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THD ANALYSIS OF LFAC TRANSMISSION SYSTEM

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ABSTRACT

This paper deals with the design of filters and THD analysis of a low-frequency ac (20Hz) transmission system. The LFAC system is interfaced with the 50Hz main power grid with a cycloconverter. The wind power is collected in dc form, and is connected to the LFAC transmission line with a twelve pulse inverter. The waveforms at the sending end and receiving end of the transmission line are plotted.THD analysis of LFAC system is carried out. 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. 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 [1].
HVAC transmission is advantageous because it is relatively straightforward to design the protection system and to change voltage levels using transformers. However, the high capacitance of submarine ac power cables leads to considerable 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 (LCC-HVDC) using thyristors and 2) voltage-source converter HVDC (VSC-HVDC) using self-commutated devices, for example, insulated-gate bipolar transistors (IGBTs) [2].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[3].
LCC-HVDC systems are capable of handling power up to 1 GW with high reliability[2]. 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. 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. The reduced efficiency and cost of the converters can be identified as drawbacks of VSC-HVDC systems[4]. HVDC is applied for distances greater than 100 km for offshore wind power transmission.Due to the limitations of HVAC and HVDC when applied for offshore wind farms, low-frequency ac (LFAC) transmission has been a alternative solution [5] − [8].
In LFAC systems, an intermediate-frequency level is used, which is created using a cycloconverter that lowers the grid frequency to a smaller value, 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 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. Using transformer, 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 ,

$$X = 2\pi f L$$

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[6].

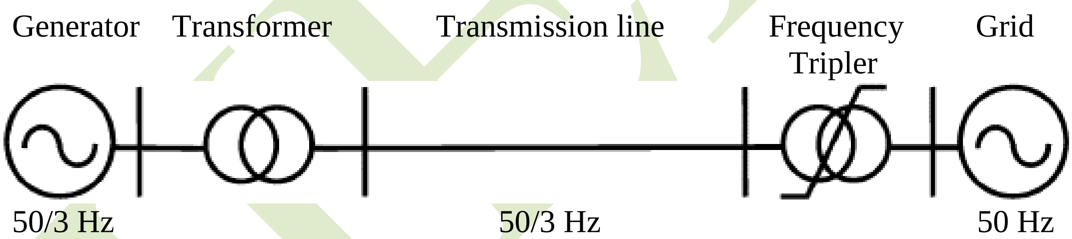

Figure 1: Basic structure of LFAC

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.

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[6].

LFAC SYSTEM FOR OFFSHORE WIND POWER

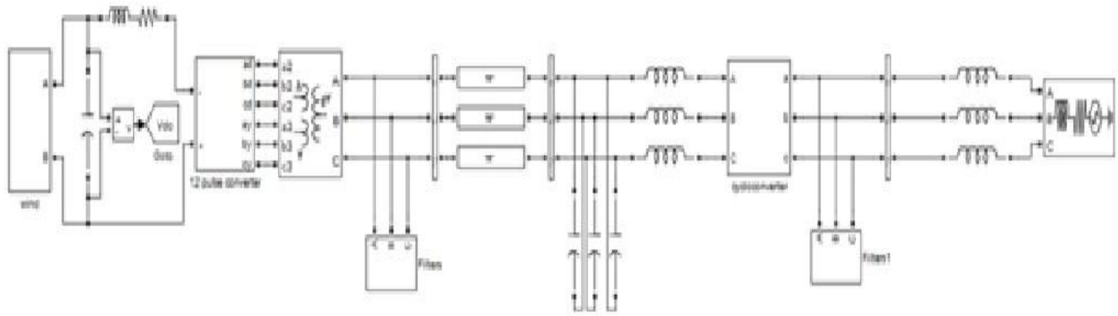

Figure 2: Configuration of LFAC Transmission System

In LFAC transmission the wind turbines are assumed to be interconnected with a medium-voltage dc grid. 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 [9] and or by the series connection of wind turbines. By eliminating grid-side inverters, a medium-voltage dc collection system can be formed by interconnecting the rectified output of the generators[10].
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.
The operation of the LFAC transmission system can be understood 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. The cycloconverter which is used as a frequency changer produces harmonics of low order, hence filters are needed to add in the system[7].

