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# PERFORMANCE OF LFAC SYSTEM FOR STEADY STATE

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## ABSTRACT

HVAC power transmission using submarine power cables has limitation of charging current at nominal frequency. Therefore, HVDC power transmission technology has been established. However, a new intermediate technology of Low Frequency AC Transmission is established for transmission of power. This paper deals with the performance of a low-frequency ac (20Hz) transmission system for steady state. The LFAC system is interconnected with the 50Hz grid with a cycloconverter. The wind power from the offshore is in the form of dc, and is interconnected to the LFAC transmission line with a twelve-pulse thyristor inverter. The waveforms at the sending end and receiving end of the transmission line are plotted. The circuit model of LFAC system is simulated in MATLAB/SIMULINK.

**KEYWORDS:** LFAC, Wind Power, Cycloconverter.

## INTRODUCTION

The wind is a clean and inexhaustible resource available all over the world. Recent progress in wind technology let the capacity of wind power increases significantly year by year. The challenges wind power introduces into power system planning and operation are mainly related to the fluctuating nature of wind velocity. Besides, the remote locations of many wind power plants often create significant bottlenecks for large-scale transmission of generated electricity.

Wind energy in particular, has shown strong growth and penetration, with several technologies showing sound economic fundamentals, even in the presence of minimal government subsidies. Significant levels of wind-penetration are being seen, with similar high levels targeted in many countries over the next two decades. As the world moves towards higher level of penetration of wind resources on the grid, there is increasing pressure to locate the large wind farms offshore, where the issues of noise and the impact on the landscape are somewhat ameliorated. Several offshore wind farms have been recently completed, providing experience of the challenges faced and the solutions needed.

Offshore wind power plants in future will have significant importance for electric generation due to its greater space availability and better wind energy potential in offshore locations [1], [2]. Research is ongoing for the integration of offshore wind power plants with the grid. Recently, high-voltage ac and high-voltage dc are well-established technologies for transmission [3].

HVAC transmission is advantageous because it is easy to design the protection system and to change voltage levels using transformers. But, the high capacitance of submarine ac power cables leads to charging current, which, in turn, reduces the active power transmission capacity and limits the transmission distance. HVAC is adopted for relatively short (up to 50–75 km) underwater transmission distances.

Two classes of HVDC systems exist, depending on the types of power-electronic devices used: 1) line-commutated converter HVDC using thyristors and 2) voltage-source converter HVDC using self-commutated devices, for example, insulated-gate bipolar transistors (IGBTs) [4].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[5].

LCC-HVDC systems are capable of handling power upto 1 GW with high reliability[4]. LCCs consume reactive power from the ac grid and introduce low-order harmonics, which results in the requirement for auxiliary equipment, such as capacitor banks, ac filters, and static synchronous compensators. 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 can be identified as drawbacks of VSC-HVDC systems[6]. HVDC is applied for distances greater than 100 km for offshore wind power transmission.

Due to these limitations of HVAC and HVDC when applied for offshore wind farms, low-frequency ac (LFAC) transmission has been a alternative solution[7] − [10].

In LFAC systems, an intermediate-frequency level is used, which is created using a cycloconverter that lowers the grid frequency to a smaller value, typically to one-third its value. 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 HVAC. This leads to substantial cost savings due to the reduction in cabling requirements.

## PRINCIPLE OF LFAC SYSTEM

The ac electricity supplied by grid has two basic parameters: voltage and frequency. After the transformer was invented, different voltage levels could be used flexibly in generating, transmitting, and consuming electricity to guarantee efficiency for different segments of the power system. The lower frequency electricity can be used to transmit larger power for longer distance, and the higher frequency electricity can be used more efficiently to drive the electric tools.

There are three factors limiting transmission capability, i.e., the thermal limit, stability limit, and voltage drop limit. For the long-distance ac transmission, the thermal limitation is not a significant impediment. Its load ability mainly depends on the stability limit and voltage drop limit. The stability limit of an ac transmission line can be approximately evaluated by

$$P_{max}=\frac{V^2}{X}$$

where V is the normal voltage, and X is the reactance of the transmission line. We can see from the above equation that transmission capacity is proportional to the square of the normal voltage and inversely proportional to the reactance of the transmission line. The voltage drop ΔV % can be evaluated by

$$\Delta V\% = \frac{QX}{V^2} \times 100$$

where Q is the reactive power flow of transmission line. Thus, the voltage drop is inversely proportional to the square of voltage and proportional to the reactance of the transmission line.

