Power converters for wind turbines: Current and future development

Md Rabiul Islam[*], **Youguang Guo,** and **Jianguo Zhu**

Centre for Electrical Machines and Power Electronics, University of Technology Sydney, NSW-2007, Australia
[*]Corresponding author: e-mail: Md.Islam@uts.edu.au and Rabiulbd@hotmail.com, Tel: +61 2 9514 2337

The wind turbine generator system requires a power conditioning circuit called power converter that is capable of adjusting the generator frequency and voltage to the grid. Several types of converter topologies have been developed in the last decades; each of them has some advantages and disadvantages. Mainly two converter topologies are currently used in the commercial wind turbine generator systems. Most of the proposed converters require line filters and transformers to improve the power quality and step-up the voltage level, respectively. These heavy and bulky components significantly increase the tower construction, and turbine installation and maintenance costs. Recent advances in power semiconductors and magnetic materials have led to the development of new structure of converters, which would be a possible solution to reducing the size, weight, and cost of power converters. In this chapter, a comprehensive study of power converter technologies, current research and development is conducted.

Keywords: wind turbine generator; power converters; research and development; advanced devices and materials

1. Introduction

Wind energy has continued the worldwide success story as the wind power development is experiencing dramatic growth. According to statistical data the cumulative installed wind power capacity in 2006, 2009 and 2012 were 74.0, 158.86 and 282.43 GW respectively; almost doubled in every three years. The dynamic growth of wind power directly pushes the wind technology into a more competitive area. Therefore, it is essential for scientists and researchers to find out the effective technologies for the wind power generation systems. The variable nature of wind energy sources (in terms of the real power, reactive power, output voltage, and frequency) is a major challenging issue. The conversion of an input AC power at a given frequency and voltage to an output power at different frequency and voltage can be obtained with static circuits called power converters, containing controllable power electronic devices. Various power converters have been developed to fulfil the requirements of the wind power generation. Each of them has some advantages and some disadvantages. The traditional converter voltage level is in the range of 380–690 V due to the low generator voltage rating and the use of two-level converter topology. To reduce the electrical losses, a power frequency (50/60 Hz) power-transformer is commonly used in wind power generation system (usually installed inside the turbine nacelle) to step-up the voltage to medium voltage level (e.g. 11–33 kV), as shown in Fig. 1. This heavy and bulky transformer significantly increases the weight and volume of the nacelle as well as mechanical stress of the tower. Nowadays components can handle higher current and voltage ratings, the power loss decreases and the devices become more reliable for the control of megawatt scale power thanks to the power electronics as a rapidly developing technology. The price is still decreasing, and power converters are becoming more and more attractive which means improving the performance of wind power generation systems. With the advent of new power semiconductor devices, different soft magnetic materials with high magnetic saturation flux density and low specific core loss are conceived to reduce the weight and volume of medium or high frequency-link [1]. These recent advances have led to the development of new medium voltage converter system, which would be a possible solution to eliminate the transformer of the wind turbine generator systems. This chapter aims to a comprehensive study of traditional converter technologies for wind turbine generator systems. In addition the challenges, current research and development trends, possible future directions of the research to develop new converter topology for future wind turbine are also considered in this chapter.
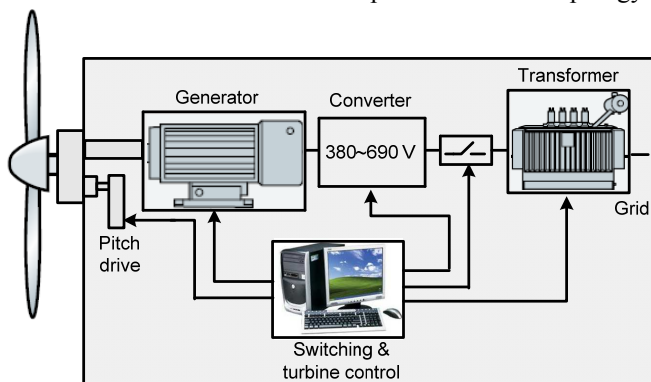

Fig. 1 Fully-rated converter based wind turbine generator system.

## 2. Converters for wind turbine generator systems

In the last two decades different converter topologies have been investigated for power conditioning of wind turbine generator systems. All the proposed converters have some advantages and some disadvantages. Only diode rectifier based unidirectional converter and back to back bidirectional converter topologies are commonly used in the commercial wind turbine generator systems.

2.1 Diode rectifier based converter

In this converter system a variable frequency and variable magnitude AC power from the wind turbine generator is firstly converted to a DC power by a diode rectifier circuit and then converted back to an AC power at different frequency and voltage level by a controlled inverter. The diode rectifier (uncontrolled rectifier) based converter system transfers power in a single direction e.g. from generator to the grid. This type of power converter is normally used in a wound rotor synchronous generator (WRSG) or a permanent magnet synchronous generator (PMSG) based wind power generation system instead of an induction generator. In WRSG based system, to achieve variable speed operation the systems use an extra excitation circuit, which feeds the excitation winding of WRSG. The PMSG based wind turbine generator systems are equipped with a step-up chopper circuit. The step-up chopper adapts the rectifier voltage to the DC-link voltage of the inverter. Controlling the inductor current in the step-up chopper can control the generator torque and speed. The diode rectifier with step-up chopper based power conditioning system is illustrated in Fig. 2. The output voltage and input current of the diode rectifier and step-up chopper based converter system are shown in Figs. 3 and 4, respectively. The frequency spectrum of the output voltage of diode rectifier and step-up chopper based wind power conditioning system is depicted in Fig. 5. In this converter system the grid side inverter controls the active and reactive power delivered to the grid. The output voltage of this converter system is in the range of 380–690 V. Therefore, a step-up transformer is commonly installed inside the nacelle to feed-in the energy into an medium voltage grid. Many power semiconductor vendors such as Semikron, ASEA brown boveri (ABB), IXYS, and Mitsubishi Electric produce devices specially designed for this type of converter in a module form, all the devices in a single pack, which reduces the cost and complexity of the power conditioning system. Semikron developed SKS 660F B6U+E1C+B6CI 250 V06 and IGDD6-4-426-D3816-E1F12-BL-FA modules for diode rectifier based power conditioning systems. According to the internal circuit configuration the SKS 660F B6U+E1C+B6CI 250 V06 module is suitable for PMSG based wind turbine generator systems and IGDD6-4-426-D3816-E1F12-BL-FA module is suitable for WRSG based wind turbine generator systems. Mitsubishi Electric developed CM100MXA-24S module with this converter topology which can be used for both WRSG and PMSG based wind turbine generator systems.
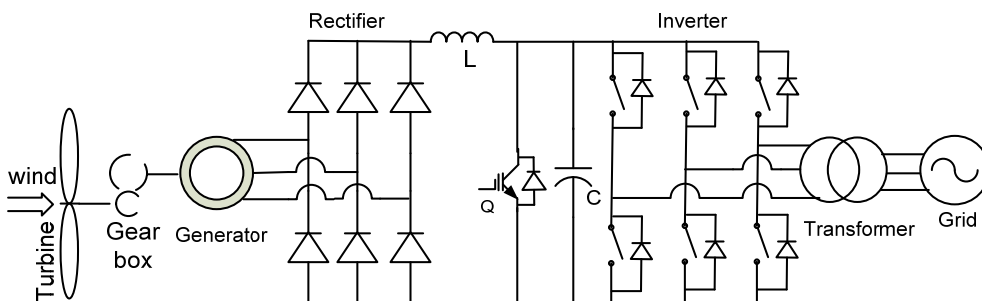
Fig. 2 Diode rectifier based converter topology
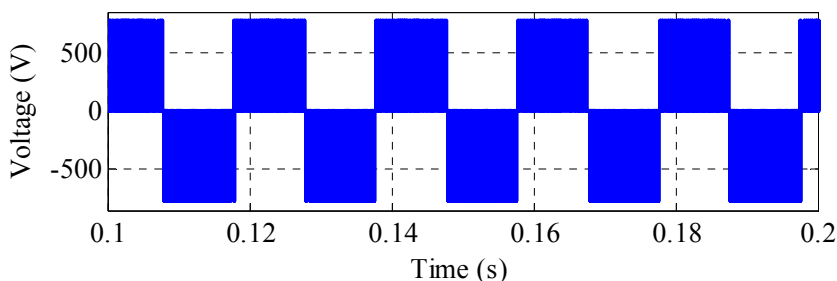
Fig. 3 Output voltage of diode rectifier based converter, where inverter switching frequency is 2 kHz.

