. Transformers are used to change the voltage levels for transmission, line design and protection systems, which are used in HVAC systems can also used for LFAC transmission system. Thus, LFAC transmission is technically and economically suitable configuration for transmission of power from wind farm to power grid.

The investment cost comparison of HVAC, HVDC and LFAC transmission technology is shown in below figure which includes terminal cost and investment cost with respect to the distance [3]

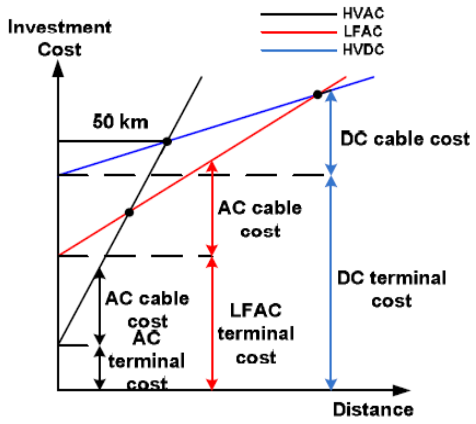


Figure 3. Cost Comparison of Transmission Systems

The crossing points at 50km shown in the Figure 3 are called break-even distance. For the distance less than break-even, HVAC transmission tends to be more economical than HVDC transmission and costlier for long distance. Compared to HVDC transmission

LFAC transmission has less cable cost and terminal cost. The investment cost of LFAC technology is greater than HVAC and less than HVDC system. If the frequency of LFAC transmission system decreases further, the slope of the system reduces. This shows that LFAC system is a new alternative solution for transmission of power from generating station to power grid, and best suitable for the medium transmission line for the distance 30km to 180km.

3. Design of Wind Turbine and LFAC System

The integration of wind power plants with power grid is a major issue. Low Frequency AC transmission (LFAC) system is most suitable and cost effective solution for transmission of electrical power from wind plants to grid.

3.1. Design of Wind Turbine

Renewable energy resources such as solar and wind energy can provide clean, reliable, secure energy products and services to meet the rapid increase in demand. Especially, wind energy among them has become most promising alternative energy resource because of more feasible mass power generation. Since, wind power is randomly varying and it has to capture wind over wide area for stable and reliable operation. Offshore wind plants are expected to represent a significant component of future electric generation due to greater space availability and better wind potential [6]-[8]. Electric power can be produced from wind energy by using wind turbine generator. The maximum power extracted from the wind is given as

$$P_{max} = (1/2)\, C_P A V_3 \qquad (4)$$

Where, C_P is power coefficient, A is the area of wind intercepted by rotor blades, V is the wind velocity.

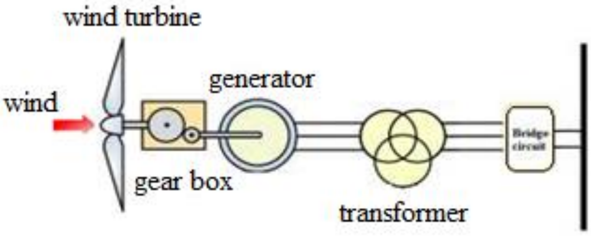


Figure 4. Wind Turbine with Generator

Wind turbine transforms kinetic energy into mechanical energy and then in to electrical energy by means of generator. Here, wind turbine is connected to asynchronous generator and output from the generator is coupled to three phase transformer and rectified to DC.

At steady state, average value of the DC current I_{dc} is equal to I_w. The power delivered from the wind turbine is given as

$$P_w = V_{dc} I_w \qquad (5)$$

For 12-pulse converter, the rms value of the current at the transmission side is given as

$$I = \frac{2\sqrt{6}}{\pi n s} I_w \qquad (6)$$

3.2. Design of LFAC System

The following assumptions are considered for the steady state analysis of LFAC transmission systems.

- The receiving end is modeled as a 20Hz voltage source of nominal magnitude.
- The power losses of the reactor, thyristors, filters and transformers are ignored.
- The resistance and leakage inductance of transformers are neglected.
- The AC filters are represented by an equivalent capacitance corresponding to the fundamental frequency.