Therefore, in order to raise transmission capability, we can either increase the voltage level or decrease the reactance of the transmission line. The reactance is proportional to power frequency f,

$$X= 2\pi fL$$

where L is the total inductance of the transmission line. Hence, decreasing the electricity frequency f can proportionally increase transmission capability.

The LFAC uses fractional frequency to reduce the reactance of the transmission system; thus, its transmission capacity can be increased several fold. For instance, when frequency is 20 Hz, the theoretically transmission capability can be raised three times [8].

We can also look through the principle of LFAC from another perspective. It is well known that the velocity of electricity transmission is approximately equal to the light velocity, 300000 km/s. When electricity frequency is 50 Hz, the wave length is 6000 km; for 50/3 Hz, the wave length enlarges to 18000 km. Thus, when frequency is 50 Hz, a transmission line of 1200 km corresponds to one fifth of the wave length; for the 50/3 Hz case, this transmission line only corresponds to one fifteenth of the wave length. Therefore, the "electrical length" decreases to one third. This is the essential reason why the LFAC can increase transmission capability several fold and remarkably improve its performance.

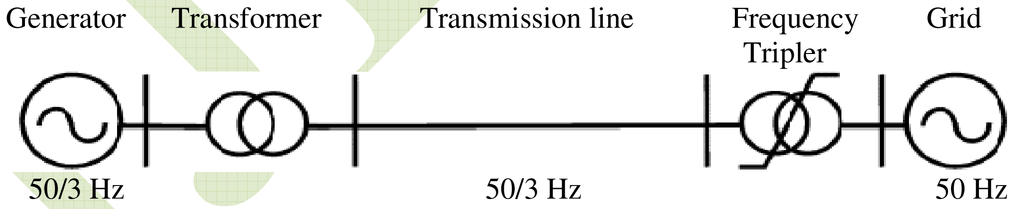

**Figure 1: Basic structure of LFAC**

The basic structure of LFAC is illustrated in Fig.1. The wind power generator in the figure generates ac power of low frequency (say 50/3 Hz), which is then stepped up by a transformer and transmitted to the receiving end of the transmission line where the low frequency ac power is stepped up to the industrial frequency. The wind power generator can easily generate low-frequency electric power because its rotating speed is usually very low. To generate low-frequency power, the only change for the generator is to reduce its pole number. This change has little influence on cost and efficiency of the wind power unit.

For the transformer, since the electric power that has to be stepped up is of low frequency, the core section area and the coil turn number must be increased. Therefore, the cost of the transformer in LFAC is higher than that of the conventional transformer. The conventional transmission line can be used in LFAC without any change. The frequency changer is the key equipment in LFAC, which can be either the saturable transformer or the power electronic ac–ac frequency changer, such as the cycloconverter. The ferromagnetic frequency changer has advantages of simpler structure, lower cost, and more reliable operation, while the electronic type is superior in higher efficiency and more flexible in installation[8].

## OFFSHORE WIND POWER LFAC SYSTEM

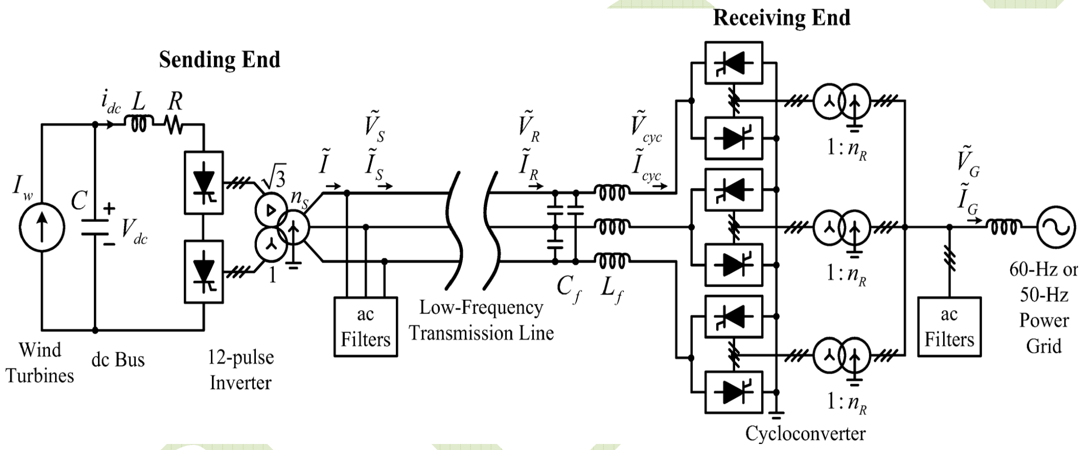

**Figure 2: Configuration of LFAC Transmission System**

In LFAC transmission the wind turbines are assumed to be interconnected with a medium-voltage dc grid, 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 improved production costs.

