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Power Devices Loading in Multilevel Converters for 10 MW Wind Turbines

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Abstract- Several promising multilevel converter solutions for 10 MW wind turbines using permanent magnet synchronous generators are proposed, designed and compared both with one-stage gear-box drive and direct drive systems. The current and loss distributions, as well as the utilization of power devices in each converter are analyzed based on simulation results. Finally, the total loss and efficiency comparison are given. It is concluded that five-level and three-level H-bridge topologies show higher efficiency either in the power conversion or in the device utilization compared to the three-level Neutral-Point-Clamped topology with both the direct-drive and one-stage gear box drive systems.

I. INTRODUCTION

The development of wind energy generation technologies has several significant trends in the past ten years [1], [2], [4]. The rapidly growing size and capacity of wind turbines are reducing the price pr. produced kWh continuously. The shortage of onshore land and booming need for renewable energy make newly established wind turbines moving from onshore to offshore wind farms. With stricter power grid integration requirements, the power electronics converters are playing more and more essential role in the whole generation system, and they are changing from partial rated power to full rated power of the wind turbines, requiring medium voltage rating to handle the acceptable current rating in the components. As the cutting-edge achievement, 5 MW offshore wind turbines with full rated power converter are already commercialized by some manufacturers, and 6 MW is about to be shown on the market as announced.

It is expected that 10 MW wind turbines will be the next longer-term target to be conquered according to the technology trends. However, there are still no final and dominant configurations on this power level, and questions still exist on such as: the type and rotating speed of the generator, the topology and voltage levels/ratings of the converter, the availability as well as cost pr. kWh of the whole system, etc.

The 10 MW wind turbines are supposed to be located at large and remote wind farms, where special considerations related to the power converters need to be seriously taken into account [3], such as grid codes compatibility [4], reliability, power density, voltage ratings, efficiency and number of components, etc.

In this paper, several promising full rated multilevel converters for 10 MW wind turbines are proposed and

basically designed using Permanent Magnet Synchronous Generator (PMSG). The evaluation will mainly focus on the power devices loading in each of the converter solution. Simulation results regarding current and loss distributions, total loss as well as efficiency performance are presented.

II. POSSIBLE CONFIGURATIONS

As the interface between wind turbines' generator and power grid, the wind power converter has to satisfy the requirements on the both sides, as summarized in Fig. 1.

For the generator side: The current flowing in the generator's stator should be controlled to adjust the rotating speed. This will contribute to the active power balance when grid faults and help to extract the maximum power from the wind turbines [2]. Moreover, the converter should have the ability to handle variable fundamental frequency and voltage amplitude of the generator's output.

For the grid side: The converter must comply with the grid codes regardless of the wind speed. That means it should have the ability to control the injected/absorbed reactive power Q , and perform a fast active power P response. The fundamental frequency as well as voltage amplitude on the grid side should be almost fixed under normal operation, and the total harmonic distortion of the current must be maintained at a low level [4].

Inherently, the converter needs to satisfy both the generator side and grid side requirements with a cost effective and easy maintenance solution. That requires a high power density, reliability, modularity of the whole converter system. Moreover, the wind power converter may need the ability to storage the active power, and boost up the voltage from generator side to the grid side.

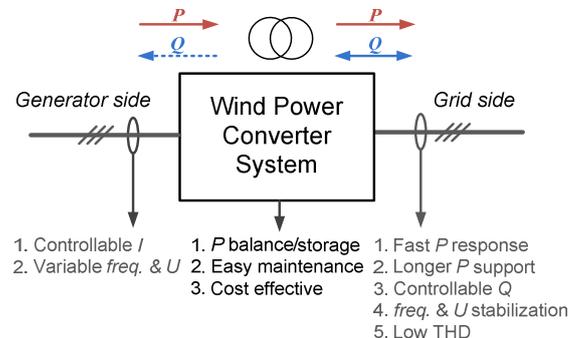


Fig. 1. Requirements for the modern wind power converter system. (I represents the current, U represents the voltage, $freq.$ is the fundamental frequency, P is the active power, Q is the reactive power, and THD is the total harmonic distortion of current).

According to the overall demands, four multilevel converter configurations for 10 MW wind turbines are proposed as follows [5]-[9], all of which can achieve the medium voltage rating.

A. Three-level Neutral Point diode Clamped back-to-back topology (3L-NPC BTB)

The three-level neutral point diode clamped converter is one of the most commercialized multilevel topologies on the market. It is usually configured with a back-to-back structure for wind turbines, as shown in Fig. 2, which is called 3L-NPC BTB for convenience.