4. Control of System Components

Generating systems cannot be directly connected to power grid systems. Power electronic devices are used for interconnection of renewable energy to power grid for robust and reliable transmission of power. Switching devices can permit to control the electrical signals and change in the voltage and frequency levels. Therefore, in LFAC system at sending and receiving end thyristor based 12-pulse inverter and 6-pulse cycloconverter are used for conversion.

4.1. Inverter Control

Thyristor based converters can transmit more power with increased reliability [13]. At the sending end of the LFAC system, 12-pulse thyristor based inverter is used to generate low frequency AC power. The control structure of an inverter is shown in the Figure 5. By adjusting the voltage V at the inverter terminal, the DC bus voltage can be regulated. Cosine wave crossing method is applied to determine the firing angle [14]. Firing pulses are generated by the crossing points of both wanted and threshold voltages of reference voltages. This method establishes 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 by

$$\alpha_S = \cos^{-1}\left(\frac{V^*}{V_P}\right) \tag{7}$$

Where V_P is the peak value of cosine wave, V^* is the reference voltage and α_S is firing angle of sending end inverter. For inverter mode of operation, the voltage is $V<0$ and $90<\alpha<180$. V and V_s are related by

$$V = \frac{6\sqrt{6}}{\pi n_s} V_S \cos(\alpha_s) \tag{8}$$

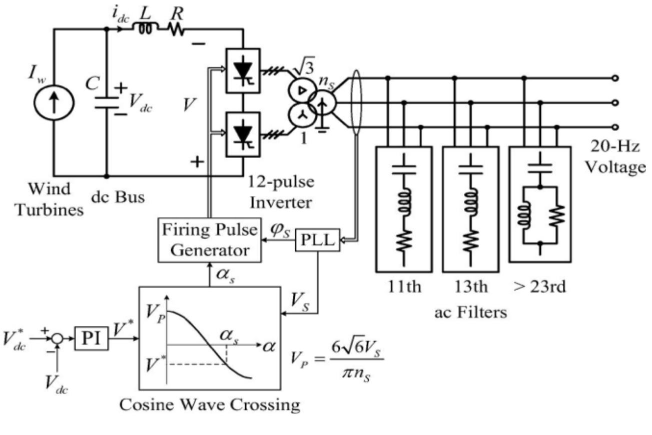


Figure 5. Inverter Control

A phase locked loop provides an angular position of ac side voltage, which is used for generating firing pulses.

4.2. Cycloconverter Control

The structure of receiving end controller is illustrated in Figure 6. The objective of controller is to provide a constant 20Hz voltage and to modulate frequency, magnitude and phase angle of output voltage. The frequency level is limited to 20Hz because higher frequency can cause distortion.

The basic principle of controller is to continuously vary the firing angles of converters. Cosine wave crossing method with circulating current free mode operation is considered for switching sequence. According to the controller algorithm, partial circulating current mode can prevent discontinuous operation during bank exchange function from positive to negative bank with minimal circulating loss. Cosine wave crossing method is used to reduce total harmonic distortion (THD) of output voltages [15].

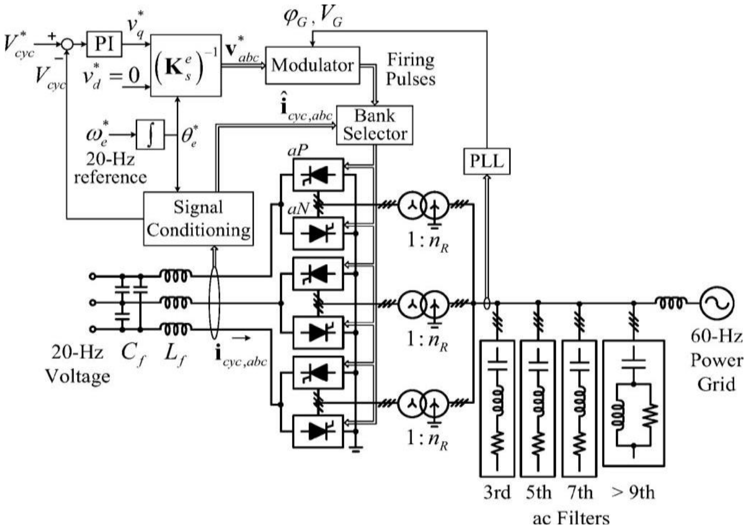


Figure 6. Cyclconverter Control

The fundamental component of cycloconverter voltage is obtained with the signal conditioning block shown in Figure 7.