Although it is a cost effective choice, the power quality of this converter system is critical to the selection. A summary of advantages and disadvantages is presented as below:
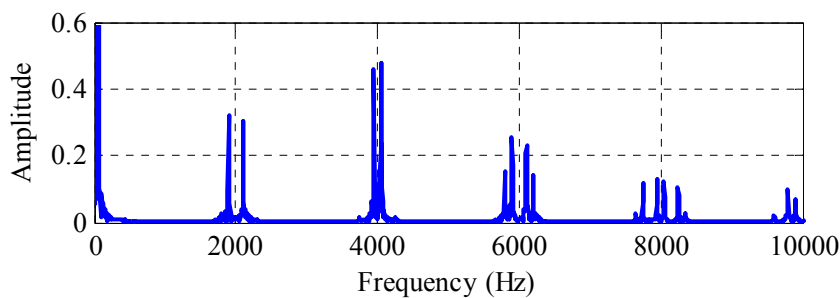
Advantages:
- Low system production cost and
- Simple to implement

Disadvantages:
- Diode rectifier produces a large amount of harmonics (input current), which affects the performance of the utility system
- Higher harmonic losses (output voltage) and
- Unidirectional power handling capability
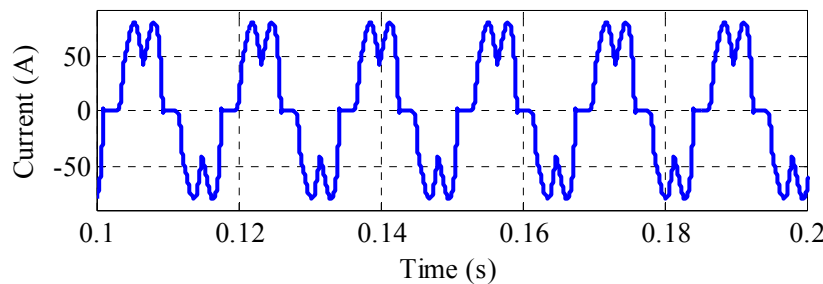
**Fig. 4** Input current of diode rectifier based converter.

Fig. 5 Output voltage frequency spectrum of diode rectifier based converter system.
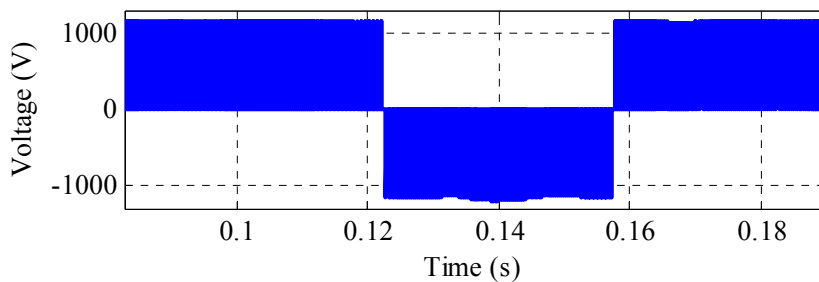
2.2 Back to back converter

The controlled rectifier and controlled inverter based converter is called back to back converter consisting of two conventional pulse width modulated (PWM) voltage source inverters (VSIs). It differs from the diode rectifier based converter for the rectification stage, where the diode rectifier with chopper circuit is replaced by controlled rectifier as shown in Fig. 6. The controlled rectifier gives the bidirectional power flow capability, which is not possible in the diode rectifier based power conditioning system. Moreover, the controlled rectifier strongly reduces the input current harmonics and harmonic losses. The output voltage and input current waveforms of a back to back converter are illustrated in Figs. 7 and 8, respectively. The grid side converter enables to control the active and reactive power flow to the grid and keeps the DC-link voltage constant, improving the output power quality by reducing total harmonic distortion (THD). The generator side converter works as a driver, controlling the magnetisation demand and the desired rotor speed of the generator. The decoupling capacitor between grid side converter and generator side converter provides independent control capability of the two converters. A simulation analysis of back to back converter based wind turbine generator system was carried in [2]. The harmonic spectrums of the back to back converter are shown in Fig. 9. Due to some special features this converter topology has received great attention recently. Many power semiconductor manufacturers such as Semikron, ASEA brown boveri (ABB), Hitachi, Siemens, IXYS, and Mitsubishi Electric produce components in a module form, all the devices in a single pack; suitable for this converter, which makes the converter compact and lightweight. As an example, Semikron developed SKS C 120 GDD 69/11-A3A WA B1B module for power conditioning of synchronous and double-fed generator based wind power systems. The back to back converter can be used for PMSG and squirrel cage induction generator (SCIG) based wind power generation systems. Siemens employs back to back converter for power conditioning of SCIG based wind turbine generator systems. The voltage rating of the most common generators is usually in the range of 380–690 V except that Repower employs 6.6 kV DFIG. Therefore, converter voltage level is also in the range of 380–690 V due to the low generator voltage rating and the use of two-level converter topology. In order to integrate the wind turbine with local medium voltage grid a step-up transformer is normally installed inside the nacelle of the wind turbine. In the last two decades a lot of research

