A State of Art Review on Offshore Wind Power Transmission Using Low Frequency AC System

Seetha Chaithanya*, V. Naga Bhaskar Reddy **, R. Kiranmayi***

* Department of Electrical Engineering, Research Scholar, Jawaharlal Nehru Technological University Anantapur, Anantapuramu, A.P, India.

** Department of Electrical & Electronics Engineering, Professor, Rajeev Gandhi Memorial College of Engineering and Technology, Nandyal, A.P, India.

*** Department of Electrical Engineering, Professor, Jawaharlal Nehru Technological University Anantapur, Anantapuramu, A.P, India.

(seethachaithu@gmail.com, nagabhaskarreddy@rgmcet.edu.in, kiranmayi0109@gmail.com)

‡ Corresponding Author; Seetha Chaithanya, Jawaharlal Nehru Technological University Anantapur, Anantapuramu, A.P, India. Tel: +91 9985076184. seethachaithu@gmail.com

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Abstract- Offshore wind power generation, transmission and integration around the world are becoming higher, and it provides technical and economic challenges for future practitioners and industries to make an alternative transmission system to an existing system in reduction of cost. In most of countries, e.g. The German government planned to install 25000MW of offshore wind farms by 2030. The greater part of offshore wind farms are integrated with High Voltage AC (HVAC) transmission to the onshore grid. Offshore wind farms are integrated with High Voltage DC (HVDC) transmission for long distances (>50km) to the grid because of capacitive cable current in HVAC. The major challenge in HVDC transmission is the installation, operation and maintenance (O&M) of the Voltage Sourced Converter (VSC) HVDC substation in the offshore climate. Currently, in case offshore wind farm the research have been fastened to reduce the complexity with increasing reliability and minimizing cost.

This paper gives a comprehensive review of integration of offshore wind farm via Low Frequency AC or Fractional Frequency AC (LFAC or FFAC) transmission. LFAC transmission is adopted from HVAC and it is operated at one third of nominal frequency (16.67 Hz). As compared to HVDC the main advantage of LFAC is an absence of the offshore converter station, hence system complexity and cost reduced. In design considerations, especially the offshore transformer is one of the challenges. This paper presents a comprehensive review on components and its design considerations of offshore novel LFAC transmission. The offshore wind turbine considerations, collector network and different types of onshore frequency converters explained in detail.

Keywords: LFAC, HVDC, Cycloconverter, Offshore wind farm, HVAC.

1. Introduction

Energy security and CO2 reduction are vital to ensuring a sustainable energy future. Large volumes of new, low carbon generation are needed and offshore wind plays a key role in the energy systems. The offshore wind is a good competitor for fossil fuel plants in European countries and global as well [1]. Challenges on the shortage of land, consistently stronger wind potential and public opposition in case of onshore wind plants are driving wind power plants to offshore. With the opposition to near shore the offshore wind farms are further planned. The feasibility study and present research focus on the increasing reliability and minimizing cost of offshore wind farms. Fig.1 shows the yearly onshore and offshore wind farms installations in Giga Watt (GW) in the Europe from 2005 to 2016 [2,3]. From Fig.1 it can be seen that, over the past 12 years the wind farm installations have been steadily increasing. 3 GW is the maximum level of offshore installation in 2015.

Fig. 1. The annual onshore and offshore wind installations in Giga Watt (GW) in the Europe from 2005 to 2016.

The transmission of wind power from offshore plants to the onshore grid is a major challenge for industry and academia as well. Many transmission configurations and design topologies have been proposed for power transfer. HVAC transmission is one of the good solutions for transmission of offshore power at 50 or 60 Hz, if the distance is less than 50 km to shore [4]. The traditional wind farms near to shore are built with HVAC transmission as considering the cost [5]. HVDC is another promising solution for offshore wind power for long distance transmission to near shore grid. HVDC transmission with VSC or Line Commutated Converter (LCC) based transmissions are the two approaches for offshore wind power for greater distances [6]. In these types of transmission the offshore power collector substation operates at a nominal frequency (50 or 60 Hz) and it is converted to High Voltage DC by the converter for transmission to the onshore grid. Currently, VSC-HVDC is more advantage than LCC-HVDC, because of its control & design for long distances at a range more than 200 KM for power levels on the order of 300-400 MW [7, 8].