The required dc voltage level can be built by using high-power dc–dc converters [11] and or by the series connection of wind turbines. For example, multi-MW permanent-magnet synchronous generators with fully rated power converters are commonly used in offshore wind plants. By eliminating grid-side inverters, a medium-voltage dc collection system can be formed by interconnecting the rectified output of the generators[12].

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).

At the sending end of the LFAC system, a dc/ac 12-pulse thyristor-based inverter is used to generate low-frequency (20-Hz) ac power, as shown in Fig. 1. At the onshore substation (the receiving end), a thyristor-based cycloconverter is used as an interface between the low-frequency side and the 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.

## OPERATION OF LFAC SYSTEM

The LFAC transmission system is shown in Fig.2, assuming a 50-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) cycloconverter 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 cycloconverter.

Simply, 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.

## SYSTEM COMPONENTS

### Asynchronous Generator

An asynchronous generator is a type of AC electrical generator that uses the principles of induction motor to produce electrical power. An asynchronous generator operates at a speed faster than the synchronous speed. AC asynchronous motor usually can be used as a generator, without any internal modifications. Asynchronous generators are useful in applications such mini hydro power plants, wind turbines. Therefore asynchronus generator is used to generate electrical energy from wind turbines.

### Twelve Pulse Inverter

Figure 3: 12 pulse inverter at the sending end side

At the sending end of the LFAC system, a dc/ac 12-pulse thyristor-based inverter is used to generate low-frequency (20 Hz) ac power. It is connected to a three-winding transformer that raises the voltage to a higher level for transmission.

## Cycloconverter

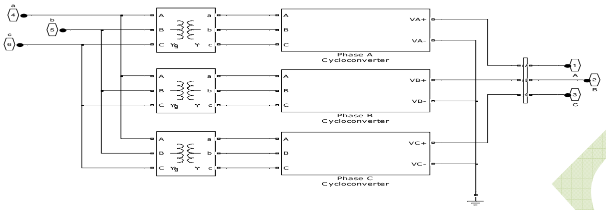

**Figure 4: Cycloconverter**

The frequency converter is the key equipment in LFAC, which can be either the saturable transformer or the power electronic ac–ac frequency changer, such as the cycloconverter. The ferromagnetic frequency changer has advantages of simpler structure, lower cost, and more reliable operation, while the electronic type is superior in higher efficiency and more flexible in installation. Hence, 6 pulse thyristor cycloconverter is used as the frequency converter here.

Both the two terminals of the cycloconverter in LFAC are connected with voltage sources. Because 50-Hz system is the receiving terminal, 20 Hz transmission system is the supplying terminal, both the p-group and n-group of the cycloconverter should be mainly operated in their inversion mode. Thus, the cycloconverter in LFAC becomes a frequency tripler stepping up 20 Hz electric power to 50 Hz. The synchronizing circuit measures and compares frequencies, magnitudes, and phases of voltages at the two terminals of the cycloconverter.

When voltages at two terminals satisfy the following conditions:

Difference of magnitudes less than 5%
Difference of frequency less than 0.5%
Difference of phases less than 5°

The synchronizing circuit sends starting impulses to the control circuit of the cycloconverter.

The control circuit guarantees that p-group and n-group correctly operate by turns in each half cycle. The cycloconverter in LFAC is operated in non circulating current mode, or blocking mode. Therefore, zero crossing of the current at the end of each half cycle is detected and is used to regulate the control signals either to p-group or n-group, depending on whether the current goes to zero from negative to positive or from positive to negative, respectively. The waveform of the 20 Hz voltage is synthesized by the sinusoidal modulation of the fire angle. The fire angles are calculated and stored in a digital circuit in advance, which are successively used to control the cycloconverter in operation.

