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A Unidirectional Cascaded High-Power Wind Converter with Reduced Number of Active Devices

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Abstract –

Wind turbine systems (WTSs) have become one of the significant contributors to renewable energy and pledge the formidable reduction of global dependence on fossil fuel. With the development of the economy, the demand for energy has been substantially growing. Wind power, particularly from offshore wind farms, is one of the best solutions. Voltage to a medium voltage level such as 10kV, which is favored for reducing the generator current, mitigating issues such as cable twisting in low-voltage, high-current configurations. In order to reduce the number of required active power devices, this project presents a unidirectional-power-flow medium voltage high-power cascaded wind power converter. The proposed topology uses a unidirectional cascaded H-bridge rectifier as the generator-side converter to connect the medium-voltage permanent synchronous wind generator. The proposed topology reduces the number of active power devices and their associated gate driver circuits, control, etc. A zero dead time modulation method is also presented for the generator side converter, which can eliminate the dead time and improve the voltage and current waveform quality. Furthermore, the proposed topology will not increase the converter power losses as analyzed in the project, or sacrifice dynamic control performance. MATLAB/Simulation results are presented, which validate the proposed unidirectional power conversion system.

Keywords – Cascaded H-bridge, unidirectional power flow, Wind power converter, zero dead time modulation.

I. INTRODUCTION

Offshore wind power refers to the arrangement of wind farms in bodies of water to produce electricity from wind. Better wind speeds are available offshore compare to on land, so offshore wind power's contribution in terms of electricity absolute is greater. Conversely, offshore wind farms are reasonably expensive. Offshore wind power capacity is conventional to reach a total of 75 GW worldwide by 2020, with significant contributions from China and the United States. Offshore wind power plants are accepted to represent a significant constituent of the future electric generation portfolio due to superior space convenience and better wind energy potential in offshore locations. The integration of offshore wind power plants with the main power grid is a subject of incomplete research. In order to increase the amount of captured wind power per turbine and reduce the average cost of wind power generation, the power level of a single wind turbine also increases rapidly. In addition, it is generally the case that the maintenance cost of fewer larger wind turbines is lower than those with smaller wind turbines. Hence, larger wind turbines are preferred. At present, the power rating of a single offshore wind turbine has reached 14MW, and is being developed towards even higher power levels. For large wind turbines in the range between 10-20MWs, the low voltage (e.g., 690V) systems suffer from many engineering issues, such as excessive current, large number of paralleled units, lower efficiency, and difficulty in twisting bulky cables. Although the cascaded H-bridge wind power converter shows many advantages as mentioned above, a large number of power devices are required. In several unidirectional power- flow rectifiers are evaluated and compared, proving the unidirectional-power-flow cascaded H-bridge rectifier has lower cost and higher reliability. In the modeling and control of unidirectional power-flow cascaded H-bridge rectifier was presented. Conventional unidirectional power flowing converter has to work at unity power factor condition. Otherwise, the converter current will be distorted at the zero crossing points. In contrast, the unidirectional-power-flow cascaded H-bridge rectifier has the ability to work when the power factor is lower than 1. Based on the topology, this project presents a unidirectional-power-flow medium-voltage cascaded wind power system by replacing two active power devices with diodes at the upper bridge arm in each H-bridge rectifier. Reducing the number of power devices is beneficial for reducing the cost of power devices and improving the system reliability. The proposed topology can realize wind power generation in steady-state and dynamic conditions without increasing the system losses or sacrificing control performance. Moreover, with a proposed zero dead time modulation method, there is no need to set dead time for the generator-side converter, which is beneficial for reducing the low-frequency harmonics of the converter output voltages and currents.

II. OFFSHORE WIND FARM SYSTEM

Due to topographic factors, wind speeds at different altitudes on land vary greatly, which leads to large changes in wind speed in the vertical direction. As a result, imbalances in the forces acting on the top and bottom of the wind turbines cause the transmission system to be easily damaged.

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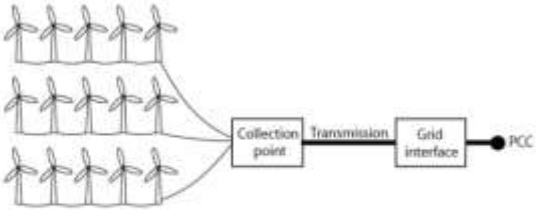

Fig. 1 A basic offshore transmission system.

Offshore wind power systems usually consist of offshore wind farms, power transmission cables, and distribution lines, as shown in figure 1. Many wind turbines are grouped and connected to a local AC or DC grid to form an offshore wind farm. This local grid is then connected to the power transmission cable via a converter or transformer, and eventually, the energy is transmitted to the onshore power distribution system. In a wind farm, there are generally two types of wind turbine connection, which are star and loop connections as shown in figure 1. The different layouts of offshore wind farm transmission systems are also shown below. (It is worth noting that the layouts of offshore shown in figures 2, 3 and 4 are star connection, and figure 5 is loop connection).