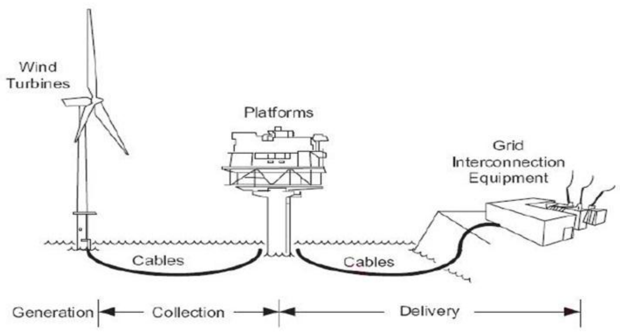


Fig. 2. A typical construction of offshore wind farm integration.

Offshore converter is one of the major challenges, because of large power electronic equipment. It may reduce the reliability and increased cost for far offshore [9]. If any failure occurs, the O&M are concerned problem, thereby rising supply interruption and downtime. Fig.2 shows a typical construction of offshore wind farm integration.

Besides VSC-HVDC and LCC-HVDC, in order to reduce the complexity of the offshore network and to improve the overall feasibility a novel transmission system High Voltage Low Frequency AC (LFAC) has been proposed [10-12]. LFAC is an adaption from HVAC technology and works at a frequency of one-third nominal frequency. Many advantages have been identified in existing literature from LFAC. At a lower frequency the power transfer capacity and transmission distance has been increased as compared to HVAC [12]. Another main advantage as compared to HVDC is an absence of the offshore converter station. Hence, increased reliability and reduced complexity and cost [13]. The elimination of offshore converter depends on the type of wind turbine production. If the generation is AC at 16.7 Hz frequency, that is possible by the type-4 turbines (Permanent Magnet Synchronous Generator with full converters). Generally, for offshore wind plant type-4 wind turbines are used [14]. The LFAC system transfers offshore wind power from the collector network at lower frequency to frequency converter, whereas the frequency converter synchronize the low frequency to grid frequency. The complexity of the network reduced by this system, because the number of conversion steps may reduce and it leads to increase reliability, which includes DC wind turbines connected to High Voltage DC grid [15]. Gomis et al. [16] explore the integration of DC wind turbines to LFAC system.

In this paper a comprehensive and comparative review has been carried out on LFAC system. Section 2 presents existing transmission topologies for offshore wind power. Section 3 covers the background of LFAC. Moreover, it describes the LFAC basic working principle. Section 4 reviews the design considerations of LFAC. This section focuses on the design of wind turbine and transformer and the types of the onshore frequency changer. Finally, section 5 concludes the paper and provides advantages of LFAC.

2. Different Transmission Topologies for Offshore Power

For most offshore applications, HVAC transmission will be used for small distances (~50 km) because of its simple construction [17]. This method is more economical than the other topologies for small distances. However, the cables have considerable higher capacitance. As a result, the charging current is more in case of HVAC cables which will cause heavy power loss. As the distance of transmission increases, the active power will become zero. Beyond the 50Km distance reactive power compensation is essential. So, additional compensation equipment is required. Therefore, the HVAC solution is less suitable for wind farms far from the coast [18]. Another issue associated with this transmission is the fault occurrence. If the fault occurs on the wind farms that affect the both wind farm and grid as well [19]. The HVAC system consists of offshore wind farm, substation, AC submarine cable and onshore substation.

The trend of offshore installation is going deeper into a sea because of higher wind potential [1]. For this, HVAC is not a feasible solution. For long distances and when the power levels are high, the HVDC transmission is a feasible option for integrating an offshore wind farm to grid [20, 21, 22]. In HVDC transmission, distance of transmission doesn't have any limit, because of no effect of reactive current and resonance in DC cable [23]. The two transmission approaches in HVDC are LCC- HVDC & VSC-HVDC. The LCC-HVDC has lower power losses than VSC transmission. But commutation voltage, low short circuit ratio level of the AC grid at the converter station and reactive power consumption from the grid are the drawbacks of the system. Reactive power consumption may result the low-order harmonics. So, additional auxiliary equipment required [24]. Other approach is VSC-HVDC scheme; it can provide some extra technical characteristics. It is self-commutating and for its operation does not need an external voltage source. The reactive power flow control is independent of the active power control. So there is no commutation failure. Therefore, there is no requirement of auxiliary equipment like filters, capacitor banks [25]. Offshore converter station and its cost are the major drawbacks of VSC-HVDC. In order to decrease the complexity of offshore wind farm, Blasco et al. [26] proposed that offshore converter has to be replaced with a diode based rectifier and the onshore VSC remains same. In this system, the main advantage is that the power electronics used for offshore are robust and reliable.