and development have been reported to improve the performance of this converter. New control schemes were proposed to improve the performance of inverter section [3, 4] and field programmable gate array (FPGA) based reconfigurable control strategy has been proposed [5]. An integrated control strategy of back to back converter has been developed for direct drive PMSG based wind turbine systems [6].
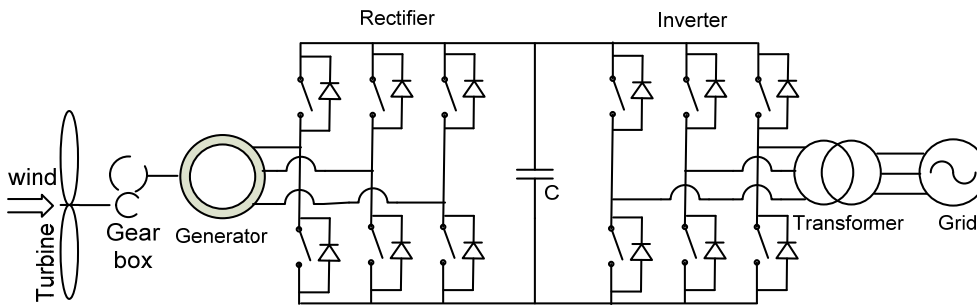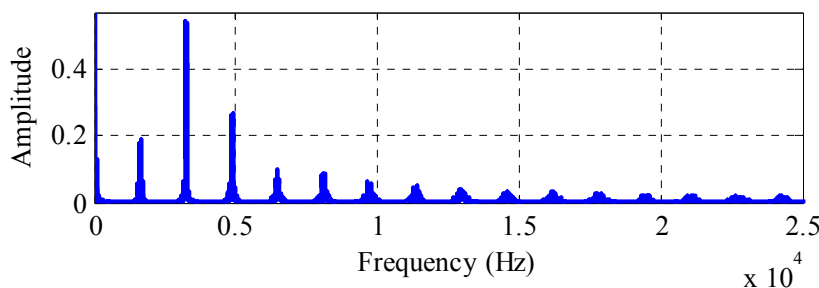

Fig. 6 Back to back converter based wind turbine generator system

**Fig. 7** Output voltage of back to back converter
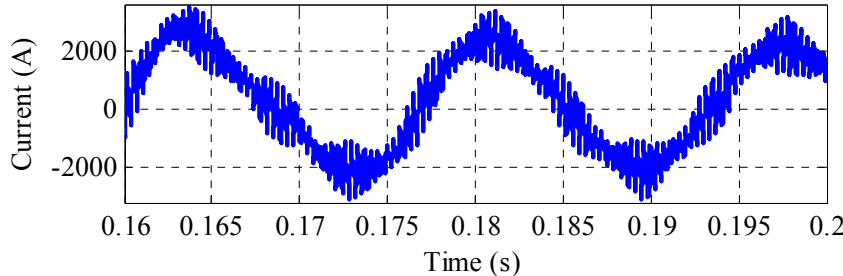
Fig. 8 Input current of back to back converter

Fig. 9 Frequency spectrum of the output voltage of back to back converter

Recently, the back to back converter has also attracted significant interest for partial rating converter applications, where the wind turbine system employs doubly-fed induction generator (DFIG). The block diagram of DFIG based wind turbine generator system with back to back converter is shown in Fig. 10. Several manufacturers such as ABB, Repower, Vestas, GE Wind, and Ecotecnia currently employ DFIG concept for modern wind turbine systems. To obtain sub- and sup-synchronous speed operations the rotor side converter must be able to handle slip power in both directions. When the turbine speed is below the synchronous speed, the power input to the system through the stator winding is

balanced by subtracting a small portion of power from the system through the rotor circuit. On the other hand when the shaft speed is above the synchronous speed the power is balanced by adding a small portion of power to the system through the rotor circuit [7]. To improve the performance of the back to back converter based wind turbine generator system several literatures have proposed different control topologies. In 1996, the engineering and design of a DFIG, using back to back converter in the rotor circuit with vector control scheme was described [8]. In order to improve the fault ride-through capabilities and crowbar dynamics of the system an internal model control controller has been proposed in [9]
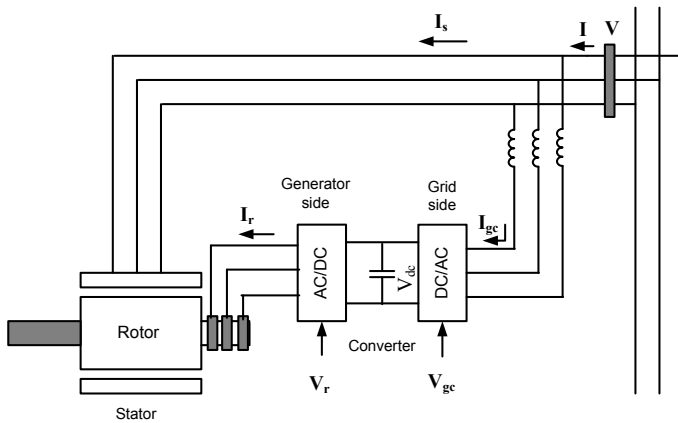
Fig. 10 DFIG based wind turbine generator system with back to back converter.

Advantages:
- The back to back converter is a bidirectional power converter
- The DC-link voltage can be boosted to a level higher than the amplitude of the grid line to line voltage in order to achieve full control of the grid current
- The capacitor between the inverter and rectifier makes it possible to decouple the control of the two inverters, allowing the compensation of asymmetry on both the generator side and the grid side.
- The component costs are low (commercially available in a module form).

Disadvantages:
- The presence of the heavy and bulky DC-link capacitor increases the costs and reduces the overall lifetime of the system
- Another important drawback of the back to back converter is the switching losses. Every commutation in both the grid inverter and the generator inverter between the upper and lower DC-link branch is associated with a hard switching and a natural commutation
- The back to back converter consists of two inverters, so the switching losses might be even more pronounced
- The high switching speed to the grid may also require extra EMI-filters, and
- The combined control of the controlled rectifier and inverter is quite complicated
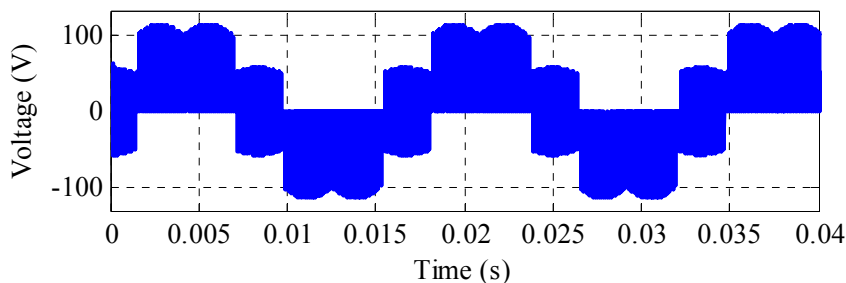
2.3 Matrix converter