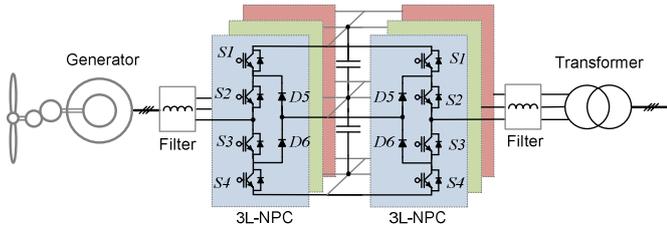


Fig. 2. Three-level Neutral Point Clamped back-to-back configuration for wind turbines. (3L-NPC BTB)

The mid-point potential fluctuation of the DC bus is a main drawback of the 3L-NPC BTB, but this problem has been extensively researched and considered solved [7]. However, it is found that the loss distribution between the outer and inner switching devices in a switching arm is unequal, and this problem may lead to a de-rated converter power capacity when it is practically designed [7], [8].

B. Three-level H-bridge back-to-back topology (3L HB-BTB)

This solution is composed of two H-bridge converters which are configured with back-to-back structure, as shown in Fig. 3. It can achieve the similar output performance of the 3L-NPC BTB, but the unequal loss distribution and clamped diodes are eliminated [3].

Because only half of the DC bus voltage is needed in 3L-HB BTB compared to the 3L-NPC BTB, there are less series connecting capacitors and no mid-point in the DC bus. The cost of DC link capacitors can thereby be reduced.

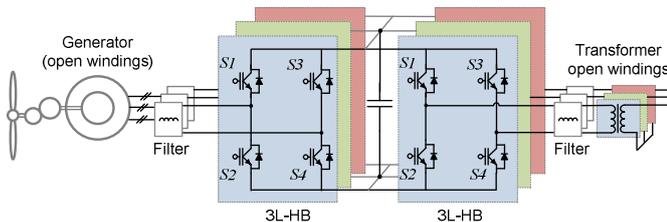


Fig. 3. Three-level H-bridge back-to-back converter for wind turbines. (3L-HB BTB)

However, 3L-HB BTB solution needs an open winding structure both in the generator and transformer in order to achieve isolation between each phase. This feature has both advantages and disadvantages: on one hand, open winding structure enables relative isolated operation of each phase, potential fault tolerant ability is thereby obtained if one or

even two phases of the generator or the generator side converter are broken. On the other hand, an open winding structure requires double cable length and weight to connect with generator and transformer. Extra cost, loss and inductance in the cables may be a major drawback. Because zero-sequence current path is introduced in this configuration, special components or control methods are needed to block the zero-sequence current [9].

C. Five-level H-bridge back-to-back topology (5L-HB BTB)

The 5L-HB BTB configuration is composed of two back-to-back H-bridge converters making use of 3L-NPC switching arms, as shown in Fig. 4. It is an extension of 3L-HB BTB, and shares the same special requirements for open-winding generator and transformer.

With switching devices of the same voltage rating, 5L-HB BTB can achieve five-level output voltage and double voltage amplitude compared to the 3L-HB BTB solution. These features enable less current rating in the switching devices as well as in the cables [9], [10].

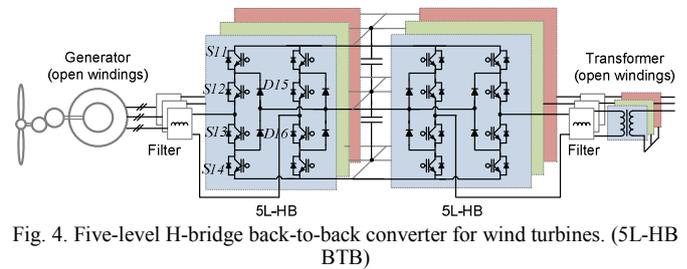


Fig. 4. Five-level H-bridge back-to-back converter for wind turbines. (5L-HB BTB)

However, compared to 3L-HB BTB, the 5L-HB BTB introduces more power devices, which will increase the cost and could reduce the reliability of the total system. Moreover, this configuration introduces the drawbacks of unequal loss distribution of power devices as well as mid-point potential in the DC link like the 3L-NPC BTB topology.

D. Three-level Neutral Point diode Clamped topology for generator side and Five-level H-bridge topology for grid side (3L-NPC + 5L-HB)

Generally, the output quality requirements of grid side are much stricter than those of the generator side. To adapt this “unsymmetrical” requirements for wind power converters, this “compound” configuration employs 3L-NPC topology on the generator side, and 5L-HB topology on the grid side to achieve an unsymmetrical performance, as shown in Fig. 5.