Ronan mere et al. [27] has been proposed another approach which is the single centralised converter for multiple wind turbines instead of the wind turbine with individual converter. This method works with variable voltage and frequency, but the V/f (voltage to frequency) ratio should be fixed [28]. The major drawback of this method is wind turbines within the wind farm have the same speed. The maximum energy capture will not be possible for individual wind turbines. The variable frequency approach has less power loss as compared to fixed frequency approach [29]. The variable frequency approach has many advantages like maximum energy production with a variable wind speeds as compared to existing approach. Another approach is using of a DC collection grid. But DC fault clearance is drawback of this method. Moreover, DC circuit breakers are difficult in design and more costly. These all approaches may increase the complexity and cost [30]. Fig.3 shows the basic structures of HVAC and HVDC integration of offshore wind farm to the grid.

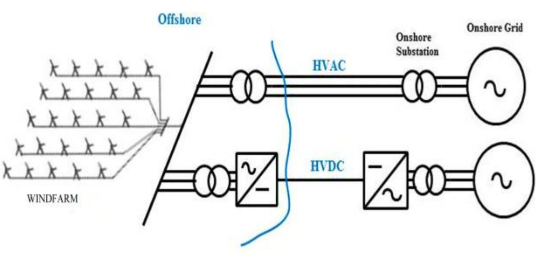


Fig. 3. The basic configurations of HVAC and HVDC integration of offshore wind farm to the grid.

3. The Background of LFAC

Germany, Austria, Norway, Switzerland and Sweden, countries are mainly used the lower frequency 16.667 Hz at 15KV, Costa Rica and USA uses 20 Hz and 25 Hz respectively in the electric traction system [31]. In the early days for electric traction DC motors were used, because of its speed control characteristics. For the long distance DC is not a good option for railway lines. Later universal motors are proposed for AC traction. For nominal frequency the eddy currents induced in the winding of universal motor may lead to overheating [32]. To overcome that propulsion motor operating at lower frequency was proposed to minimize losses and design complexity. For long distance railway lines low frequency system is advantageous.

In 1994, X. Wang [33] was firstly proposed the Fractional Frequency Transmission System (FFTS) for long distance hydro power plants to increase the transmission capacity. For offshore wind farms Schutte et al. [34] proposed that the low frequency AC. If the transmission network is HVAC used, the low frequency AC can be used within the wind farm collector network and for the transmission network to onshore. An onshore frequency converter is needed to integrate a low frequency AC to the onshore grid. If the transmission network is HVDC used, the low frequency AC can be used in the wind farm collector network of the offshore wind farm.

3.1 LFAC basic principle

In HVAC cable transmission the charging current or reactive current is the main limitation for power transmission capability. The charging current (I_c) depends on the frequency (f). Therefore the charging current is reduced by lower frequency from the Eq. (1).

$$I_c = 2\pi flCE \tag{1}$$

The reactive power generated by the cable (Q_c) can be calculated by Eq. (2) and the Eq. (3) expressed the active power transmission to the line length (l) [11].

$$Q_c = I_cE = 2\pi flCE^2 \tag{2}$$

$$P = \sqrt{S^2 - (2\pi flCE^2)^2} \tag{3}$$

Where C = Cable capacitance, S = Apparent power, P = Active Power Transmission along the line, E = Rated voltage.

The transmission capacity enhancement is possible by decreasing the reactance of the cable if resistance is neglected. The impedance is dominated by the line reactance X_L, and is proportionate with respect to frequency f of the line as shown in Eq. (4). Therefore, the active power transmission capability increased.

$$X_L = 2\pi fL \tag{4}$$

Jonathan et al. [35] illustrated that the offshore wind power transmission at different frequencies of a 220KV XLPE cable. From Fig. 4 it can be observed that reducing frequency may result in increasing of active power transmission length. Transmission capacity would increase by reducing the reactance of the line. To decrease the reactance of the line, the LFAC utilize low frequency. For example, 16.7 Hz frequency is ideally three times of the transmission distance can be increased that at 50Hz.