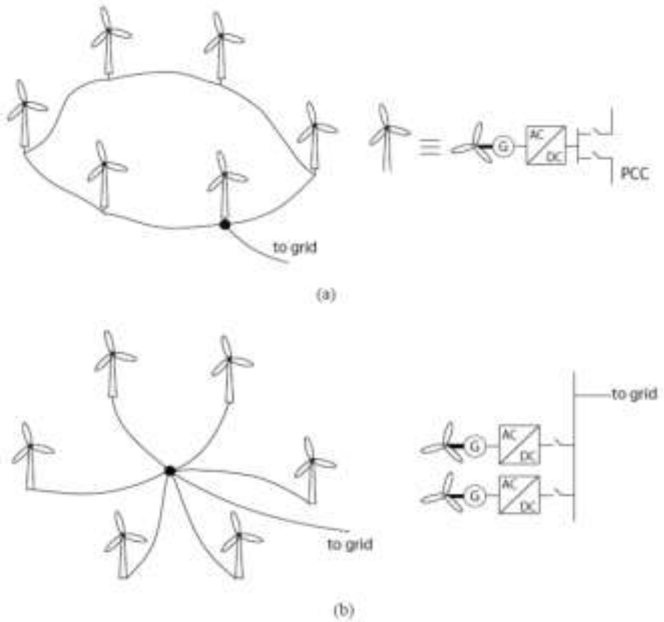

Fig.2 Wind turbine connection mode: (a) loop connection (b) star connection.

However, there is no such problem at sea, where the surface is very flat with almost no resistance, and the average wind speed is high with less variation compared to that on land. Moreover, changes in wind direction at sea are also smaller than on land, and so the wind energy at sea is more stable. It is well known that the power generated by a wind turbine is proportional to the cube of the wind speed, and the wind speed at sea is about 20% higher than that on land. Therefore, the annual generating capacity of an offshore wind turbine can be 70% higher than that on land. A larger power generation capacity means larger wind turbine blades, which leads to restrictions on their transport on land. However, this would be much easier at sea. Furthermore, onshore wind farms possess other restrictions such as the availability of land resources and other environmental and operational constraints. Moreover, most major developed cities in the world are situated on the coast, which means that offshore wind energy is the most attractive source of energy. Therefore, it can be concluded that offshore wind power will have broader prospects in future global energy supply systems.

1) AC collection for wind farms:

Figure 3 shows a typical schematic diagram of the AC collection of a wind farm, where the output voltage of each wind turbine is generally about 690V. However, for a wind power system with AC collection mode, the voltage level of the AC connection network for the wind turbines is between 20kV and 35kV, which requires the output terminal of each wind turbine to be connected to a medium voltage transformer in order to raise the voltage level and render it suitable for connection to the AC network. Then another high voltage transformer is employed on the offshore platform, as shown in figure 3, and this boosts the voltage to facilitate the employment of HVAC transmission lines.

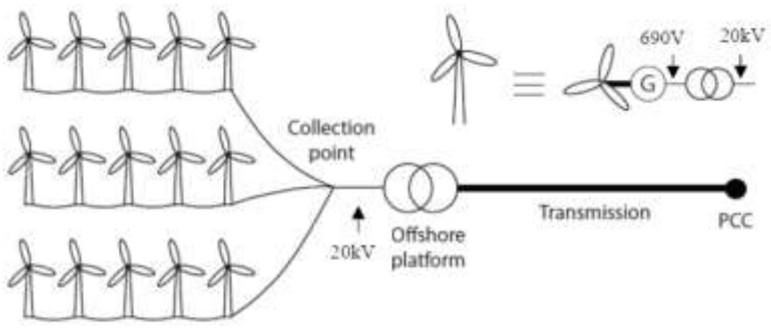

Fig.2.9 General offshore HVAC transmission system with AC collection network.

2) Mixed AC/DC collection for wind farm:

Similarly to the AC collection arrangement described above, power is here collected using an AC medium voltage network. Transformers are again employed to raise the voltage produced by the wind turbines, and then another high voltage transformer is employed between the AC collection point and the rectifier side of the HVDC transmission lines, as illustrated in figure 4.

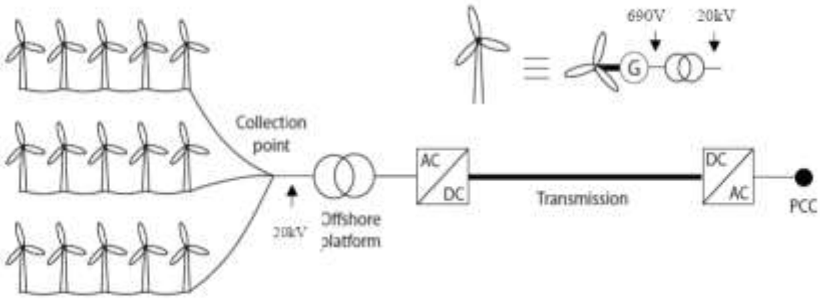

Fig.4 General offshore windfarm HVDC transmission system with mixed AC/DC collection network.