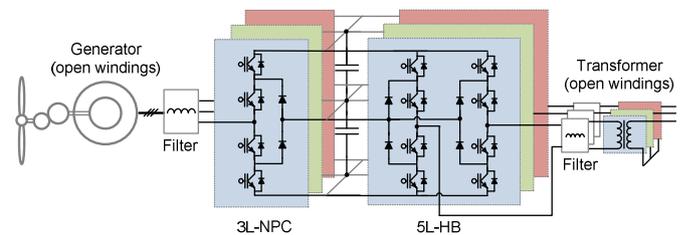


Fig. 5. Three-level Neutral Point Clamped and five-level H-bridge converter for wind turbines. (3L-NPC + 5L-HB)

On the generator side, this configuration has a similar performance of 3-NPC BTB, while on the grid side, it shares the same performance of 5L-HB BTB. The voltage levels and amplitude of the grid side is higher than those on the generator side. It is noted that, an open winding structure in the generator is avoided, cable length on the generator side is reduced to half, but the potential fault tolerant ability is also eliminated. This converter configuration has less switching devices compared to 5L-HB BTB.

III. BASIC DESIGN OF CONVERTERS

The basic design of each converter is based on 10 MW rated active power. The parameters of 10 MW PMSG with one-stage gear box (PMSG_1G) and direct (PMSG_DD) drive are shown in Table I [11], [12], the gear box ratio for PMSG_1G is designed at 9.7 to achieve an optimal tradeoff between the cost of generator and gear box as claimed in [11]. All the power switching devices have the commutated voltage of 2.8 kV in order to utilize the available and dominant 4.5 kV high-power IGCT/IGBT on the market. For simplicity of analysis, the power grid is considered as three 20kV/50Hz ideal AC voltage sources, the resistance in the generator and the wires is not taken into account, DC bus capacitance is assumed high, and the transformers are assumed ideal.

Table I. Parameters for 10 MW PMSG [11], [12].

Parameters	PMSG_DD	PMSG_1G
Rated wind speed v_w (m/s)	11.7	
Rated rotor speed n_r (rpm)	10	
Air gap diameter D (m)	10	4.2
Stator length l (m)	1.8	0.9
Number of pole pairs N_p	165	74
Gear ratio R	-	9.7
Rated shaft speed n_s (rpm)	10	97
Rated electrical frequency f_e (Hz)	27.5	120
No load induced voltage E_p (Vrms)	3748 / 1874	3600 / 1800
Synchronous inductance L_s (mH)	11 / 2.76	3.16 / 0.79

Note: PMSG_DD means the direct-drive permanent magnet synchronous generator system, while PMSG_1G means the one-stage gear box drive system.

A. Design of grid side converters

According to the commutated voltage of power devices (2.8 kV), the DC bus and maximum output voltage of each configuration can be determined. The equivalent switching frequency f_s of grid side converter is designed at 800 Hz to get an acceptable switching loss of the power devices. The output filter inductance is designed to limit the maximum current ripple to 25% of the rated maximum current amplitude, and the filter capacitance is not taken into account. The power factor PF is set at 0.9, which is the boundary value in normal operation according to the grid codes [4]. The power control method of the converters can be found in [3].

B. Design of generator side converters

The equivalent switching frequency of the generator side converter is designed as 10 times of the generator's maximum fundamental frequency f_e . For simplicity, filters on the

generator side are not considered. Constant stator voltage control is used at rated output power, and the maximum torque control is used at half and quarter rated output power of PMSG [11]. Because there is a zero-sequence-current path, the third harmonic injection modulation method cannot be applied in the generator side converter with 3L-HB and 5L-HB topologies [9]. The detail parameters of the different converter solutions are shown in Table II.

Table II. Parameters for 10 MW converters.

Configurations	3L-NPC BTB	3L-HB BTB	5L-HB BTB	3L+5L
DC bus voltage	5.6kV	2.8kV	5.6kV	5.6kV
IGBT number	24	24	48	36
Diode number ¹	36	24	72	54
PWM methods	PD-PWM	Unipo-PWM	POD-PWM	PD/POD-PWM
Grid side converter $PF=0.9$, $P_{rated}=10$ MW, $f_s=800$ Hz				
Apparent power	13.38 MVA	13.38 MVA	12.45 MVA	12.45 MVA
Rated output voltage ²	3970V	3970V	7400V	7400V
Primary side voltage ³	3300V	3300V	6600V	6600V
Rated current	1944A	1944A	972A	972A
Filter inductance	1.13mH	1.13mH	2.89mH	2.89mH
Transformer ⁴	Y/Y	O/Y	O/Y	O/Y
Fault tolerant ability	No			
Generator side converter (PMSG_DD / PMSG_1G)				
Apparent power	10.36 / 10.84 MVA			
Rated stator voltage	3300V	3300V	6600V	3300V
Generator induced voltage ⁵	3246 / 3118V	3246 / 3118V	6491 / 6237V	3246 / 3118V
Rated current	1813 / 1897A	1813 / 1897A	906 / 948A	1813 / 1897A
Stator inductance	2.76 / 0.79mH	2.76 / 0.79mH	11 / 3.16mH	2.76 / 0.79mH
First band switching freq.	275Hz / 1200Hz			
Fault tolerant ability	No	Yes	Yes	No

Note:

1. Include clamped diodes and anti-parallel freewheeling diodes.
2. Line-to-line rms voltage of the converter output.
3. Line-to-line rms voltage in the windings of converter side transformer.
4. No-load line-to-line rms induced voltage in the generator.