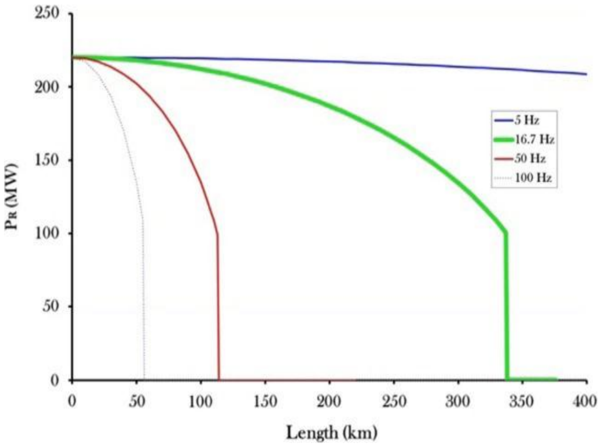


Fig. 4. Offshore wind power transmission capability curves at different frequencies for a 220KV XLPE cable [35].

For transmission of hydro power X. Wang [33] was proposed FFTS firstly. The paper concludes that HVAC has limited transmission distance at 550KV, whereas the FFTS increases the capacity of transmission from 850 MW to 1700 MW for 550KV. In the next paper by X. Wang [36] a hardware model was developed for frequency converter (cycloconverter) with same as early configuration, which concludes that the transmission capacity increased 2.5 times, but the limitations of cycloconverter are low power factor and harmonics in output voltage. Later X. Wang [37] investigated a case study on the integration of wind farm to a large distance grid. A comparative case study has been carried out on 10,000 MW wind farm integration via FFTS. This paper concludes that FFTS can transmit more power than conventional 50Hz AC system, but the cost of transformer and cycloconverter are more expensive.

4. The Design Considerations of LFAC

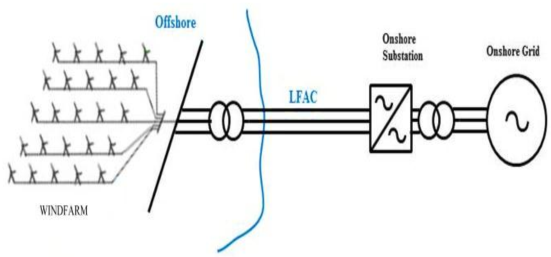


Fig. 5. The connection of an offshore wind power plant using LFAC.

Fig.5 shows the connection of an offshore wind power plant using a LFAC. The wind farm is assumed to produce low frequency power, which is possible by type-4 wind turbine. The low frequency power then stepped up by the low frequency transformer, and then transmits via LFAC system. On the onshore side a frequency changer synchronizes the low frequency to grid frequency.

4.1 Offshore wind turbine

In design considerations of LFAC one of the important considerations is design of wind turbine. Due to lowering the frequency the transformer size will be increased. At present scenario, the transformer and converter are placed inside the nacelle [38]. For future wind turbine the transformer need to place at base of the wind turbine because of the size [39]. The behaviour of LFAC is also depends on type of the generator used. In the literature Liserre et al. [40] explained different generator configurations for Mega Watt (MW) wind farms, which are SCIG (Squirrel Cage induction generator), DFIG (Doubly Fed Induction Generator) and PMSG. Nan Qin [41] explores the SCIG based wind farm with LFAC. The author found that limitations are increased oscillations and short circuit current with fixed speed wind turbine generator. Therefore, it indicates re-design of gear box ratio and winding, etc. DFIG based LFAC system was proposed in [42] and suggested by simulation results is that no much difficulty of operation was found at low frequency. The author has done the steady state simulation under variable wind and fault condition. Results show the reactive power control is needed at line side for improving the operation of the cable. Later Jing li et al. [43] proposed the DFIG based FFTS offshore integration. The author used eigen value analysis to evaluate the dynamic damping response of the system. Both eigen value and time domain simulations are stated that the damping of the system is reduced. However the size and weight of SCIG and DFIG based wind turbines are high for low frequency AC [13].

In the current trend the PMSG based offshore wind farms are gaining popularity because of their less weight, size and maintenance than other configurations [44, 45, 46]. PMSG with fully rated converter has the ability to produce low frequency power for LFAC system [12, 13, 44]. Recently, Shenquen liu et al. [47] proposed PMSG based FFTS offshore wind farm in two cases. In the two cases the author proposed that point to point FFTS (PP-FFTS) and multi terminal FFTS (MT-FFTS) and compared with PP-HVDC & MT-HVDC. The author concluded that the PMSG based PP & MT- FFTS are cheaper and high reliable than PP & MT- HVDC.