The matrix converter (MC) is a unique topology of AC to AC power converter that eliminates the need for an intermediate DC conversion and the passive reactive filter components associated with this DC-link. It is a direct or single stage AC to AC converter topology. The converter consists of an array of bidirectional switches positioned at the intersection points of the input and output phases. The output is synthesized by selective closings and openings of the switches. A filter on the input side aids commutation and prevents switching generated harmonics from propagating to the power input. MCs offer the potential for significant size and weight reductions in power converter applications due to the absence of any large energy storage elements, such as DC-link capacitors [10]. Compared to a conventional back to back converter the MC is of much smaller size. Due to these special features MC has attracted great attention in the last few years. A high power MC was patented in 1999 [11]. In 2005, a 150 kVA MC has been fabricated and tested [12] for electric vehicle applications. The MC topology was implemented commercially in 2008 [13]. Recently MC has attracted interest for wind power applications. A matrix converter based wind power generation system is depicted in Fig. 11. The output voltage and input current waveforms are close to sine wave, as illustrated in Figs. 12 and 13, respectively. Therefore, the THD coefficient of MC is much better than those of the back to back and diode rectifier based converters. The frequency spectrum of output voltage is depicted in Fig. 14. Several literatures have introduced the application of matrix converter in variable speed wind turbine generator systems. In 2009, an MC was implemented

for induction generator based wind turbine generator system [14]. In the same year, for performance enhancement and efficiency optimization a modified MC was proposed for SCIG based wind turbine generator systems and a simulation work was reported in [15]. Due to its advantages compared with back to back converter the MC is currently replacing the back to back converter from DFIG based wind turbine generator systems. The layout of an MC converter with DFIG based wind turbine generator system is illustrated in Fig. 15. An MC was fabricated and tested with DFIG based wind turbine generator system in [16] where space vector modulation (SVM) scheme was used to control the MC, regulating the rotor torque and magnetizing currents.
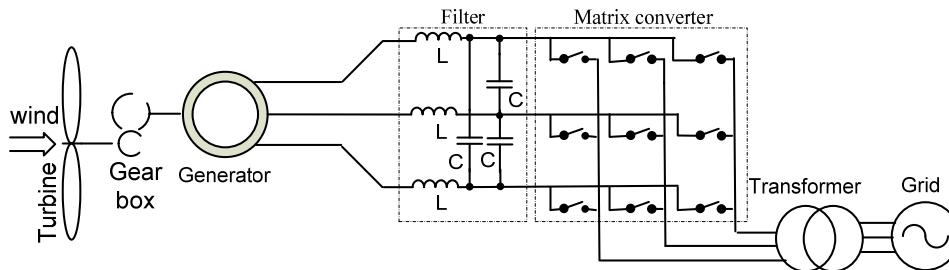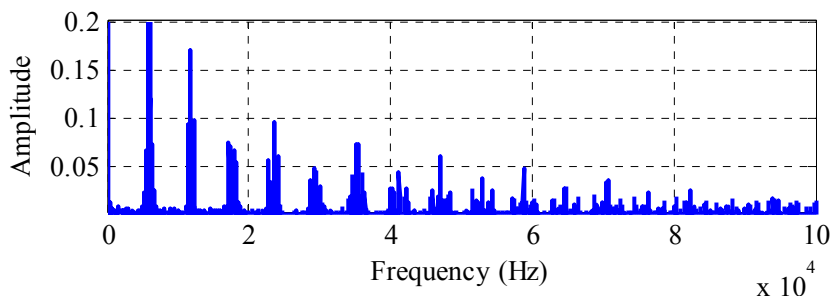

Fig. 11 Matrix converter based wind turbine generator system.

Fig. 12 Output voltage of a matrix converter.
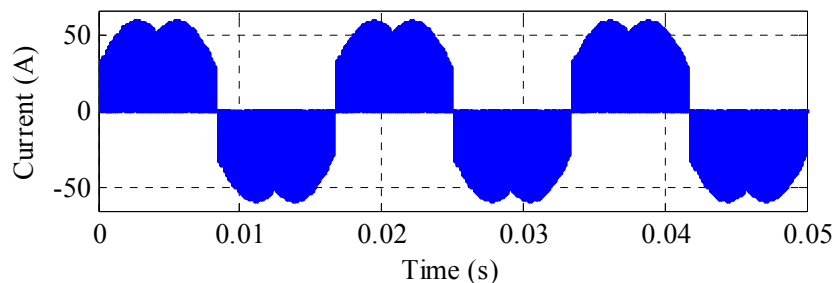
Fig. 13 Input current of a matrix converter.

Fig. 14 Frequency spectrum of the output voltage of matrix converter.

Advantages:
- Matrix converters offer the potential for significant size and weight reductions in power converter applications due to the absence of large energy storage elements, such as DC-link capacitors [10].

- Although the matrix converter includes six additional power switches compared to the back to back converter, the absence of the DC-link capacitor may increase the efficiency and lifetime for the converter.
- Depending on the realization of the bi-directional switches, the switching losses of the matrix inverter may be less than that of the back to back converter, because half of the switching becomes natural commutations.
- Provide practically sinusoidal waveforms of the input and output currents with negligible low order harmonics.
- Thermal stresses of the semiconductors in a matrix converter are lower than those in a conventional converter.

Disadvantages:
- The DC-link voltage can not be boosted as that of back to back converter. Without entering the over-modulation range, the maximum output voltage of the matrix converter is 0.866 times the input voltage.
- To achieve the same output power as the back to back converter, the output current of the matrix converter has to be 1.15 times higher, giving rise to higher conducting losses in the converter [17].
- Due to the absence of the DC-link, there is no decoupling between the input and output of the converter. In ideal terms, this is not a problem but in the case of unbalanced or distorted input voltages, or unbalanced load, the input current and the output voltage also become distorted.
- Modulation technique and commutation control are more complicated than those in the conventional PWM inverter.
- The protection of the matrix converter in a fault situation is not as good as that of back to back converter.
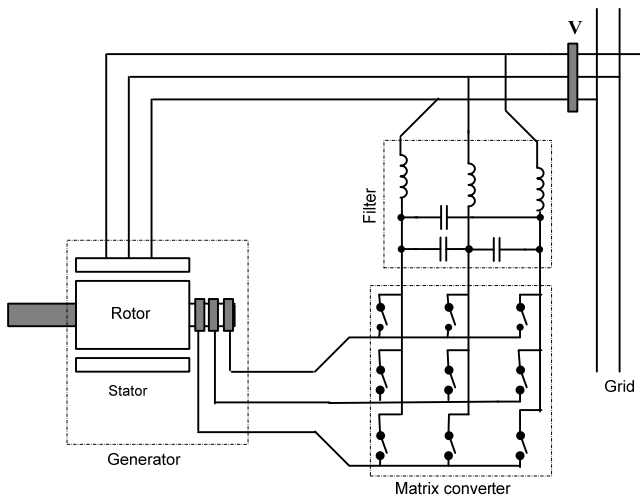

Fig. 15 Layout of DFIG based wind turbine generator system with matrix converter.