IV. ANALYSIS OF POWER DEVICES LOADING

In order to evaluate the power devices loading in different converter solutions, the current and loss distributions in the power devices need to be first investigated. Simulations are carried out based on PLECS blockset in Simulink [15], and the simulation settings are the same as the basic design parameters shown in Table I and Table II.

A. Current distribution

The simulated current distribution in one switching arm of the power devices for 3L-NPC BTB, 3L-HB BTB and 5L-HB BTB converter solutions are shown in Fig. 6, in which the situations for both grid side and generator side converters with direct-drive PMSG are indicated respectively. The 3L-NPC+5L-HB configuration is not shown because it shares the same current distribution with the generator side converter in 3L-NPC BTB as well as the grid side converter in 5L-HB BTB respectively. It is defined that a power switch S is composed of one IGCT/IGBT T and one anti-parallel freewheeling diode D , and the positive current in the switches

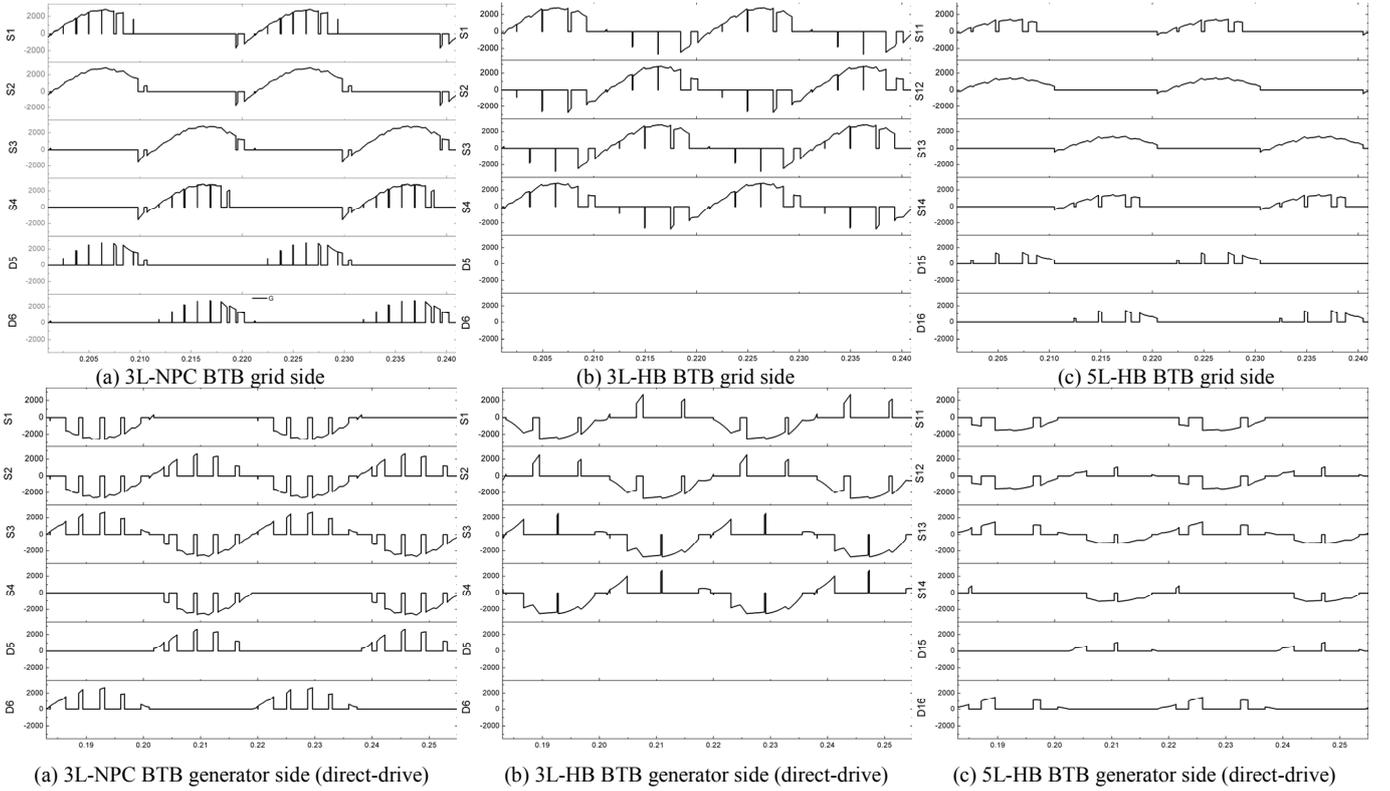


Fig. 6. Current distribution in power devices of different converter solutions ($P_G=10\text{MW}$, $PF_{\text{gridside}}=0.9$).

indicates the current flowing in T , while the negative current indicates the current flowing in D . The numbering of the switches is shown in Fig. 2- Fig. 4.