4.2. Low frequency transformer

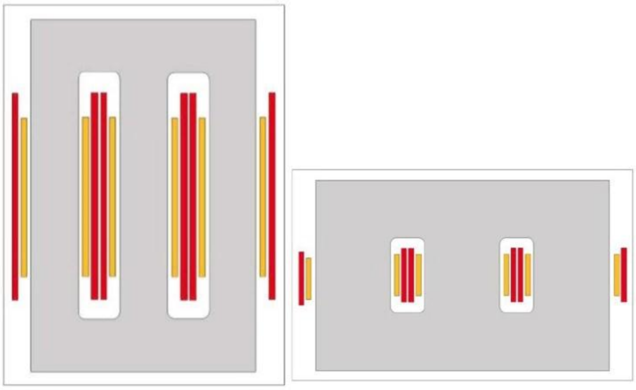
As compared to HVDC platform the main advantage of LFAC is the elimination of converter station, which result reduction of offshore platform space. But lowering frequency may increase the size of the transformer. This is the major drawback of LFAC. P.B.Wyllie et al [48] explore the design of a low frequency transformer. As it is clear from transformer Eq. (5) reduction in frequency may increase in either width of the core or number turns.

$$E = 4.44fBNA \tag{5}$$

Where E = Applied voltage, f = Frequency, B = Flux density, N = Number of turns, A = Core cross-sectional area.

In [48] the author concludes that the thickness of the core increases approximately 1.43 times of conventional 50Hz transformer. That means lowering three times frequency may increase three times core cross section area.

Fig. 6 (a) & (b) shows the 16.67 Hz transformer wide and tall designs for LFAC.



(a) (b)

Fig. 6. The 16.67 Hz transformer (a) Tall and (b) Wide designs for LFAC.

4.3. DC collection Network

The collection network is also a main consideration for LFAC transmission. From the existing literature the collection network are two types for LFAC. One is low frequency AC collection, i.e. 16.67 Hz and another is DC collection [12, 49]. The main drawback of low frequency AC collection wind turbines needs to design for low frequency power. Hao Chen et al. [12] used DC collection system for offshore power. If DC collection network is used, there is no need to re-design the wind turbines for low frequency power. The author explores that due to the offshore inverter cost & conversion steps of the network were increased. Moreover, additional filtering equipment required to mitigate the harmonics, which was contributed by offshore inverter.

4.4. Onshore frequency changer

4.4.1. Cycloconverter

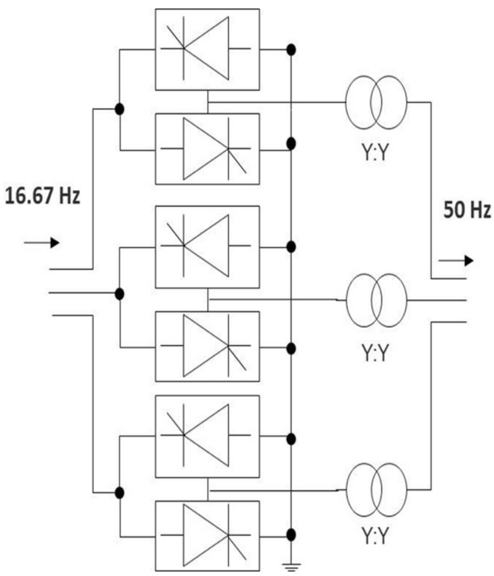


Fig. 7. Three phase 36-pulse cycloconverter.

For AC to AC application, for LFAC the frequency converter is not a popular option. The thyristor based thirty-six pulse frequency converter (cycloconverter) converts one frequency AC to another frequency AC. The three phase input of low frequency wave converts to nominal frequency output and for each phase of output has a positive and negative six pulse converter. The cosine angle control method is used to control the thyristor firing angle in each converter. The firing pulse generated depending on the output frequency [12]. Fig. 7 shows the three phase 36-pulse cycloconverter [50].