3) DC collection: parallel-connected wind turbines

Unlike the previous collection scenario, each wind turbine, in this case, is equipped with an AC/DC rectifier with an output voltage of about 690V. However, the typical voltage of the DC collection network for an offshore system is between 20kV to 40kV, and therefore a medium voltage DC/DC converter is required to raise the voltage. The output of the medium voltage DC/DC converters will then serve as input to the high voltage DC/DC converter that facilitates the connection with the HVDC transmission lines.

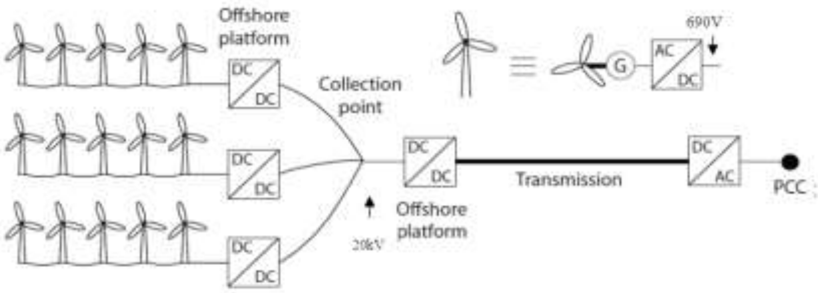

Figure 5 General offshore HVDC transmission system with a DC collection (parallel-connected wind turbines) network.

4) DC collection: series-connected wind turbines

In this case, all wind turbines in the same cluster are connected in series as shown in figure 6. This enables the achievement of high voltage without additional DC/DC boost converters. However, if one wind turbine is out of service, then the other wind turbines need to compensate for the voltage loss, which results in increased voltage stress and energy loss.

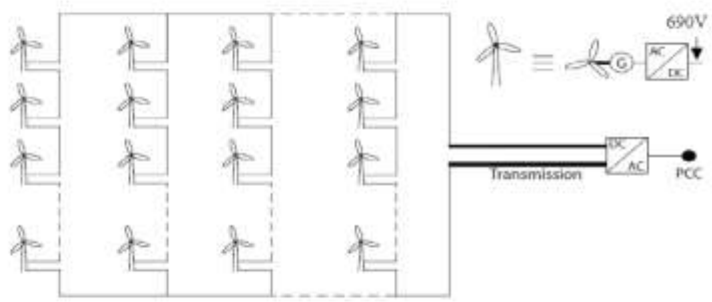

Fig.6 General offshore HVDC transmission system with DC collection (series-connected wind turbines) network.

III. PROPOSED SYSTEM

In order to further raise the voltage level, a cascaded H-bridge (CHB) wind power converter topology, as shown in Fig.7. This topology has a similar structure as the conventional CHB converter in motor drive systems, but with the opposite power flow direction. The wind generator is connected to the CHB rectifier where the generator voltage can be as high as 10kV, and each H-bridge unit is connected to the grid (33kV or 66kV) through a three-phase inverter and a multi-winding grid-frequency (50Hz/60Hz) transformer. The higher voltage level can be achieved by this topology using low-voltage power devices. The high voltage, hence the lower current can significantly reduce the copper losses (I2R), cable weight and mitigate the cable twisting problem. Moreover, it has a modular structure and fault-tolerant operation capability, which is suitable for 10-20MW large wind turbines.

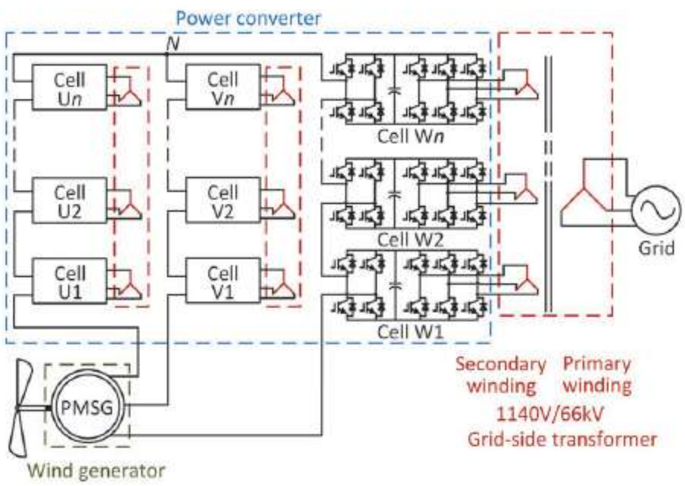

Fig.7. Wind power conversion system using the cascaded H-bridge converter.

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However, in this topology shown in Fig. 7, each CHB converter is in essence a single-phase converter, where there is large low-frequency (double of the fundamental frequency) power ripple in each cell, requiring large DC capacitors to attenuate the dc-link voltage ripple. In a control method was proposed to balance the power, including the ripple power, between the grid-side inverter and the H-bridge rectifier, thus reducing the required dc-link capacitors. Reference further proposes a new cascaded wind power converter based on a four-port isolated DC/DC converter as shown in Fig.8, to eliminate the low-frequency pulsating power. In this topology, the low-frequency power ripple from the single phases can be transferred to the magnetic core of the four-winding high-frequency transformers and then cancelled.