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FILTER DESIGN FOR LFAC SYSTEM

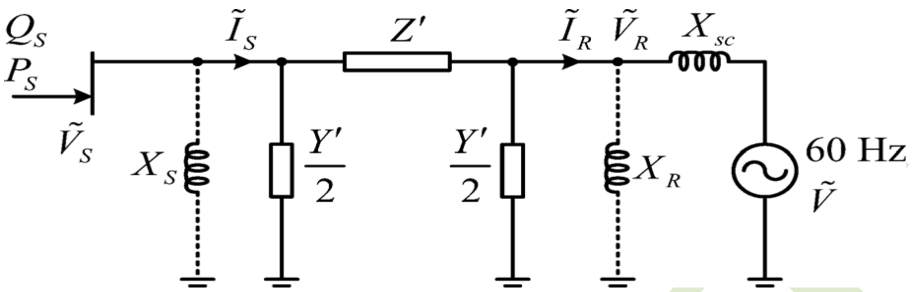

Figure 3: Equivalent circuit of the 50-Hz transmission system.

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 as shown in fig.3. 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). 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)[12]. Here, it is assumed that the total reactive power requirement is divided equally among the three filters. The quality factor for each filter can be determined using the method presented[12]. 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 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 it can be shown [11] 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 voltage has harmonics of order 3, 5, 7, , without sub harmonic and inter harmonic components. However, the harmonic components [11] 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, indicated by $z_r(\omega_n)$.

The design procedure presented here takes into account the voltage harmonics of order 5, 7, 11, and 13. For cycloconverters, the amplitude of the voltage harmonics only depends on the voltage ratio r and the fundamental power factor at the 20-Hz side, under the assumption of sinusoidal output current[11], which is sufficient for design purposes. Generally, the voltage harmonics tend to become worse with decreasing r. Here, we set r = 0.9. Fig. 8 illustrates the relationship between the per-unit amplitudes of the voltage harmonics under consideration and the power factor angle φ computed on formulas in [11]. For the 5th and 7th voltage harmonics, the amplitudes are symmetric with respect to φ = 0°, and positive φ (i.e., reactive power consumption by the cycloconverter) can result in reduced amplitudes of the 11th and 13th voltage harmonics. At φ ≈ 85°, minimum amplitudes are obtained. However, this value is unacceptably low, so φ = 35°, is selected (for operation at rated power).

After φ has been determined, it follows that there is a linear relation between L_f and C_f ,since $Q_{cyc}^{20}/P_{cyc}^{20}$.These initial parameters might not yield the required power factor angle φ = 35° due to the simplifying assumptions made in the analysis. For, given a value for L_f, the capacitance C_f that leads to the right power factor angle can be found by searching around its initial guess value. Therefore, if L_f varies within a certain range, a number of pairs (L_f, C_f) can be obtained. Among these candidates, a selection is made such that the magnitudes $z_r(\omega_n)$ for $n = 5,7,11,13$ are deemed to be adequately large.

SIMULATION RESULT

The LFAC system, simulations have been carried out using Matlab/Simulink. The wind power plant is rated at 180 MW, and the transmission distance is 160 km.

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

Fig. 4,5,6,7 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 = 13.79%). Due to the LC filter, the voltages at the receiving and sending ends have reduced THD values (4.39% and 2.89%, respectively).