It is interesting to note that in 1930s the step down cycloconverters were used in Germany for railway traction using universal motors. The general applications of cycloconverter may include rolling mills and slip-power recovery scherbius drives [51]. But in case of LFAC transmission cycloconverter used as step-up cycloconverter. The thyristor as power switches (line commutated) based step down cycloconverters has frequency conversion ratio limit (output to the input frequency, i.e., f_0/f_i) is 0.7 due to poor quality of the output voltage wave. The poor power quality of output wave due to the production of the inter and sub harmonics. The change of harmonic frequency spectrum can be evaluated from the Eq. (6) [52].

$$f_{oH} = | 6f_i \pm (2n+1)\, f_0 | \tag{6}$$

Where f_{oH} = Harmonic frequency, f_i = input frequency, f_0 = output frequency and n = positive integer from 0 to ∞.

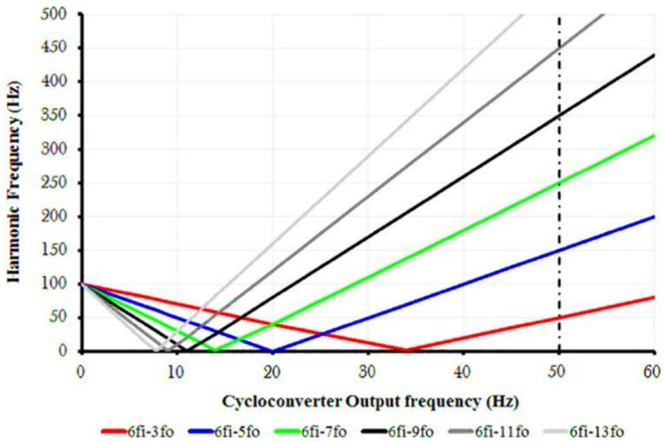


Fig. 8 The harmonic frequency spectrum with naturally commutated converter [53].

Fig. 8 [53] displays the harmonic frequency spectrum with the naturally commutated converter. The cycloconverter conversion ratio is f0/fi (fi=16.67Hz & f0=50Hz). If the order of harmonics under the desired output frequency is called as sub-harmonics. The inter harmonics that are present at frequencies, when these are not the direct multiples of output frequency. For LFAC the f0/fi ratio required is 3, which means the harmonics that are present at frequencies which are direct multiples of the output frequency and is shown from Fig. 8. Moreover, the sub-harmonics, inter harmonics and low order harmonics are very difficult to filter, which require high capacity and complex design filters. In cycloconverters, if thyristors are replaced by fully controlled switches (GTO's or IGBT's) called as forced commutated converters, the sub and inter harmonics were not produced because of complex switching [52]. However, forced commutation may produce large lower order harmonics, which are complex to filter.

In the existing literature, many authors were proposed cycloconverter for LFAC system. Nakagawa et al. [55] was presented 6-pulse cycloconverter for LFAC. The author proposed the three phase output balancing control to enable the operation of cycloconverter stable. The paper concludes that the large harmonics need to mitigate. Yongnam cho was presented two papers [56, 57] about time domain simulation of cycloconverter and same is used for remote wind farms using LFAC. The LFAC technical and economic benefits have been discussed for remote wind farms. A case study was presented in [12] for LFAC integration with 20 Hz to 60 Hz conversion. The author concluded that cycloconverter has significant harmonic distortion (THD is 14.8%) and the cycloconverter control and mitigation of harmonics are complex.

4.4.2 Matrix Converter

As from the above discussion the lower order harmonics are the major issue in cycloconverter. The mitigation of lower order harmonics can be done by the matrix converter. The matrix converter is adopted from forced commutated cycloconverter. In matrix converter the variable output voltage can be created by the bi-directional switching. It doesn't have any storage system, which result in increased efficiency and reliability [58,59]. However, the protection of matrix converter in a fault situation is not as good as that of other converters. Other disadvantages of matrix converter compared to back to back converter are higher conduction losses and the limitation of the output voltage (86.6% of the input voltage) [60]. Fig.9 shows the matrix converter [35].

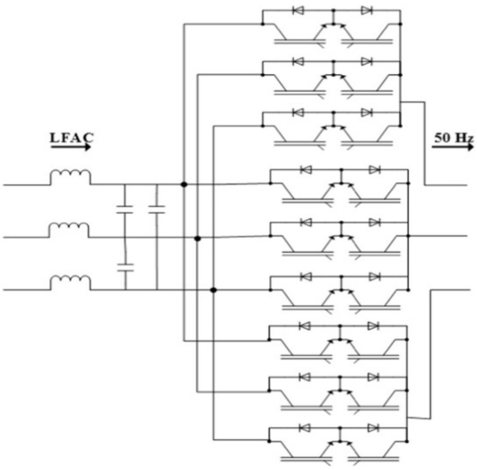


Fig. 9. The Matrix converter.