It can be seen that, for all of the converter solutions, the load current mainly locates in the T (IGCT/IGBT) of the grid side converters, while it locates in the D (anti-parallel diodes) of the generator side converters. In 3L-NPC BTB, load current is switched more frequently compared to the 3L-HB BTB and 5L-HB BTB, but the numbers of power devices which switch the load current are twice in 3L-HB BTB and 5L-HB BTB. Finally, 3L-HB BTB has more equal current distribution among the power devices compared to the other two configurations.

B. Loss distribution

The loss simulation method for power devices shares the same idea in [13], press-pack IGCT 5SHY35L4512 (commutated voltage 2.8kV/ maximum current 3.3kArms) and diodes 5SDF16L4503 (2.8kV/2.59kArms) from ABB are chosen as the switching power devices for 3L-NPC and 3L-HB topologies. IGCT 5SHY35L4510 (2.8kV/2.67kArms) and diodes 5SDF10H4503 (2.8kV/1.74kArms) from ABB are chosen for the 5L-HB topology. Switching loss (E_{on} , E_{off} , E_{rr}) and forward conduction voltage with relation to load current are acquired from the datasheets of each device. For simplicity of analysis, the junction temperature of power devices is assumed as 125°C , and losses in the reactive components are not considered in this paper.

The loss distribution of power devices in the grid side and generator side converters (with both direct-drive and one-stage gear box drive PMSG) are illustrated in Fig. 7. It can be

seen that, the loss distribution characteristics are quite different not only between configurations, but also between generator side and grid side converters.

For the grid side converter, 3L-NPC BTB shows dramatically unequal loss distribution in power devices: the outer switches ($S1$ and $S4$) as well as clamped diodes (D_{npc}) dissipate much more loss compared to the inner switches ($S2$ and $S3$) by factor of three, and the loss inside a single switch is dominantly dissipated by IGCT rather than anti-parallel diode. While the 3L-HB BTB configuration shows a much more equal loss distribution performance, the loss is equally shared by each switch in a switching arm, and inside a single switch IGCT dissipates about twice more losses than the diodes. The 5L-HB BTB topology shares similar unequal loss distribution performance with 3L-NPC BTB, but the loss distribution inequality is not so serious because of half current rating and less switching losses in power devices.

For the generator side converter with direct-drive PMSG, the diodes dissipate significantly more loss than the IGCTs. The unequal loss distributions in 3L-NPC and 5L-HB topologies are improved, and the inner switches consume slightly more loss than the outer switches. Because clamped diodes in 3L-NPC and 5L-HB mainly consume conduction loss in the generator side converter, the loss dissipated in the clamped diodes is much less than that in the grid side converters.

For the generator side converter with one-stage gear box PMSG, the unequal loss distributions between switches in 3L-NPC BTB configurations become more serious because of fast growing switching loss. While the 3L-HB topology