2.4 Z-source converter

The impedance source or impedance fed power converter is abbreviated as Z-source converter. It can be used for the implementation of DC to DC, AC to DC, AC to AC and DC to AC power conversions. In 2003, effort was put to model analysis of a general Z-source converter [18], which overcomes the barriers and limitations of the traditional voltage source and current source converters and provides a novel power conversion concept. In this converter, a two-port network that consists of split inductors L_1 and L_2 and capacitors C_1 and C_2 connected in X shape is employed to provide an impedance source coupling the converter to the DC source, load, or another converter. The DC source or load can be either a voltage or a current source or load. Therefore, the DC source can be a battery, diode rectifier, thyristor converter, generator, an inductor, a capacitor, or a combination of those. In the past few years, a few research articles have dealt with the steady state and transient analysis of Z-source converter [19–21] and some topologies have been proposed to improve the performance [22, 23]. Due to its low cost and high efficiency it is well suited for the wind power generation system. Recently, research works have addressed the application of Z-source converter in wind turbine generator system [24–26]. But its uni-directional nature makes it unpopular in DFIG system. The proposed modifications in [27, 28] have dealt with the topologies of bi-directional Z-source converter. The Z-source converter based wind turbine generator system is depicted in Fig. 16.

Advantages:
- The output voltage can be any value between zero and infinity (buck and boost) regardless of the input voltage.
- It uses fewer components than conventional converters.
- Due to its shoot-through states handling ability its application is more reliable.
- Lower cost and size compared to conventional converter (inductors and capacitors can be optimally designed).
- More efficient than others.
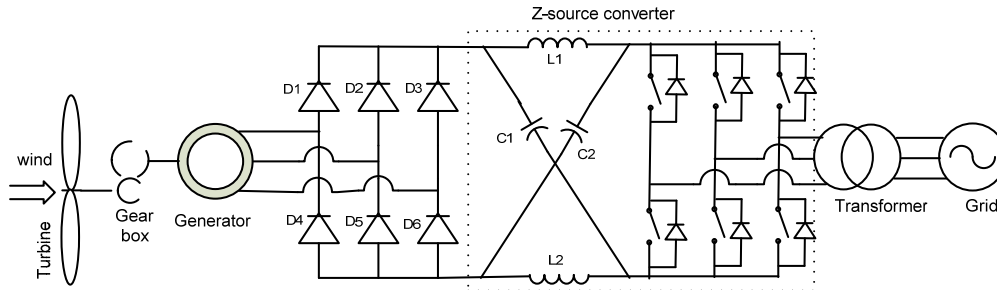
Fig. 16 Z-source converter based wind power generation system.

Disadvantages:
- To perform the voltage boost function for the Z-source stage, the Z-capacitor voltage is larger than the input voltage. Thus, high-voltage Z-capacitors should be used, which may increase the volume and cost.
- The Z-source converter cannot suppress the rush current and resonance between the Z-capacitors and Z-inductors at start-up. This causes voltage and current surges and may destroy the device [29].
- It is inherently uni-directional converter.

2.5 Improved Z-source converter

In 2011, Yu Tang proposed an improved Z-source converter [29], which has not only all the features but also overcomes the drawbacks of the Z-source converter. Exactly the same elements are used as in Z-source converter but the positions of the converter bridge and diode are exchanged and their connection direction is reversed. Because of the voltage polarity of the Z-capacitors keeps the same as the input voltage polarity, the Z-capacitor voltage stress can be greatly reduced and get the same boost voltage across the converter bridge. In this system there is no current path at start-up, so it has inherent inrush current limitation ability. The layout of wind turbine generator system with improved Z-source converter is depicted in Fig. 17.
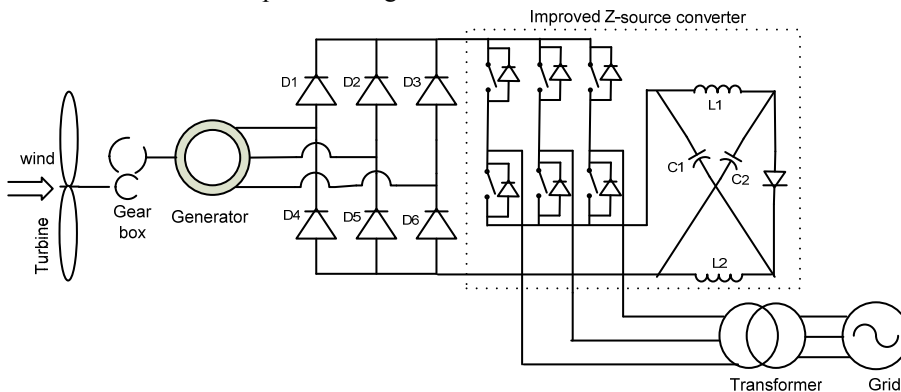

Fig. 17 Improved Z-source converter based wind turbine generator system.
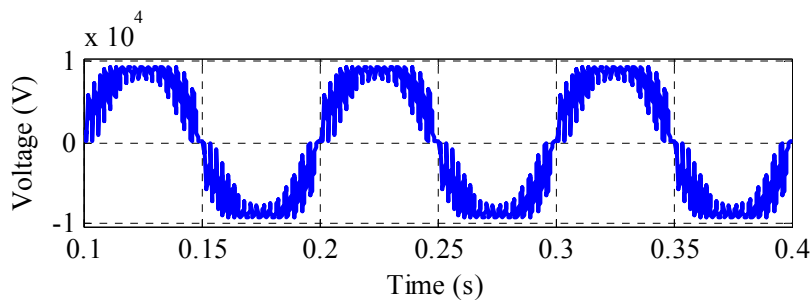
2.6 Cycloconverter

Like MC, the cycloconverter also converts AC to AC directly without using intermediate DC-link. It is also called frequency converter. The high voltage AC (HVAC) and high voltage DC (HVDC) transmission systems are mainly used for power transmission. The HVAC transmission (operated at 50 Hz or 60 Hz) is suitable when transmission distance is less than about 70 km. In this instance, the HVDC should be the best choice for long distance power transmission. But the expensive converter stations on both ends of the transmission system increase the investment cost dramatically. To reduce the electrical length of the AC transmission line and increase its transmission capacity, in 1994 lower frequency (50/3 Hz) transmission system was proposed, where cycloconverter converts the system frequency (stepping up) [30]. In the last few years several articles have been reported on the application of cycloconverter for offshore wind farms. It is well investigated that the investment cost of low frequency transmission system for offshore wind farm is less costly than the HVDC system and the maintenance costs are largely reduced as well. The design, simulation and performance evaluations of cycloconverter based low frequency transmission system for offshore wind farms have been presented in [31, 32]. Figure 18 shows the layout of offshore wind power transmission system with cycloconverter. When the generators are operated at lower frequencies the system requires only stepping-up

cycloconverter at the end of the transmission line. If the generators are operated at 50 Hz or 60 Hz, both ends require frequency converters. The output voltage and input current waveforms of a six pulse cycloconverter are shown in Figs. 19 and 20, respectively. The harmonic spectrum of the output voltage is illustrated in Fig. 21.
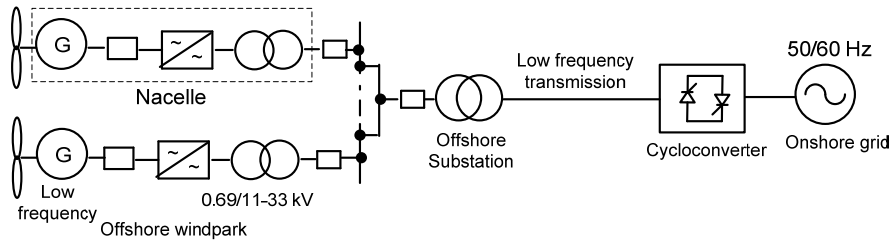
Fig. 18 Layout of cycloconverter based offshore wind power transmission system.