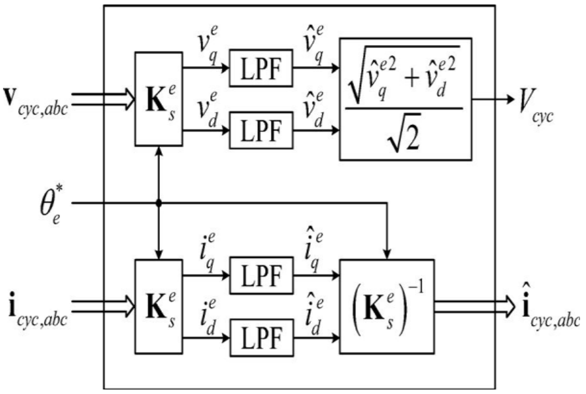


Figure 7. Signal Conditioning Block

For the positive converter, the positive converter the average voltage at 20Hz terminal is given by

$$V_{aP} = \frac{3\sqrt{6}}{\pi n_R} V_G \cos(\alpha_{aP}) \tag{9}$$

Where V_G is the rms value of line to neutral voltage at grid, n_R is the turn's ratio of transformers. The average voltages with same polarity are generated from positive and negative converter at 20Hz terminal [16]. The firing pulses S_{aP} and S_{aN} are not simultaneously applied to both converters to obtain non circulating current mode of operation which is embedded in bank selector block shown in Figure 8.

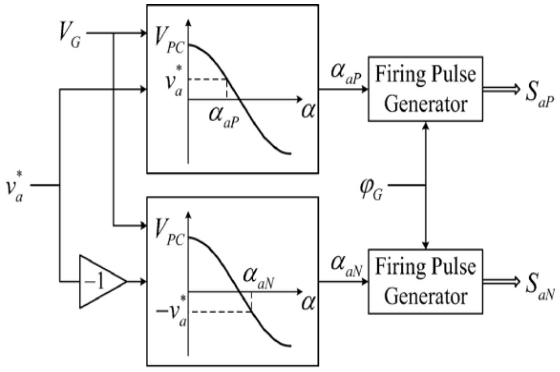


Figure 8. Modular for Phase

The maximum line to neutral rms value of 20Hz cycloconverter voltage is given as

$$V_{cyc}^{max} = \frac{3\sqrt{3}}{\pi n_R} V_G \tag{10}$$

And, the voltage ratio is defined as

$$r = \frac{V_{cyc}}{V_{cyc}^{max}} \tag{11}$$

The maximum value r=1 cannot be achieved due to the leakage inductance of transformers which can be ignored.

5. Simulation Results

To validate design of LFAC transmission system, simulation is performed by using MATLAB/Simulink software. Control methods shown in Figure5 and Figure6 are applied to control the inverter and cycloconverter. The rating of wind power plant is 180MW which is transmitted over a distance of 160Km. The transmission voltage is chosen as 132kV. The power grid voltage is 132kV line to line. The short circuit level is S_{SC} = 5000MVA, which is typical value for a 132kV system. Simulation results are shown for the 20Hz LFAC transmission system.