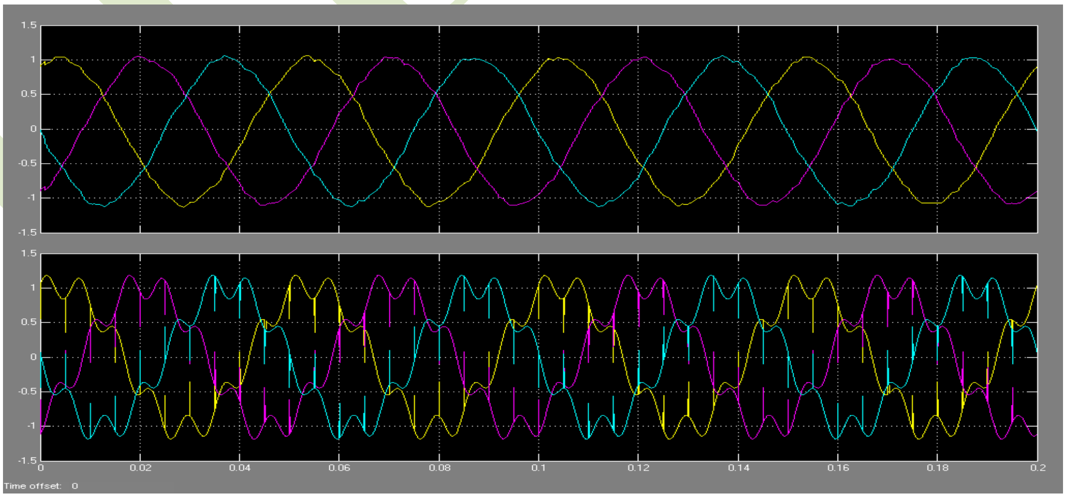

Figure 4: Simulated voltage and current waveforms at sending end

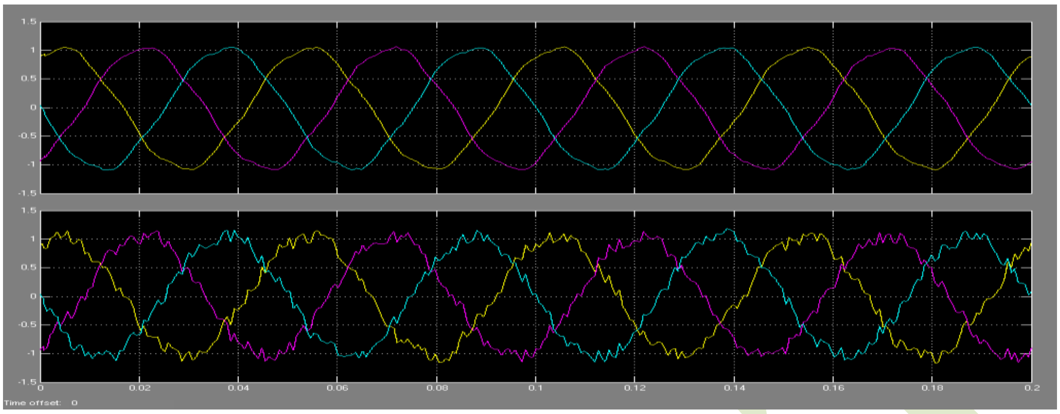

Figure 5: Simulated voltage and current waveforms at the receiving end

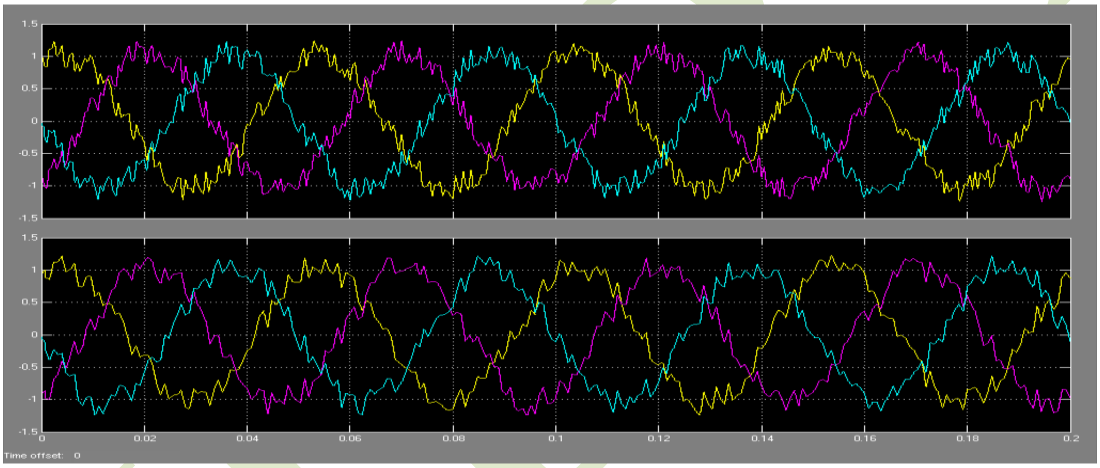

Figure 6: Simulated voltage and current waveforms at the cycloconverter 20 Hz side