# LFAC SYSTEM DESIGN

## MAIN COMPONENTS

The main power components are selected based on a steady state analysis of the LFAC transmission system under the following assumptions:

- Only fundamental components of voltages and currents are considered. The receiving end is modelled 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.

## FILTER DESIGN

At the sending end, the 12-pulse inverter produces harmonics of order $m = 12 \pm 1, k = 1,2, \ldots$, and can be represented as a source of harmonic currents. These current harmonics are filtered by two single-tuned filters for the 11th and 13th harmonic, and one damped filter for higher-order harmonics (23rd). With such filter, 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 50-Hz side and the *LC* filter at the 20-Hz side. At the 50-Hz side, if the cycloconverter generates exactly one-third of the grid frequency, and so that the line current has only odd harmonic components (3rd, 5th, 7th, etc). Sub harmonic and inter harmonic 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 50-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 voltages have harmonics of order 3, 5, 7, without sub harmonic and inter 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 orders $n = 6k \pm 1, k = 1,2, \ldots$. 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.

# SIMULATION RESULT

To verify the performance of LFAC system, simulations have been carried out using Matlab/Simulink. The Simulink model of LFAC system for steady state is shown in fig.5.The wind power plant is rated at 180 MW, and the transmission distance is 160 km.

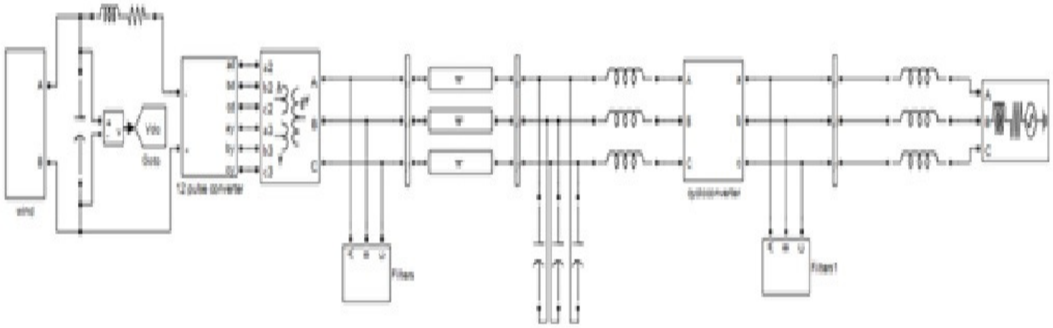

Figure 5: Simulink model of LFAC system for steady state

The following graphs presents the simulation results of wind power plant with an LFAC-transmission system connected to a power grid.

Fig. 6,7,8,9 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.