Fig. 19 Phase voltage of six pulses cycloconverter.
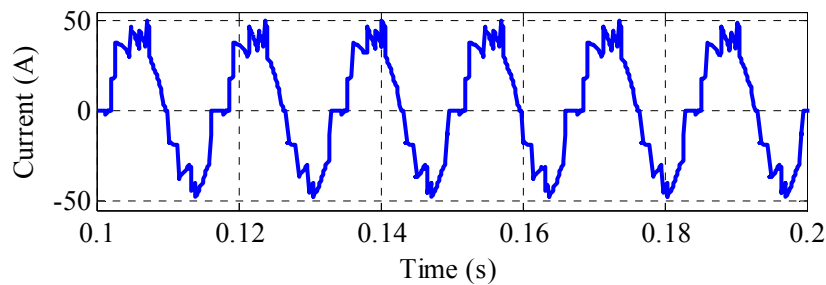
Fig. 20 Input current of six pulses cycloconverter.
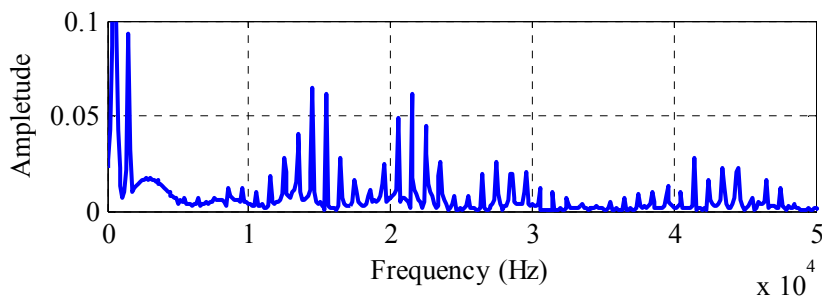
Fig. 21 Frequency spectrum of the output voltage of cycloconverter.

Advantages:
- Lower commutation and conduction losses
- Inherently bidirectional power flow capability and
- Power circuit design is compact

Disadvantages:
- There is an upper limit of output frequency
- Poor input power factor

- Lower voltage transfer ratio and
- Requires complex control circuitry

2.7 Multilevel converters

The multilevel converter is a power electronic circuit that can be operated in an inverter or rectifier mode. In 1975, the concept of multilevel converter topology was proposed and in the last few decades, several multilevel converter topologies have been patented. In order to achieve high voltage using low voltage switching devices, the multilevel converter topology uses a series of switching devices with low voltage DC sources. The renewable energy sources: wind turbine generators, solar PV arrays, and fuel cells can be used as the multiple dc voltage sources. The proper control of the switching devices superimposed these multiple DC sources in a staircase form in order to achieve high voltage at the output. Currently, there is an increasing interest in multilevel power converters, specially for medium voltage applications. In a wind turbine generator system the multilevel converter can provide a mechanism to feed this source into an existing three-phase power grid directly. Neutral point clamped (NPC), flying capacitor (FC) and series connected H-bridge (SCHB) converter topologies are the three types of multilevel converters commonly practised in high power and medium/high voltage applications. A comparative study among these three multilevel converter topologies has been reported in [33]. In addition to the (N-1) DC link capacitors, the N-level FC multilevel converter requires $(N^2-3N+2)/2$ auxiliary capacitors per phase, which increases the volume, weight, complexity, and cost of the converter and reduces the performance and lifetime [34]. Due to large numbers of capacitors, the FC topology is not suitable for wind power application. The NPC converter uses capacitors in series to divide the DC bus voltage into a set of voltage levels. To produce N levels of the phase voltage, an N-level NPC converter needs N-1 capacitors on the DC bus. The NPC converter topology has the opportunity to connect the neutral point to middle point of the DC-link, reducing the ground leakage currents, which enables this topology to form back to back connection. In 2006, a back to back NPC three-level converter based wind power system was proposed [35]. The back to back NPC three-level converter based wind power generation system is illustrated in Fig. 22. In 2013, improved control scheme has been proposed to improve the steady-state and transient operation of back to back NPC converter [36]. However, the number of clamping diodes required is quadratically related to the number of levels. When N is sufficiently high, the number of diodes required will make the system impractical to implement; the number of diodes required for each phase will be (2N-4). Therefore, this topology is not suitable for high voltage applications, where higher number of levels is required.
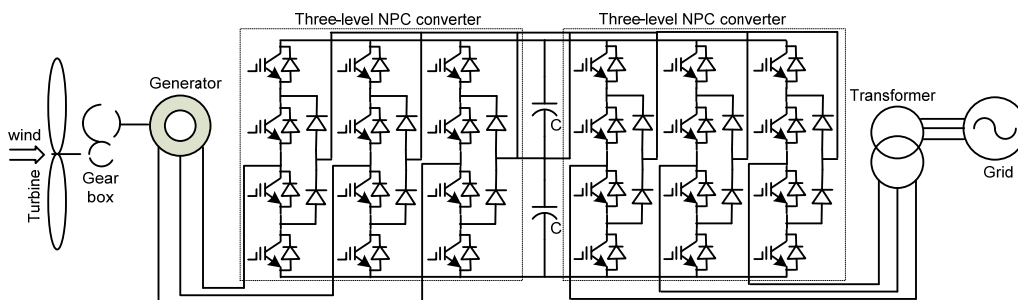
Fig. 22 Neutral point clamped multilevel converter based wind turbine generator system.