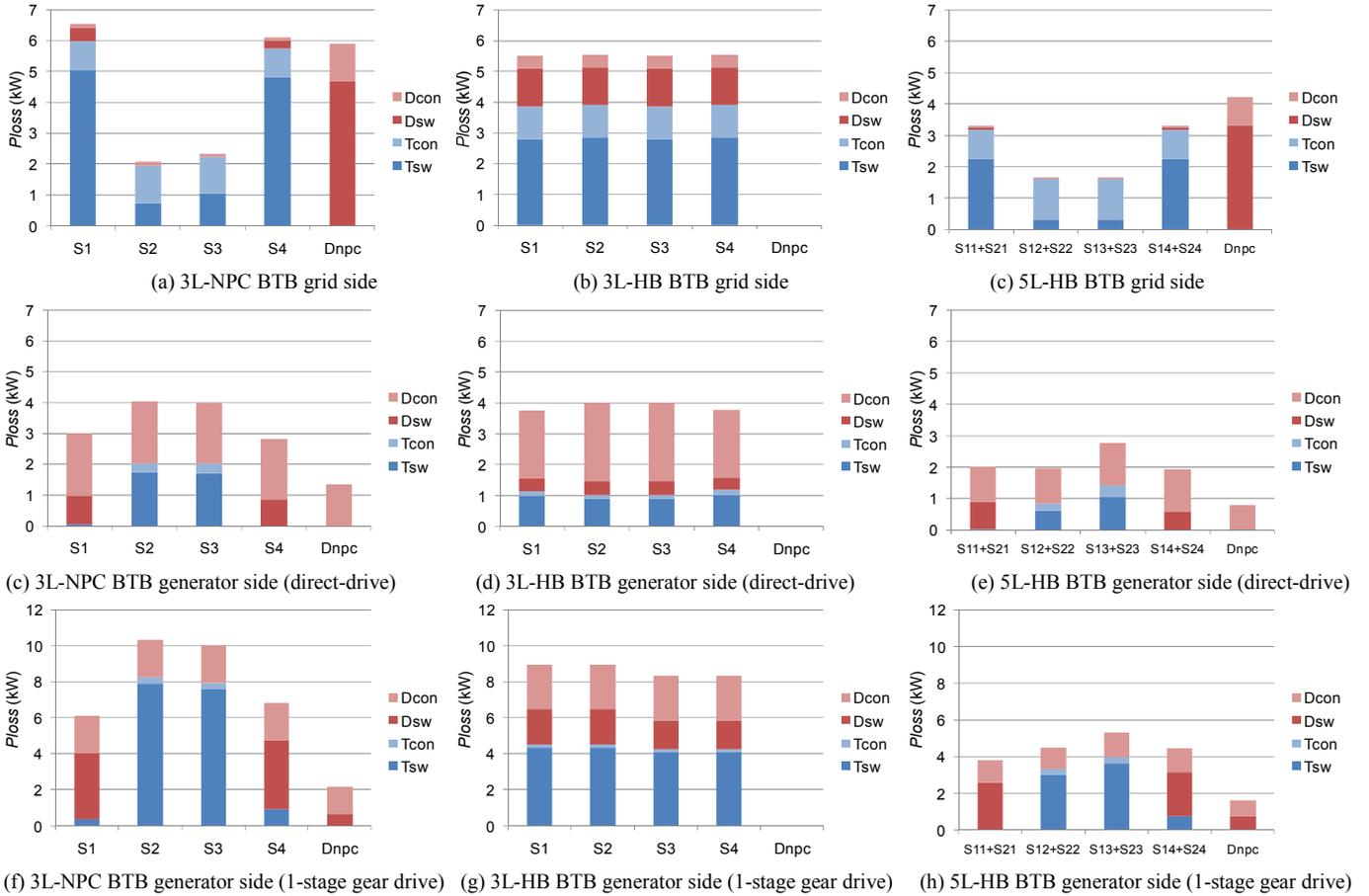


Fig. 7. Loss distribution in a switching arm of different converter solutions ($P_G=10\text{MW}$). Dcon and Dsw are the conduction and switching loss in diodes respectively, Tcon and Tsw are the conduction and switching loss in IGBT respectively.

shows a perfect equal loss distribution not only between switches but also between IGBTs and diodes.

C. Utilization of power devices

As analyzed before, the current and loss distribution in each converter solution are quite different from each other, therefore, the loading and utilization of power devices in the different converters should be also different.

According to the loss dissipation level of the IGBTs and diodes in Fig. 7, the power devices in different converters can be categorized into three types: the “hot” devices which dissipate the loss above 4kW (4kW is around the maximum loss dissipation limit for IGBTs as claimed in [14]), the “warm” devices which consume the loss between 1kW to 3kW, and “cold” devices which consume the loss below 1kW. The proportion of certain type of power devices will indicate the devices utilization and loading information of a converter:

The more “cold” devices a converter has, the less sufficient utilization and loading of the power devices, some of the IGBTs or diodes could be barely used, and the converter may have more potential to increase the power level or increase the switching frequency. The more “warm” devices a converter has, the more sufficient usage and loading of the power devices, this will be the ideal operation condition when designing a converter. The more “hot” devices a converter has, the more over loading of the power devices, some of the IGBTs or diodes could probably suffer from high junction

temperature, and the failure rate in these “hot” devices will be increased, therefore, “Hot” devices can be used as the indication of the “weak point” in the whole converter system.

The distributions of the three types of power devices at rated operating condition in each of the candidate converter solution are shown in Fig. 9, in which only one phase is illustrated for simplicity. The red color components represent the “hot” devices, yellow ones represent the “warm” devices and blue ones represent the “cold” devices. The numbers of the three types of power devices in different converter solutions are summarized in Fig. 8, in which the direct-drive and one-stage gear box drive system are illustrated respectively.

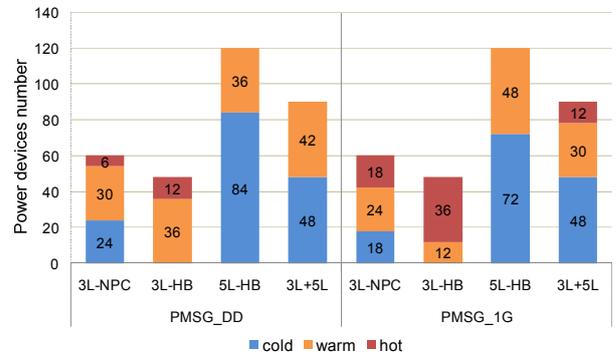


Fig. 8. The numbers of the three types of power devices in different converter solutions (rated condition, $P_G=10\text{MW}$).