In the literature in order to overcome the output voltage issues, Modular Multilevel Matrix Converters (MMMxC or M^3C) was proposed [52]. Muira et al. [61] was explored the MMMxC for LFAC system. A laboratory setup was made for 1KW capacity to verify the control schemes for LFAC conversion from 5 or 20 Hz to 60 Hz. Later, Lang Huang et al. [62] was investigated the M3C on LFAC system. A model predictive control (MPC) was proposed in this paper. The author concluded that the proposed MPC scheme is performed well for M^3C to integrate LFAC. Recently, Pengwei Sun et al. [63] was investigated M^3C for FFAC system with common control schemes. The results show that the THDs of voltages and currents of MMMxC are less than 1.5%. Although M^3C is suitable for LFAC in the existing research M^3C were not proposed for high power applications.

4.4.3 Back to Back Voltage Sourced Converter (BtB-VSC)

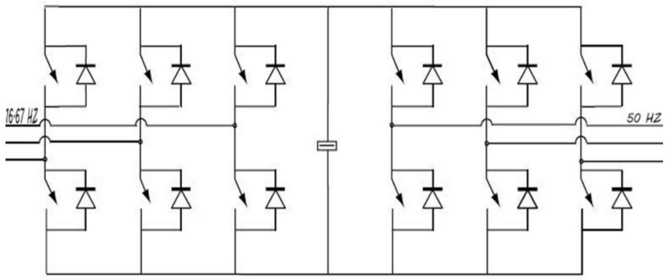


Fig. 10. BtB-VSC

The back-to-back Voltage Sourced Converters are highly relevant to wind turbines today and are most promising for high power applications. The back-to-back converter is a power converter consisting of two conventional pulse-width modulated (PWM) VSCs using IGBT's [60,64]. The topology is shown in Fig. 10. In the literature two possible frequency converters were presented, which are cycloconverter and matrix converter [12, 52, 61]. In the LFAC topology BtB converter is located at onshore, low frequency offshore platform and onshore grid connected via two VSCs with DC storage lying in between them. It has the ability of independent control over the active and reactive power because of DC link [13]. Jonathan ruddy et al. [53] was proposed the BtB-VSC onshore for LFAC integration in comparison with VSC-HVDC transmission. The author presented a techno-economic comparison in between VSC-HVDC and LFAC. The paper concluded that the VSCs can be used for both LFAC and VSC-HVDC systems. The BtB-VSC has higher power loss as compared with cycloconverter. The LFAC connection with BtB-VSC has many advantages as compared to LFAC with cycloconverter, which are increased reliability, reduced space, cost, filtering equipment and reactive power compensation. In the followed paper by Jonathan ruddy et al. [54] developed a real time hardware model for onshore BtB-VSC and compared with simulation results. The both results are comparable. In the same paper the author also introduced LC filter design for LFAC system. Moreover, research needs to concentrate more on the design and technical aspects of LFAC system.

5. Conclusion

The literature review on LFAC has been performed in this paper is indicating that the offshore collector and onshore converter schemes have more designing factors which are to be investigate more in future to reduce the complexity of the network. The future work need to concentrate on LFAC for multi terminal offshore network and the advancements in the onshore converters to reduce the cost. In this paper, it is reviewed about pros and cons of LFAC transmission system. It is also elaborately discussed about generator configurations transmission topologies and converter schemes. Past, present and future scenario of LFAC transmission is thoroughly discussed. There are two major advantages identified by the use of LFAC system for offshore wind farms. Firstly, the design of a low frequency AC system is simple for the offshore wind plants. The fact behind this is the aerodynamic rotor speed of 3-5 MW wind turbine is low, about 15-20 rpm. For a direct driven generator wind turbines, the lowering frequency AC would decrease the gearbox ratio and the number of poles of generator as well. The reduced gearbox ratio and the number of poles may result in size of wind turbines and are cheaper in cost. The absence of offshore converter is also reducing the cost. Second, the low frequency AC will enhance the transmission capability and distance of HVAC link, because of reduction in charging current. The major disadvantage of LFAC system is the size of offshore transformer that means lowering three times frequency may increase three times core cross section area. Therefore, it is likely to be more expensive. So academia, researchers and industry need to do more for development of LFAC as competitive to other transmission technologies.

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