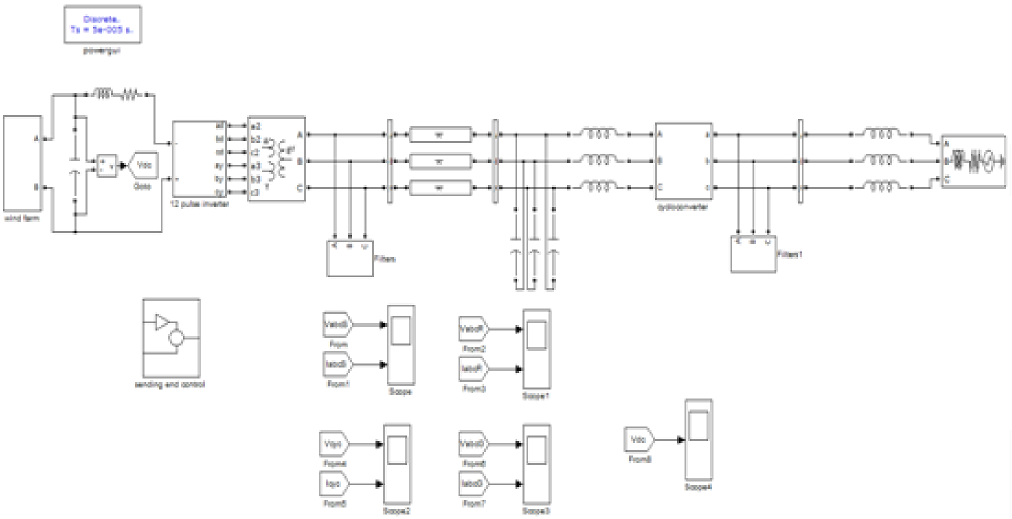
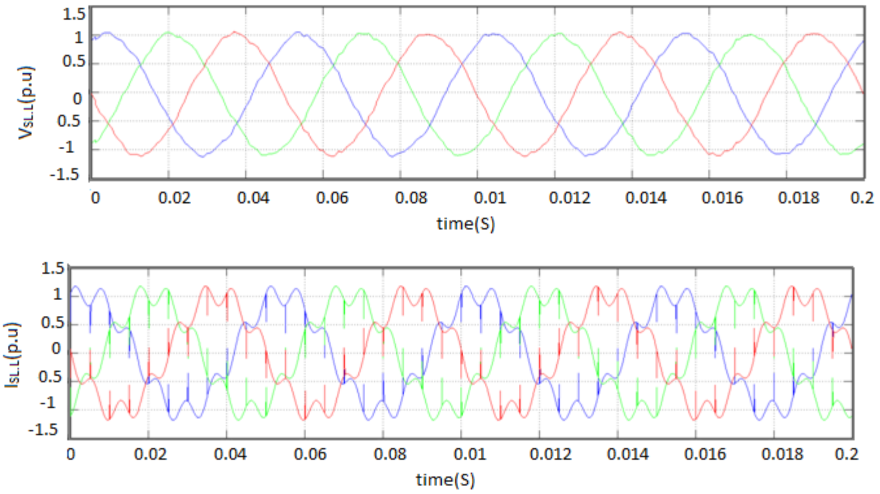
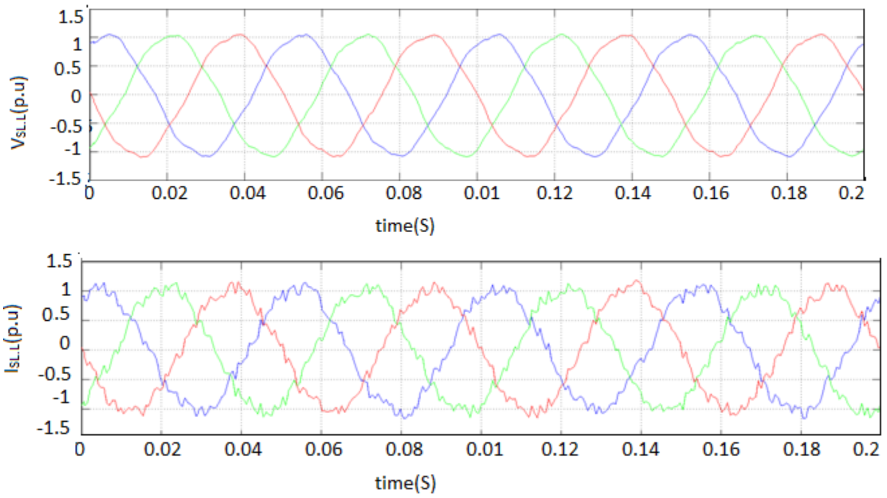