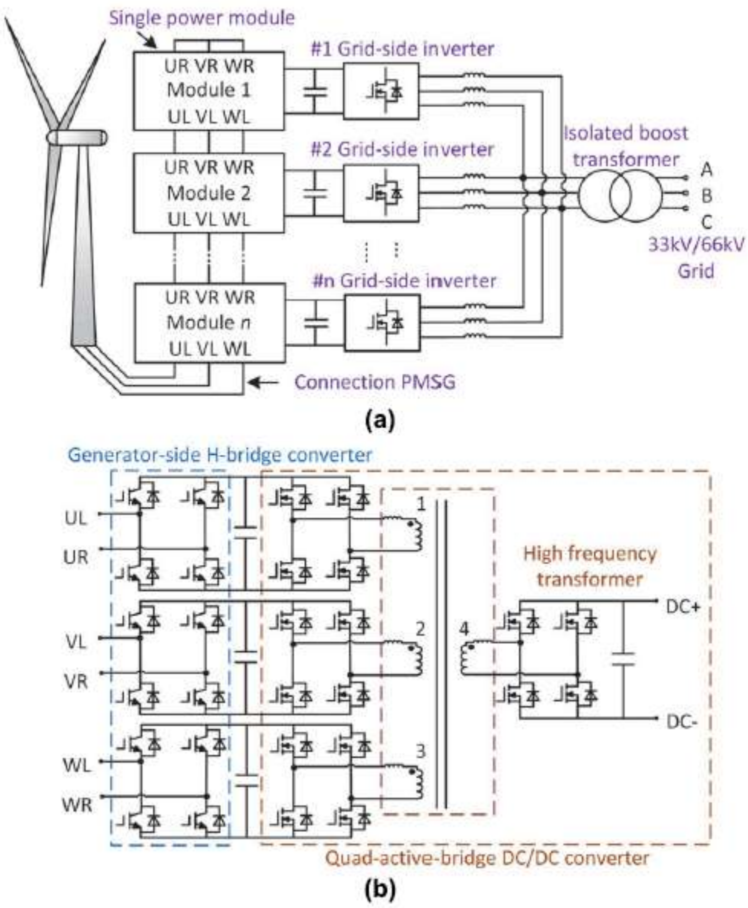

Fig.8. Power conversion system using the cascaded H-bridge converter with quad-active-bridge DC/DC converter in wind power systems: (a) The overall structure and (b) single power module.

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Although the cascaded H-bridge wind power converter shows many advantages as mentioned above, a large number of power devices are required. In several unidirectional power- flow rectifiers are evaluated and compared, proving the unidirectional-power-flow cascaded H-bridge rectifier has lower cost and higher reliability. In the modeling and control of unidirectional power-flow cascaded H-bridge rectifier was presented. Conventional unidirectional power flowing converter has to work at unity power factor condition. Otherwise, the converter current will be distorted at the zero crossing points. In contrast, the unidirectional-power-flow cascaded H-bridge rectifier has the ability to work when the power factor is lower than 1. Based on the topology in Fig. 8, this project presents a unidirectional-power-flow medium-voltage cascaded wind power system by replacing two active power devices with diodes at the upper bridge arm in each H-bridge rectifier as will be shown in Fig.9 and Fig.10. Reducing the number of power devices is beneficial for reducing the cost of power devices and improving the system reliability. The proposed topology can realize wind power generation in steady-state and dynamic conditions without increasing the system losses or sacrificing control performance. Moreover, with a proposed zero deadtime modulation method, there is no need to set deadtime for the generator-side converter, which is beneficial for reducing the low-frequency harmonics of the converter output voltages and currents.

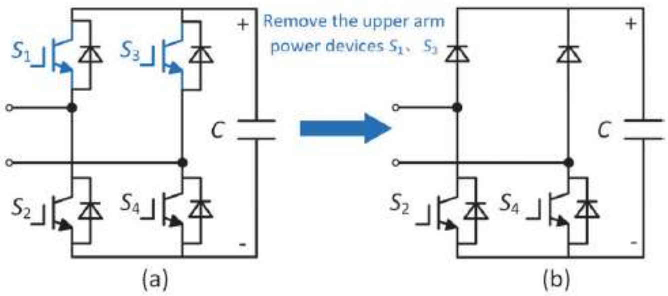

Fig.9. Derivation of unidirectional-power-flow H-bridge converter (rectifier): (a) H-bridge cell and (b) unidirectional H-bridge cell.