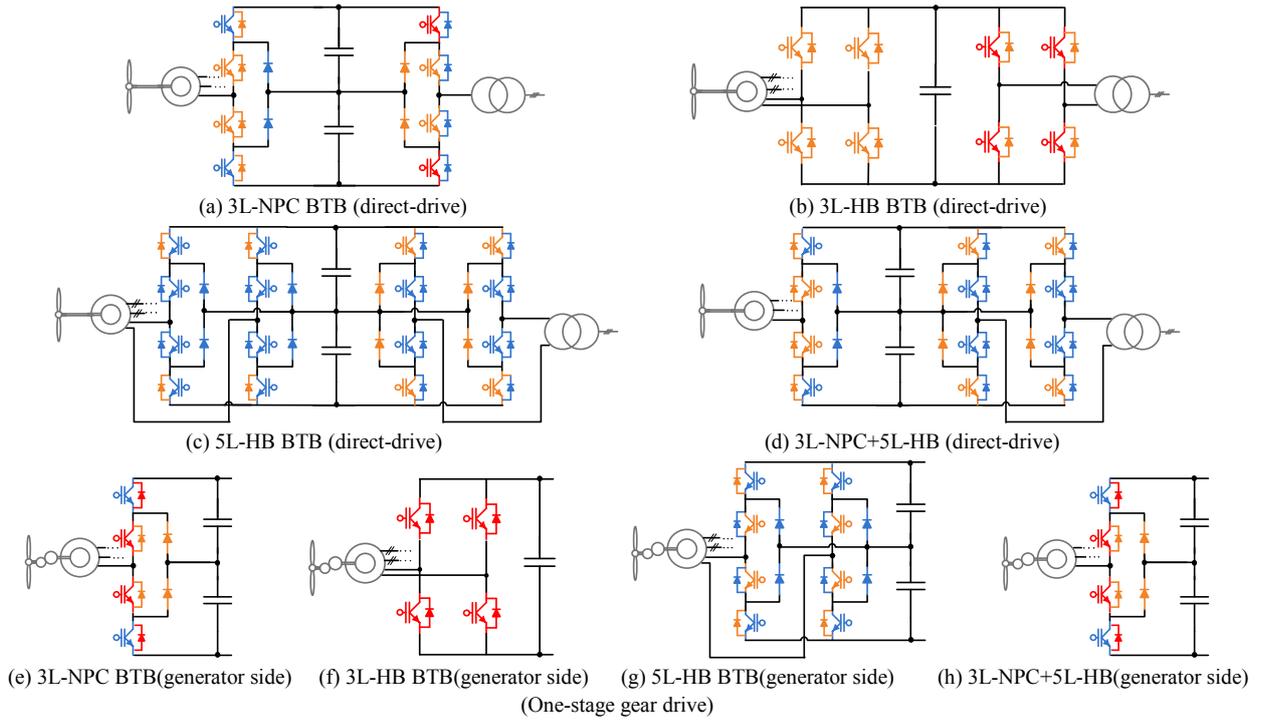


Fig. 9. The distribution of the three types of power devices in different converter solutions (rated conduction, red components mean hot devices whose loss>4kW, yellow ones mean warm devices whose 1kW<loss<3kW, blue ones mean cold devices whose loss<1kW, only one phase converter is indicated).

From the point view of power devices loading, the 3L-NPC BTB solution seem to be less attractive because some of the power devices already exceed the maximum loss dissipation limit for IGCTs, as shown in Fig. 7 (a)(c)(f), and at the same time nearly one third of the power devices are still in “cold” loading and another one third are in “warm” loading, this means a very unequal utilization of the power devices and less reliable converter system. Moreover, it is quite inefficient to optimize the device utilization by enhancing the current capacity of all power devices at the same time.

The 3L-HB BTB solution seems to be an appropriate candidate for the direct-drive system. Most of the power devices are in warm and sufficient used status, and at the same time only 25% power devices just reach the loss dissipation boundary of “hot” devices. While for the one-stage gear box drive system, because of the higher switching losses, 75% of the power devices in 3L-HB BTB just reach the loss boundary of “hot” devices. However, the optimization of the devices utilization will be more efficient by enhancing the current capacity of all power devices.

The 5L-HB BTB solution seems to be an over-rated candidate because more than half of the power devices are still in the cold status, and no devices reach the “hot” status both in the direct-drive and one-stage gear box drive system. Therefore, it still maintains a potential to further increase the power level or increase the switching frequency with the same power devices.

From the point view of device loading, the 3-NPC +5L-HB solution seems to be a good candidate in the direct-drive system and less attractive in one-stage gear drive system. The

3L-NPC generator side converter is the “weak point” of the whole converter system.

D. Total loss and efficiency

The total converter loss comparison between different solutions is shown in Fig. 10, in which the loss distribution in the IGCTs and diodes are indicated. Due to higher switching frequency, the generator side converter in the one-stage gear box drive system (PMSG_1G) shows more switching losses compared to the generator side converter in the direct-drive system (PMSG_DD). The major losses on the grid side converter come from IGCTs, while the major losses on the generator side come from the diodes.