Figure 9. Overall Simulink Model of LFAC Transmission System

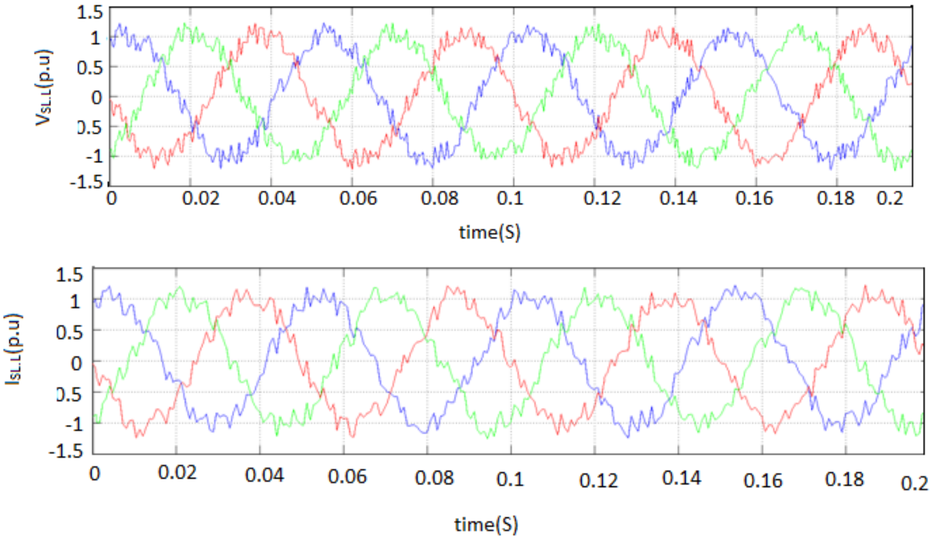
The steady state line to line voltage and current waveforms at the sending end, the receiving end, the 20Hz side of the cycloconverter and 60Hz power grid under rated power conditions are shown in Figure 10.