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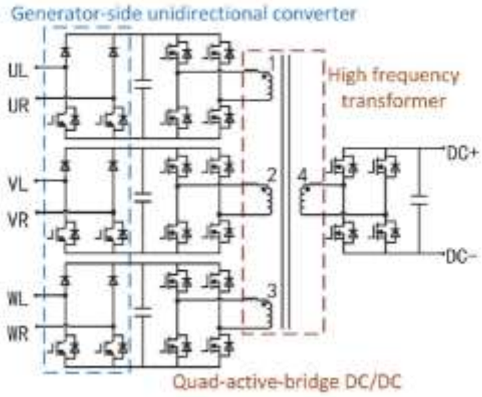


Fig.10. One power module of the proposed the wind power generation system with unidirectional-power-flowing.

For each H-bridge cell, after replacing the two power devices in the upper bridges with two diodes, unidirectional-power flow H-bridge cell can be derived as shown in Fig. 9. In this case, the power can only flow from the AC side to the DC side. Fig. 10 shows the topology of a single power module, where the input rectifiers have all been replaced with the unidirectional structure (two diodes) in comparison to the original structure shown in Fig.8(b). The overall configuration of the wind converter is the same as that shown in Fig. 8(a), where only the input rectifiers are changed. The proposed topology not only can reduce the number of required active power devices of the generator-side converter (rectifier) by half, but also can output the same high voltage as the original converter shown in Fig.8. Therefore, for a 10kV/15MW offshore wind power system, the number of required power devices can be significantly reduced given the large number of cells used. As seen, since the cascaded H-bridge converter can raise the generator voltage level to 10kV, the corresponding current is not very large (866A) for a 15MW wind turbine. At present, the current rating of a single 1700V IGBT device can reach 3600A and that of a single 1700V fast diode can reach 1800A. Therefore, the proposed generator-side CHB converter (rectifier) with unidirectional power flow for a10kV/15MW wind turbine system can be built with commercially available power devices. For example, with some margin, the active power devices can use the 1700V/1600A IGBT module FZ1600R17HP4_B21 from Infineon and the diodes can be 1700V/1800A fast diode module RM1800HE- 34S from Mitsubishi. Basically, diodes with a similar current rating as the IGBTs can be used. For the isolated DC-DC converters shown in Fig.8, if IGBT devices are used, the current level of a single commercial IGBT is sufficient to output the required power. However, if SiC MOSFETs are used to construct the above system, the current level of a single commercial SiC MOSFET may not be enough at present, given the required safety margin. Hence, two or three SiC MOSFETs can be connected in parallel to output the required power, e.g, using 1700V/650A SiC MOSFETs from Wolfspeed. One important advantage for the proposed converter is that deadtime is not required for the generator-side converter. This section presents a zero deadtime modulation method to control the generator-side converter. For the conventional cascaded H-bridge converter, a deadtime is required to avoid short circuit state between the upper and lower switches. However, the existence of deadtime will negatively affect the converter output voltage, introducing low-frequency harmonics. In general, the negative effect of deadtime varies with the modulation index *M*. With the decrease of the modulation index, the negative effect of the deadtime will be more obvious. For the wind power system, below the rated wind speed, the wind generator speed need to track the change of wind speed and thus output more power (maximum power point tracking, MPPT). Therefore, the modulation index of the generator-side converter can be low, where generator stator voltage and current can contain low-frequency harmonics, which increases the losses of generator, raise the temperature of windings and cause torque fluctuation issues.

Since the power devices of the upper bridge have been replaced by diodes in the proposed converter, the upper bridge and lower bridge will not be conducting at the same time (shoot through). Therefore, there is no need to set the deadtime. However, given the unidirectional-power-flow cascaded H-bridge cannot output negative voltage level, extra modulation techniques should be used to ensure the proper operation of the converter.