In SCHB converter topology, the individual modules are identical and completely modular in construction. The component numbers of the SCHB converters scale linearly with the number of levels, enabling high-level number attainability. High-level converter implies elimination of power transformer and lower THD with lower switching frequency, eliminating the output filters and reducing running cost. High-level number attainability also allows lower level of DC-link voltage requirement for each H-bridge cell that eliminates boosters. Moreover, in the case of a fault in one of these modules, it is possible to replace it quickly and easily. The 6.5 kV rated IGBTs can be used to design 11 kV converter with seven-level topologies. Due to these special features SCHB topology has attracted great attention, especially for designing medium voltage converter for renewable power systems [37]. However, the SCHB converter requires multiple isolated and balanced DC sources, which makes the application not straightforward [1]. In 2008, a new type of modular permanent magnet wind generator with a large number of isolated coils was proposed to generate independent sources for SCHB medium voltage converter [38]. This multi-windings generator requires a special winding arrangement as well as complicated control strategies. Moreover, this approach does not work with the existing wind generators. In 2012, medium voltage converter based compact and lightweight wind turbine system was proposed [39, 40] as depicted in Fig. 23, where a medium frequency-link generates the DC supplies. In 2013, a medium frequency transformer-link is designed and reported [1] to generate the isolated balanced multiple DC supplies for the SCHB converter from a single low-voltage commercially available classical generator. The output voltage and frequency spectrum of 11 kV seven-level converter system are shown in Figs. 24 and 25, respectively.
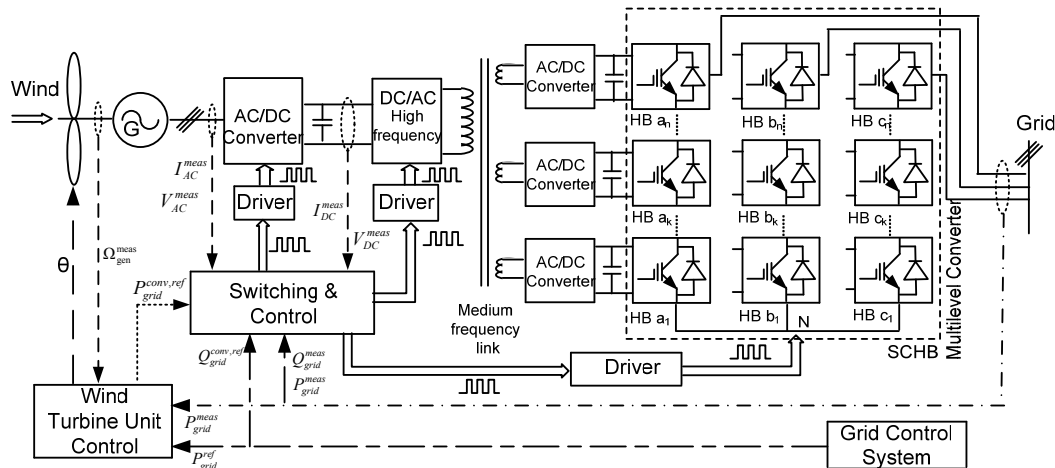
Fig. 23 SCHB converter and medium frequency transformer-link based wind turbine generator system.

Advantages:
- The main advantage of multilevel converter is the higher voltage handling capability with lower rated devices.
- It has lower switching losses and higher overall efficiency than others
- Allows a reduction in the size of the filtering elements, which affects the dynamic response of the converter.

Disadvantages:
- Requires a numbers of semiconductor devices, which increases the complexity of the control circuit
- The voltage imbalance between the upper and the lower DC-link capacitor.
- Unequal current stress on the semiconductors.

Conclusion

By summarising the above discussion it is concluded that the matrix converter is suitable for AC to AC power conversion, which is an attractive solution for adjustable speed wind turbine generator, specially DFIG based variable speed wind turbine generator systems. The SCHB converter topology may be the only possible option to design medium voltage converters economically, which enables transformer-less direct grid connection of wind turbine generator systems. The advanced magnetic materials such as Metglas amorphous alloy and nanocrystalline alloy based medium or high frequency-link might be the natural solution to generate isolated and balanced multiple DC supplies for SCHB converter from a traditional wind generator.
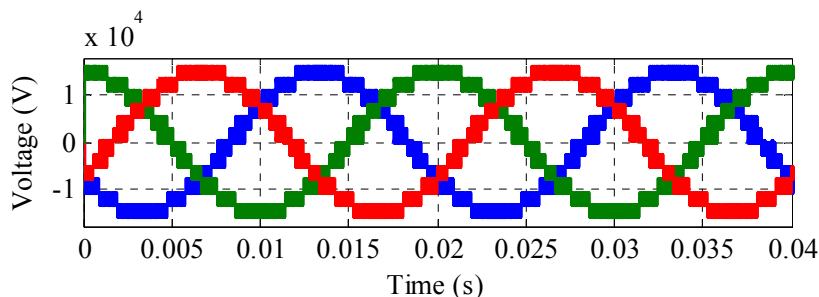
Fig. 24 Output voltage of seven-level SCHB 11 kV converter; with no filter circuit.
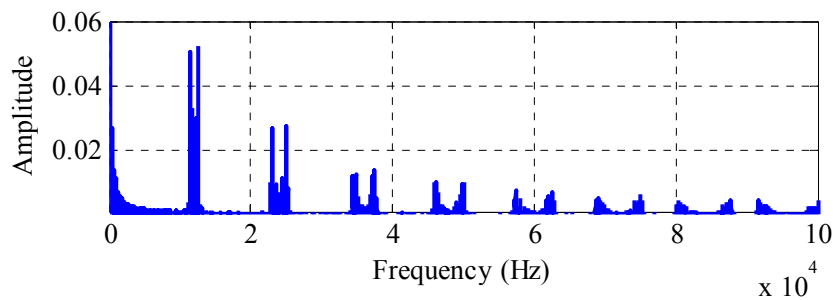
Fig. 25 Frequency spectrum of seven-level 11 kV converter; with no filter circuit.

References

[1] Islam M R, Guo Y G, Zhu J G. A medium frequency transformer with multiple secondary windings for medium voltage converter based wind turbine power generating systems. *Journal of Applied Physics*. 2013; 113:17A324–17A324-3

[2] El-hawary M E. *Principles of Electric Machines with Power Electronic Applications*. IEEE Press: A John Wiley & Sons Inc; 2002

[3] Takahashi I, Noguchi T. A new quick-response and high-efficiency control strategy of an induction motor. *IEEE Transactions on Industry Applications*. 1986; IA-22:820–827

[4] Malesani L, Tenti P. A novel hysteresis control method for current-controlled voltage-source PWM inverters with constant modulation frequency. *IEEE Transactions on Industry Applications*. 1990; 26:88–92

[5] Noguchi T, Tomiki H, Kondo S, Takahashi I. Direct power control of PWM converter without power-source voltage sensors. *IEEE Transactions on Industry Applications*. 1998; 34:473–479

[6] Li S, Haskew T A, Swatloski R P, Gathings W. Optimal and direct-current vector control of direct drive PMSG wind turbine. *IEEE Transactions on Power Electronics*. 2012; 27:2325–2337

[7] Shahbazi M, Poure P, Saadate S, Zolghadri M R. FPGA-based reconfigurable control for fault-tolerant back to back converter without redundancy. *IEEE Transactions on Industrial Electronics*. 2013; 60:3360–3371

[8] Pena R, Clare J C, Asher G M. Doubly fed induction generator using back to back PWM converters and its application to variable-speed wind-energy generation. *IEE Proceedings of Electric Power Applications*. 1996; 143:231–241

[9] Gaona D C, Goytia E L M, Lara O A. Fault ride-through improvement of DFIG-WT by integrating a two-degrees of freedom internal model control. *IEEE Transactions on Industrial Electronics*. 2013; 60:1133–1145