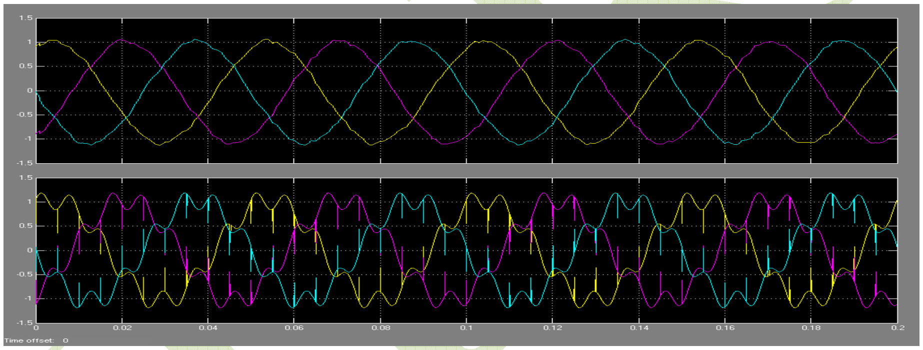

Figure 6: Simulated voltage and current waveforms at sending end

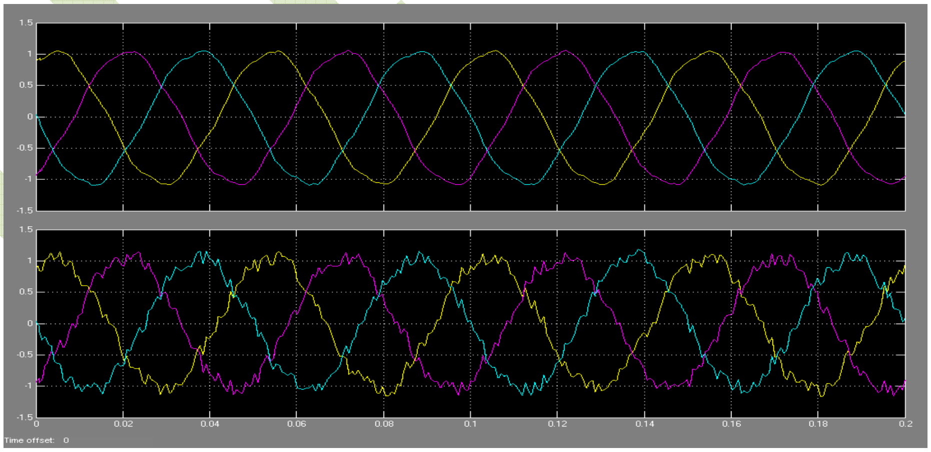

Figure 7: Simulated voltage and current waveforms at the receiving end

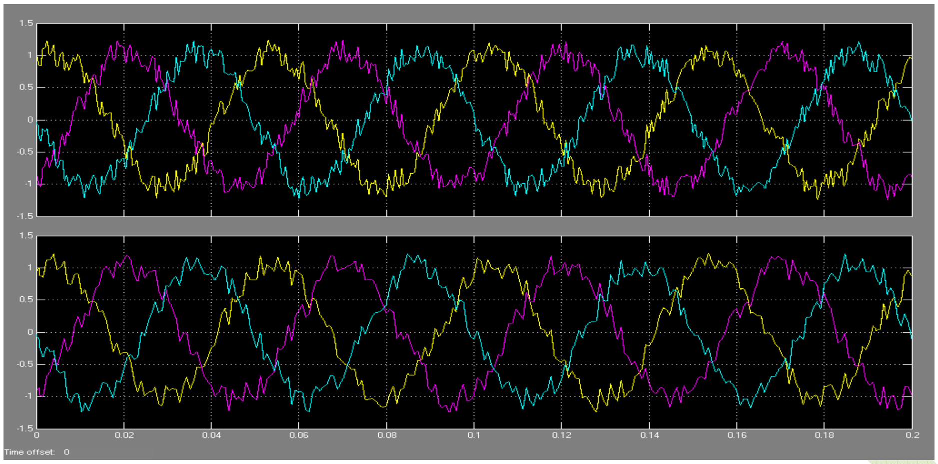

**Figure 8: Simulated voltage and current waveforms at the cycloconverter 20 Hz side**

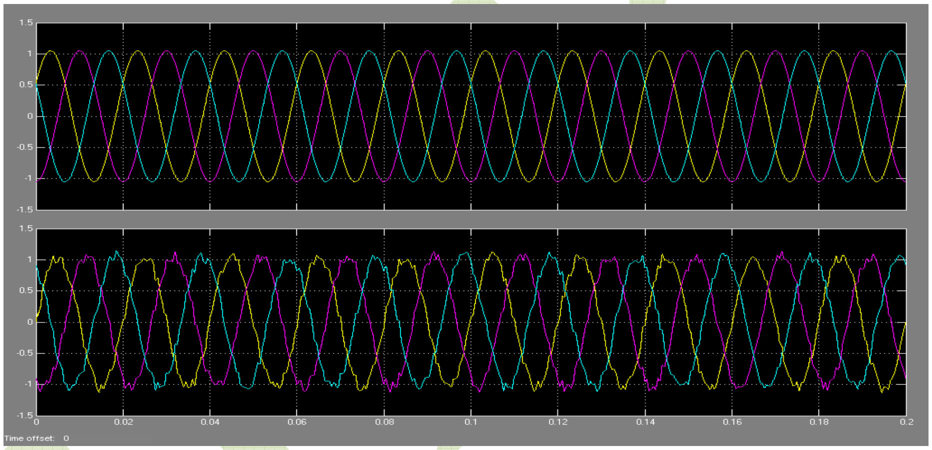

**Figure 9: Simulated voltage and current waveforms at the 50 Hz grid**

## CONCLUSION

In this paper the steady state performance of LFAC system is verified using Matlab/Simulink. The use of a low frequency can improve the transmission capability of submarine power cables due to reduced charging current. Thus, LFAC system appears to be a well established technology for power transmission over long distances compared to HVAC and HVDC.

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