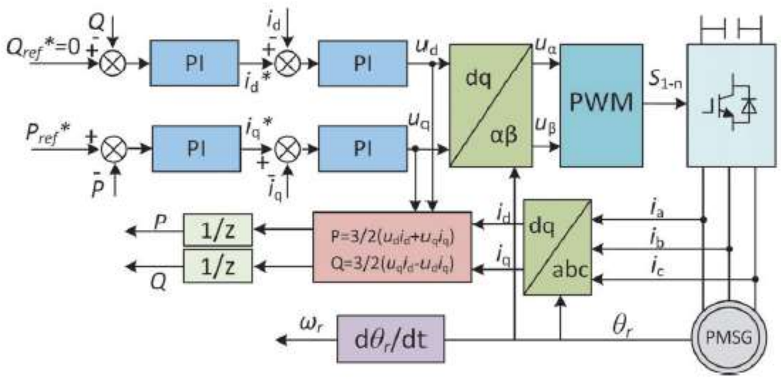


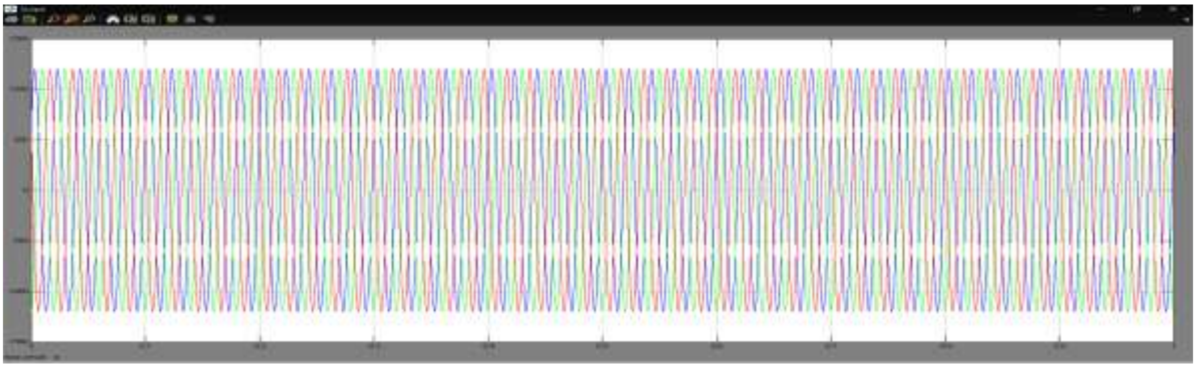
Fig.11. The unity power factor control diagram for PMSG.

Generally, there are two kinds of control methods that can be used to control the PSMG. The first kind of method is the unity power factor control (UPF) method, as shown in Fig. 11. The reactive power current reference is configured as zero to ensure generator output voltage and the current are controlled under unity power factor condition. This method can improve the generator power factor and reduce power losses of the generator-side converter. There is no doubt that the UPF control method can be directly adopted for controlling the proposed wind power converter with the unidirectional power flow structure.

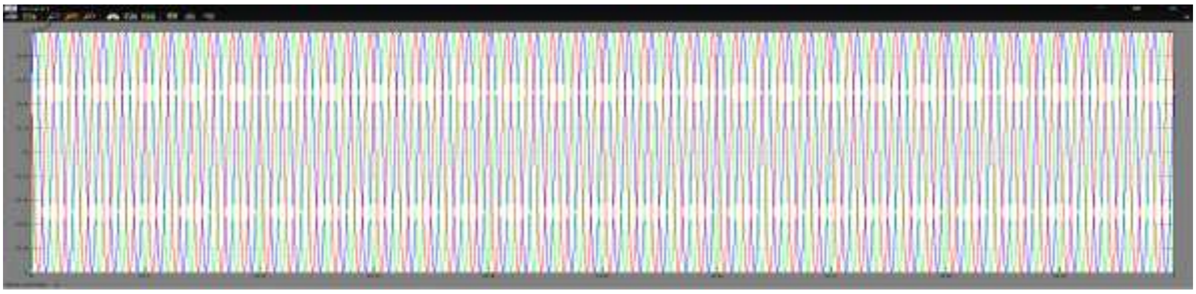
IV. SIMULATION RESULTS

In order to validate the feasibility of the proposed unidirectional-power-flow wind power system, a 10kV/15MW medium voltage high power wind power simulation system has been built in MATLAB/Simulink. The generator converter consists of 5 stages (15 cells) and the DC-link voltage of each cell is 1800 V.

CASE-1: RATED CONDITION



(a)



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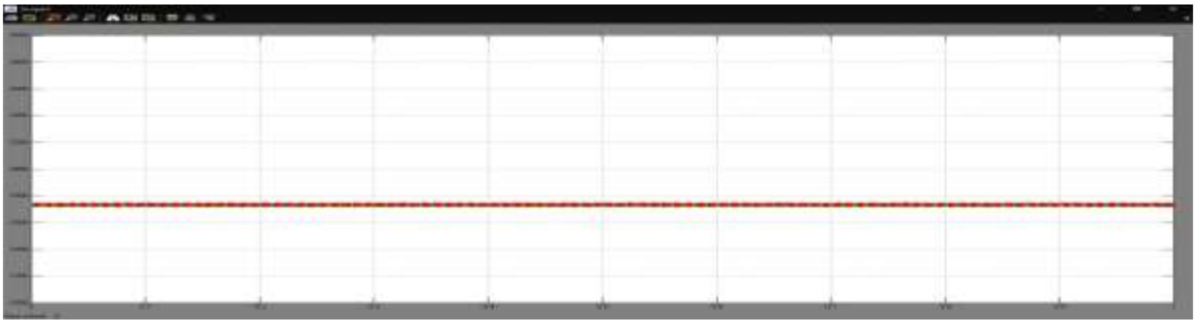

(c)

Fig:12. Unidirectional-power-flow wind power system generator side converter outputs at the rated condition: (a) PMSG output current; (b) PMSG output voltage and (c) the generator-side converter DC-bus voltage.

Fig. 12 shows the output current, output voltage and DC bus voltage of the generator-side converter at the rated condition (*M* = 0.9). As seen, the generator-side converter can operate well, where the three-phase currents can be regulated well and there is no current distortion at the zero crossing instants. In addition, the generator-side converter output phase voltages have 11 voltage levels. The DC-link voltages can be controlled well with very small voltage ripples, as shown in the zoomed waveforms in Fig. 12(c).