[10] Djahbar A, Mazari B, Latroch M. Control strategy of three-phase matrix converter fed induction motor drive system. *IEEE International Workshop on Intelligent Signal Processing*; 2005. p. 104–109

[11] Change J. Modular AC-AC variable voltage and variable frequency power converter system and control. US Patent 5 909 367; 1999

[12] Podlesak T F, Katsis D C, Wheeler P W, Clare J C, Empringham L, Bland M. A 150-kVA vector-controlled matrix converter induction motor drive. *IEEE Transactions on Industry Applications*. 2005; 41:841–847

[13] Swamy M, Kume T. Present state and a futuristic vision of motor drive technology. *11th international conference on OPTIM*; 2008. p. XLV–LVI

[14] Cardenas R, Pena R, Wheeler P, Clare J, Asher G. Control of the reactive power supplied by a WECS based on an induction generator fed by a matrix converter. *IEEE Transactions on Industrial Electronics*. 2009; 56:429–438

[15] Kumar V, Joshi R R, and Bansal R C. Optimal control of matrix-converter-based WECS for performance enhancement and efficiency optimization. *IEEE Transactions on Energy Conversion*. 2009; 24264–273

[16] Cardenas R, Pena R, Tobar G, Clare J, Wheeler P, Asher G. Stability analysis of a wind energy conversion system based on a doubly fed induction generator fed by a matrix converter. *IEEE Trans. on Ind. Elec*. 2009; 56:4194–4206

[17] Hansen L H, Helle L, Blaabjerg F, Ritchie E, Munk-Nielsen S, H Bindner, Sørensen P, Bak-Jensen B. *Conceptual survey of generators and power electronics for wind turbines*. Risø National Laboratory, Roskilde, Denmark; 2001.

[18] Peng F Z. Z-source inverter. *IEEE Transactions on Industry Applications*. 2003; 39:504–510.

[19] Loh P C, Vilathgamuwa D M, Gajanayake C J, Lim Y R, Teo C W. Transient modeling and analysis of pulse-width modulated Z-source inverter. *Industry Applications Conference;* 2005. p. 2782–2789.

[20] Loh P C, Gao F, Blaabjerg F. Topological and modulation design of three-level Z-source inverters. *IEEE Transactions on Power Electronics*. 2008; 23:2268–2277.

[21] Zimmermann M V, Piepenbreier B. Steady-state analysis of an AC-AC Z-Source inverter including discontinuous power flow. *2010 International Symposium on Power Electronics Electrical Drives Automation and Motion*; 2010. p. 815–820.

[22] Tang Y, Xie S, Zhang C, Xu Z. Improved Z-Source inverter with reduced Z-source capacitor voltage stress and soft-start capability. *IEEE Transactions on Power Electronics*. 2009; 24:409–415.

[23] Z. Gao; K Shen, Wang J, Chen Q. An improved control method for inductive load of Z-source inverter. *Power and Energy Engineering Conference (APPEEC), 2010 Asia-Pacific*; 2010. p. 1-4.

[24] Vilathgamuwa D M, Wang X, Gajanayake C J. Z-source converter based grid-interface for variable-speed permanent magnet wind turbine generators. *Power Electronics Specialists Conference, 2008. PESC 2008. IEEE*; 2008. p. 4545–4550.

[25] Jie L, Keqing Q, Xiaoliang S, Chen G C. Study on control methods of direct-drive wind generation system based on three-phase Z-source inverter. *Power Electronics and Motion Control Conference, IEEE 6th International*; 2009. p. 644–649.

[26] Supatti U, Peng F Z. Z-source inverter with grid connected for wind power system. *Energy Conversion Congress and Exposition, IEEE*; 2009. p. 398–403.

[27] Rabkowski J. The bidirectional Z-source inverter for energy storage application. *European Conference on Power Electronics and Applications*; 2007. p. 1–10.

[28] Yamanaka M, Koizumi H. A bi-directional Z-source inverter for electric vehicles. *International Conference on Power Electronics and Drive Systems*; 2009. p. 574–578.

[29] Tang Y, Xie S, Zhang C. An improved Z-source inverter. *IEEE Transactions on Power Electronics*. 2011; 26:3865–3868.

[30] Wang X, Wang X. Feasibility study of fractional frequency transmission system. *IEEE Transactions on Power Systems*. 1996; 11:962–967.

[31] Wang X, Cao C, Zhou Z. Experiment on fractional frequency transmission system. *IEEE Transactions on Power Systems*. 2006; 21:372–377.

[32] Mau C N, Rudion K, Orths A, Eriksen P E, Abildgaard H, Styczynski Z A. Grid connection of offshore wind farm based DFIG with low frequency AC transmission system. *2012 IEEE Power and Energy Society General Meeting*; 2012. p. 1–7.

[33] Islam M R, Guo Y G, Zhu J G, Dorrell D. Design and comparison of 11 kV multilevel voltage source converters for local grid based renewable energy systems. *37th Annual Conf. of the IEEE Ind. Elec. Society;* 2011. p. 3596–3601. DOI: 10.1109/IECON.2011.6119893

[34] Islam M R, Guo Y G, Zhu J G. Performance and cost comparison of NPC, FC and SCHB multilevel converter topologies for high-voltage applications. *14th Int. Conf. on Elec. Mach. and Sys.*; 2011. p. 1–6. DOI: 10.1109/ICEMS.2011.6073827

[35] Portillo R C, Prats M M, Leon J I, Sanchez J A, Carrasco J M, Galvan E, Franquelo L G. Modeling strategy for back to back three-level converters applied to high power wind turbines. *IEEE Trans. on Ind. Elec.* 2006; 53:1483–1491

[36] Alepuz S, Calle A, Monge S B, Kouro S, Wu B. Use of stored energy in PMSG rotor inertia for low voltage ride through in back to back NPC converter based wind power systems. *IEEE Transactions on Industrial Electronics*. 2013; 60:1787–1796

[37] Islam M R, Guo Y G, Zhu J G. H-bridge multilevel voltage source converter for direct grid connection of renewable energy systems. *IEEE PES Innovative Smart Grid Technologies Asia (ISGT)*; 2011. p. 1-7. DOI: 10.1109/ISGT-Asia.2011.6167142

[38] Ng C H, Parker M A, Ran L, Tavner P J, Bumby J R, Spooner E. A multilevel modular converter for a large, light weight wind turbine generator. *IEEE Transactions on Power Electronics*. 2008; 23:1062–1074

[39] Islam M R, Guo Y G, Zhu J G. A transformer-less compact and light wind turbine generating system for offshore wind farms. *IEEE International Conference on Power and Energy*; 2012. P. 605–610. DOI: 10.1109/PECon.2012.6450285

[40] Islam M R, Guo Y G, Zhu J G. 11-kV series-connected H-bridge multilevel converter for direct grid connection of renewable energy systems. *Journal of Int. Conf. on Elect. Mach. and Systems*. 2012; 1:211–219