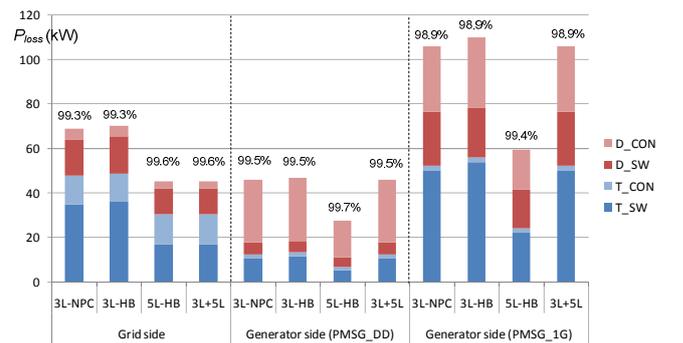


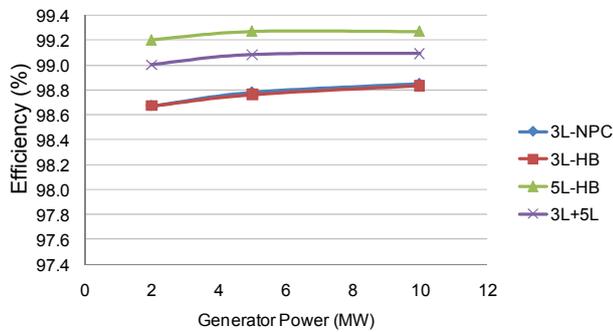
Fig. 10. Total loss comparison (rated condition, $P_G=10\text{MW}$, $PF_{gridside}=0.9$).

The total power conversion efficiency of different converter solutions at 10 MW (100% rated power), 5 MW (50% rated power) and 2 MW (20% rated power) are further shown in Fig. 11. The parameters for the generator at different output power are shown in Table III.

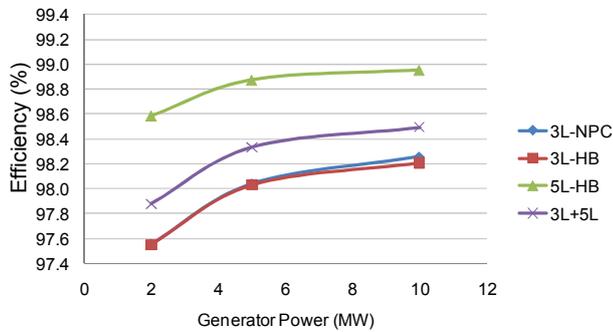
It can be seen that both in the direct-drive and one-stage gear box drive system, 3L-HB BTB and 3L-NPC BTB solutions show the similar efficiency performance at different output power, and 5L-HB BTB shows the highest conversion efficiency. Solution 3L-NPC+5L-HB is a tradeoff between numbers of switching devices and conversion efficiency.

Table III. Parameters at different generator output power.

Generator power P_G (MW)	2	5	10
Wind speed v_w (m/s)	6.8	9.3	11.7
<i>Direct drive system (PMSG_DD)</i>			
Shaft speed n_s (rpm)	6.2	8.4	10
Induced voltage E_p (Vrms)	1164/2327	1580/3159	1874/3748
Electrical frequency f_e (Hz)	17.1	23.2	27.5
First band frequency f_{1b} (Hz)	275		
<i>One-stage gear drive system (PMSG_1G)</i>			
Shaft speed n_s (rpm)	60	82	97
Induced voltage E_p (Vrms)	1118/2236	1518/3035	1800/3601
Electrical frequency f_e (Hz)	74	101	120
First band frequency f_{1b} (Hz)	1200		



(a) Direct drive system.



(b) One-stage-gear drive system.

Fig. 11. Total conversion efficiency of different converter solutions ($PF_{gridside}=0.9$).

V. CONCLUSIONS

Among the four 10 MW wind power converters, 3L-NPC BTB seems to be the least attractive solution because of less efficient power device utilization and lower conversion efficiency, especially in the one-stage gear box drive system.

The 3L-HB BTB shares the similar output and efficiency performance as 3L-NPC BTB, but the differences are in the loss distribution and potential redundancy ability, 3L-HB

BTB shows more advantages on these performances than 3L-NPC BTB.

The 5L-HB BTB is a more efficient solution both in the power conversion and device utilization, but with the cost of double switching devices compared to 3L-NPC BTB.

The 3L-NPC+5L-HB is a tradeoff solution between component number and efficiency performance, the 3L-NPC generator side converter is the “weak point” of the whole converter system.

Regarding the high switching frequency requirements and utilization of power devices, 3L-HB BTB and 5L-HB BTB are more appropriate in one-stage gear box drive system compared to the 3L-NPC BTB and 3L-NPC+5L-HB solutions.

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