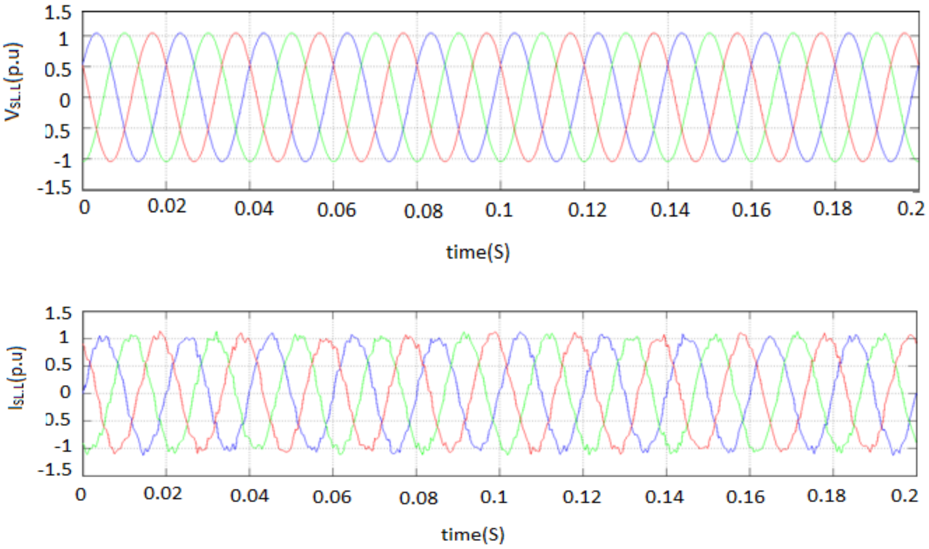
(a) At Sending End



(b) At Receiving End



(c) At Cycloconverter



(d) At Grid Side

Figure 10. Simulated Voltage and Current Wave Forms

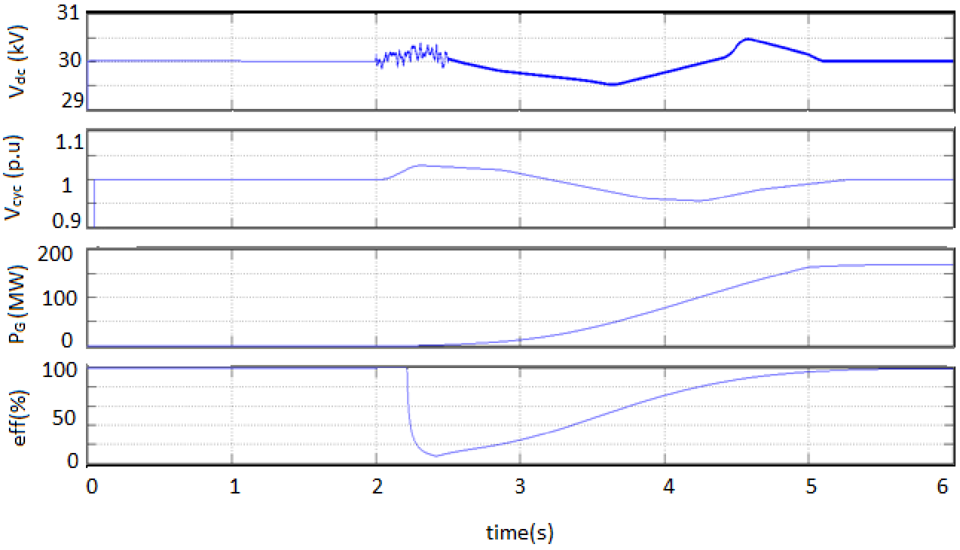
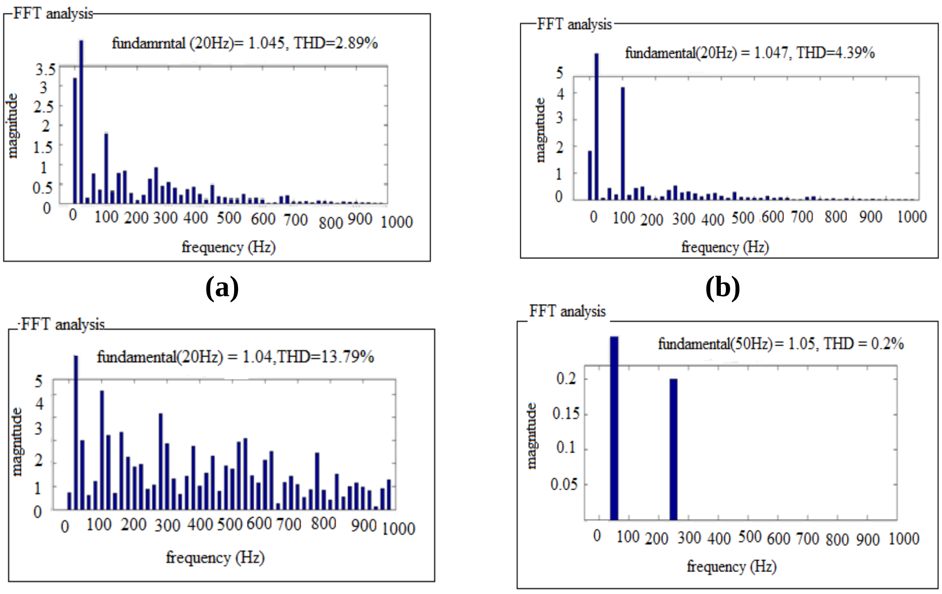


Figure 11. Transient Response

Figure11 shows the transient response of DC bus voltage at sending end, magnitude of fundamental component of 20Hz voltage generated by cycloconverter, active power injected in to 60Hz power grid, and transmission efficiency.

FFT Analysis: The 20Hz voltage generated from the cycloconverter has total harmonic distortion of 13.79%. Due to LC filter the voltage at the sending end and receiving end has reduced THD values of 2.89% and 4.39%. The THD at power grid is 0.2%



(a) (b)

(c) (d)

Figure 12. FFT Analysis of (a) Sending End, (b) Receiving End, (c) Cycloconverter and (d) Power Grid

LFAC System Simulation Parameters

- Transmission line nominal voltage: 132kV
- Transmission line maximum voltage: 145kV.
- Transmission line rated current: 825A
- Cable parameters: resistance 17.6m/km, inductance 0.35mH/km, and capacitance: 0.25 µ F/km.
- Total wind power: 180MW
- Transmission line distance: 160km.
- DC bus capacitance: 1000 µ F
- Sending end transformer rating: 214MVA, 132/13.2kV, 20Hz
- AC filters at sending end : 115 MVAr
- Receiving end transformer rating: 100MVA, 132/88kV
- AC filters at receiving end : 200 MVAr

6. Conclusion

Low frequency transmission system (LFAC) is new alternative solution for offshore wind farm. The use of low frequency can improve the power transmission capability because of reduced reactance of the transmission cable and also reduced charging current. In this paper wind power plant is interfaced with power grid using low frequency transmission cables. Design process of Low frequency AC system and its components control are verified by using MATLAB /simulink, and total harmonic distortion has been observed at inverter side, cycloconverter and at power grid. Thus, LFAC system appears to be a feasible solution for medium transmission distance. This is more reliable and cost effective transmission system.

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