CASE-2: DYNAMIC STATE

(a) Torque

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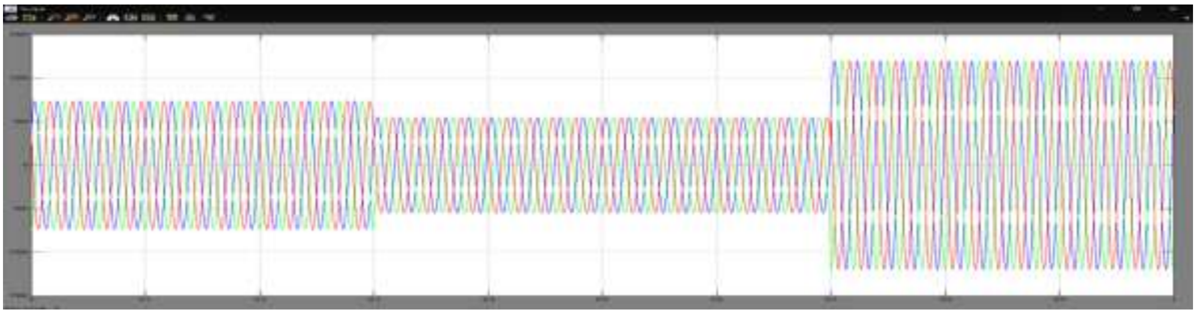
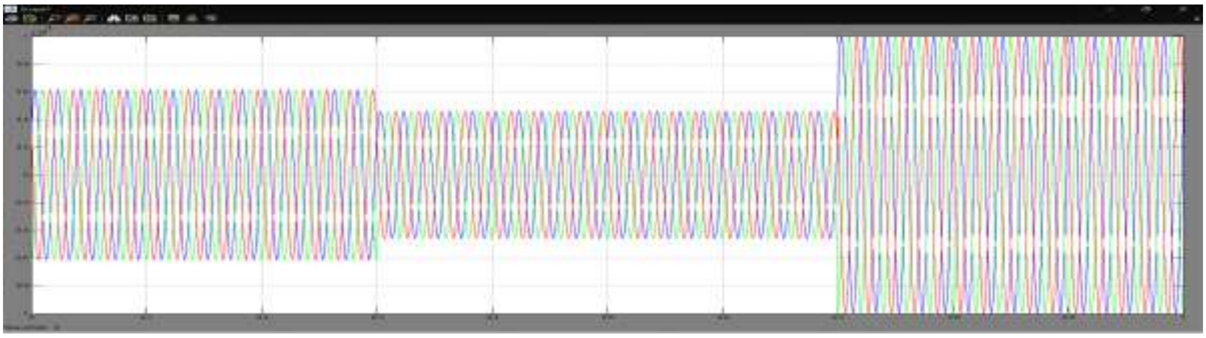


(b) Output current



(c) Output voltage

(d) Output power

Fig:13 Simulation results for the generator-side converter at the dynamic state. (Proposed system)

Fig. 13 shows the dynamic simulation results using the MTPA control method. At 0.3 s, the PMSG power is reduced from 5MW to 3MW. At 0.7s, the PMSG power is increased from 3MW to 15MW. As seen, the generator-side converter can quickly regulate the generator torques and currents.