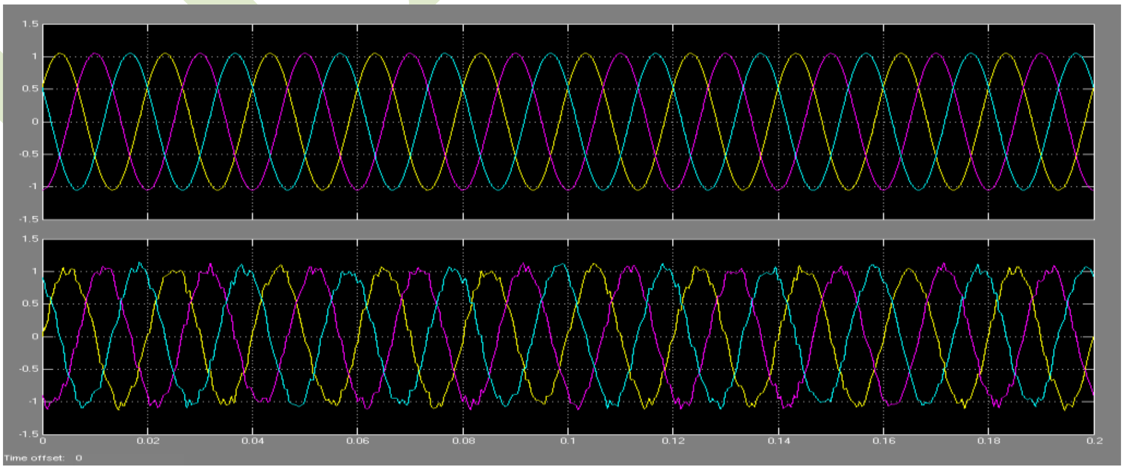

Figure 7: Simulated voltage and current waveforms at the 50 Hz grid

The following graph represents the THD values of voltages at the sending end, receiving end and at the 20 Hz cycloconverter side.
Fig.8, 9, 10 shows the bar graphs of the THD values of voltages at the sending end, receiving end and at the 20 Hz cycloconverter side.

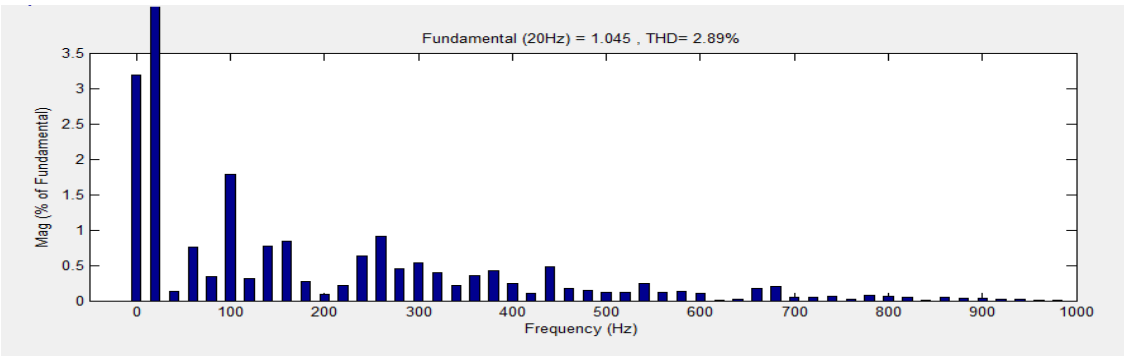

Figure 8: Graph of THD value at the sending end side voltage

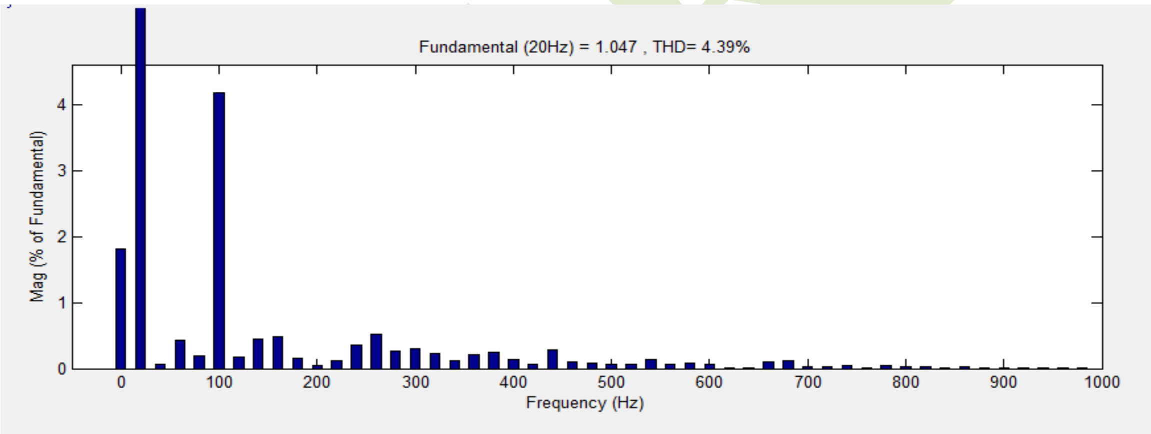

Figure 9: Graph of THD value at the receiving end side voltage

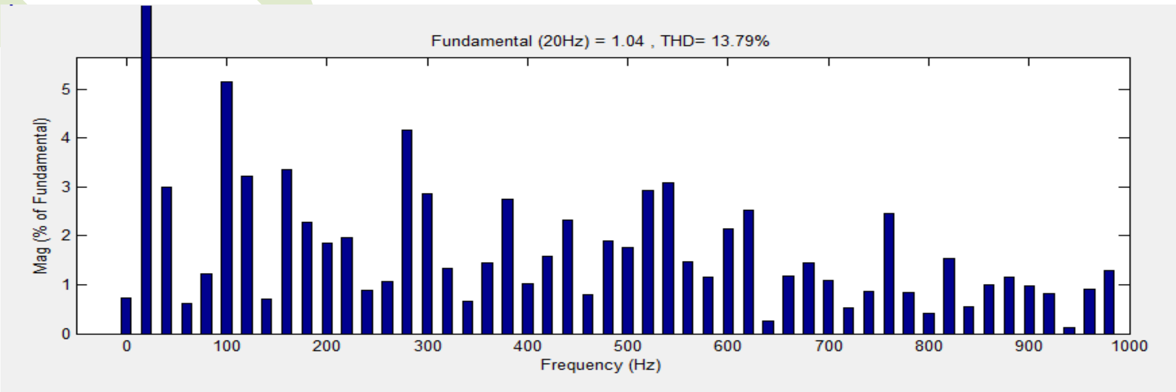

Figure 10: Graph of THD value at the 20 Hz cycloconverter side

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CONCLUSION

The cycloconverter which is used as a frequency changer produces harmonics of low order; hence filters are needed to add in the LFAC system.
A method to design filters and THD analysis for LFAC system is implemented in this paper. The 20-Hz voltage generated from the cycloconverter has THD = 13.79%. Due to the *LC* filter, the voltages at the receiving ends has reduced THD = 4.39% and sending ends has reduced THD values = 2.89% respectively. Thus, by adding the filters to the LFAC system the power quality of the system can be improved.

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