Extension system:-

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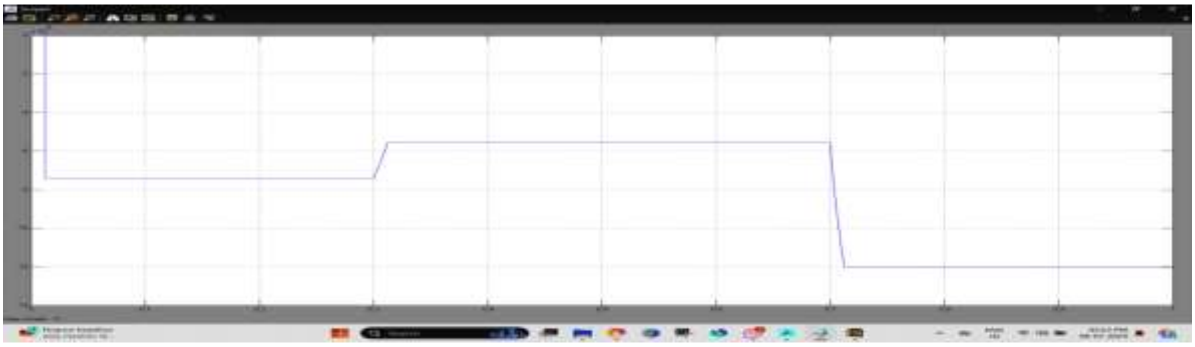
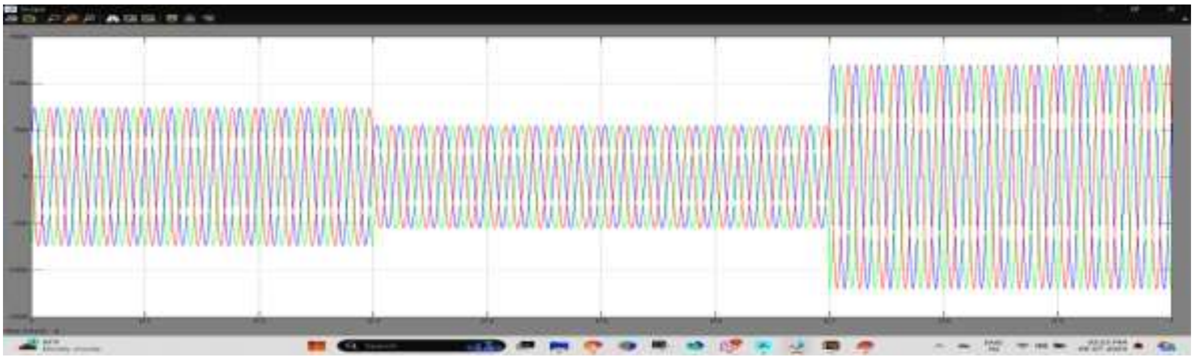
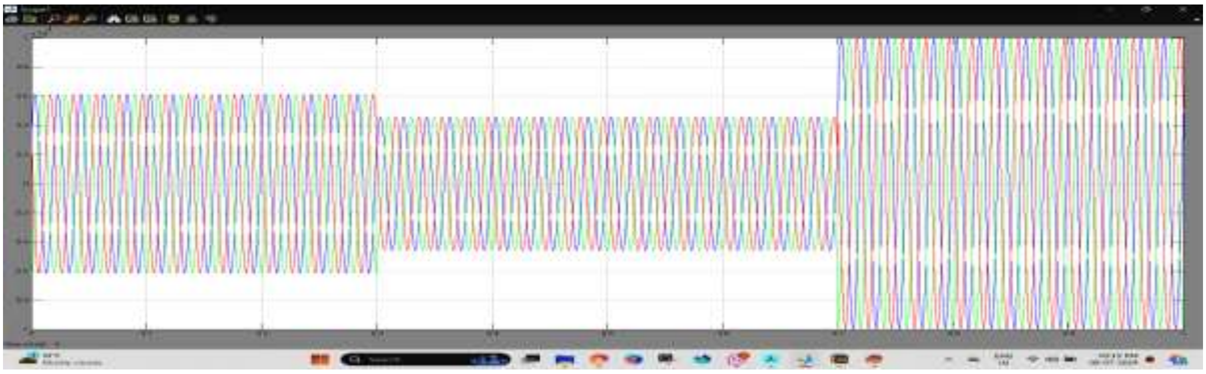


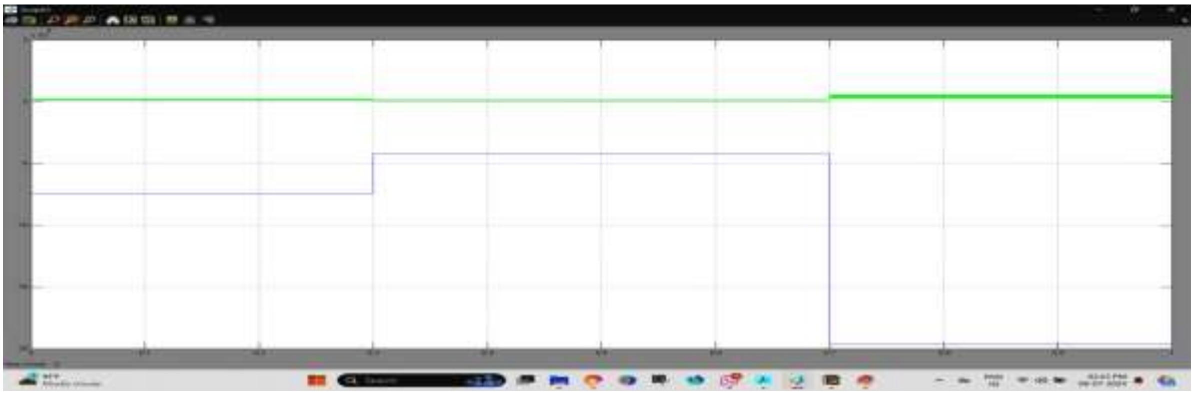
(a) Torque



(b) Output current



(c) Output voltage



(d) Output power

Fig:14 Simulation results for the generator-side converter at the dynamic state. (Extension system)

V. CONCLUSION

In this paper, a unidirectional-power-flow medium voltage high power cascaded wind power converter is proposed for high-power offshore wind turbines. The system uses a unidirectional-power-flow H-bridge converter as the generator-side converter, which can reduce the number of required power devices, and thus reduce the cost and improve system reliability. The proposed wind power system can work well at both the steady state and the dynamic state without increasing power losses or sacrificing control performance as evidenced by MATLAB simulation results. In addition, the low-frequency harmonics of the output voltage and current for the generator-side converter can be reduced by the presented zero deadtime modulation method. The proposed converter structure and control with minimal dc-link capacitor requirement and reduced number of active devices can be a viable solution for very large wind turbines.

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