Comparison of High Power Semiconductor Devices in 5MW PMSG MV Wind Turbines

Kihyun Lee,
Kyungsub Jung, and Yongsug Suh
Department of Electrical Engineering,
Chonbuk National University
567 Baekje-daero, Duckjin-gu Jeonju,
561-756, KOREA

Changwoo Kim, Taemin Cha,
Hyoyol Yoo, and Sunsoon Park
Dawonsys
3-Na 705, Shihwa Industrial Complex,
1277-4 Jungwang-Dong, Siheung-City, Gyeonggi-Do,
790-600, KOREA

ABSTRACT

This paper provides a comparison of high power semiconductor devices in 5MW-class Permanent Magnet Synchronous Generator (PMSG) Medium Voltage (MV) wind turbines. High power semiconductor devices of IGBT module type, IGBT press-pack type, and IGCT of both 4.5kV and 6.5kV are considered in this paper. Benchmarking is performed based on neutral-point clamed 3-level back-to-back type voltage source converter supplied from grid voltage of 4160V. The feasible number of semiconductor devices in parallel is designed through the loss analysis considering both conduction and switching losses under the given operating conditions of 5MW-class PMSG wind turbines, particularly for the application in offshore wind farms. The loss analysis is confirmed through PLECS simulations. The comparison result shows that IGBT press-pack type semiconductor device has the highest efficiency and IGCT has the lowest cost factor considering the necessary auxiliary components.

1. Introduction

Recently, in the multi-MW wind turbine market, the maximum power rating of a commercial wind turbine has been increased more than 6MW with a view to generate more power from wind power sites [1]. Power electronic converters in MV are generally realized as multi-level (ML) voltage source converters (VSC) instead of 2L-VSCs in order to improve the performance factors regarding switch power losses, harmonic distortion, and common mode voltage/current [2]. In the family of multilevel inverters, the three-level topology, called Neutral Point Clamped (NPC) inverter, is one of the few topologies that has received a reasonable consensus in the high power community [3]. These NPC inverters have also been implemented successfully in the industrial applications for high power drives and wind turbines [4]. A simplified schematic of a NPC inverter for 5MW PMSG MV wind turbines is presented in Fig 1 [5]-[6].

In the multi-MW wind turbine systems, there are many different types of power converter topologies and high-power switching devices. The benchmarking of these topologies and its optimal power switches is important for industry to select the most feasible solution in product development of wind turbines.

This paper investigates the utilization of three most feasible high-power switching devices for 5MW PMSG wind turbine systems; IGCT, module IGBT, and press-pack IGBT. 6.5kV and 4.5kV class devices are considered in the loss calculation of 3L NPC VSC. The loss distribution among several switching devices in the converter is also explained in this paper.

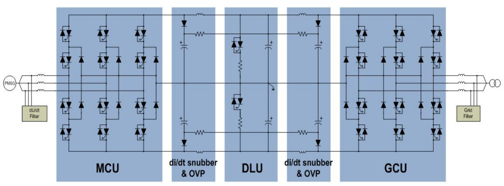

Fig. 1 Three-level neutral point clamped back-to-back configuration for 5MW PMSG MV wind turbines.

2. Target of Power Semiconductor Devices

Recent technology development of 4.5 kV and 6.5 kV IGCTs and IGBTs has been enabling a substantial improvement of MV converters in many aspects [7]–[9].

Fig. 2 Target power semiconductor devices for MV wind turbines.

A. *The Medium-voltage IGCT Press-pack*

MV IGCT press pack devices are mainly used in high power industrial applications owing to advantageous features of press pack cases compared to modules, a higher thermal and power cycling capability, and an explosion-free failure mode.

B. *IGBT Module and IGBT Press-pack*

On the market, the switching current capability of 6.5kV IGBTs modules has reached around 1500A. Recently developed press-pack IGBT devices combine the advantages of IGBTs with those of press-pack cases. Thus, press-pack IGBTs have become a competition for IGCTs in medium and high power industrial applications like MV drives for wind turbines [10].

Table I and II show the switching characteristics of target power semiconductors for the 3L-NPC VSC of 5MW PMSG wind turbines. The target power devices are 6.5kV/3800A IGCT press-pack (ABB 5SHY 42L6500), 6.5kV/1500A IGBT module (ABB 5SNA 0750G650300), and 4.5kV/4800A IGBT press-pack (IXYS T2400GB45E). Important characteristics for the loss calculation are threshold voltage (V_{TO}), slope resistance (R_T) as a function of the collector/anode current, turn-on energy (E_{on}), turn-off energy (E_{off}), operating junction temperature (T_{vj}), and thermal resistance (R_{th}).

Table I. Characteristic values of IGCT and press-pack IGBT.

	IGCT Press-pack (ABB 5SHY 42L6500)	IGBT Press-pack (IXYS T2400GB45E)
Symbol	Value	Value
V_{TO}	1 88 V	1 73 V
R_T	0 56 mΩ	0 96 mΩ
E_{on}	3 1 J (4kV / 3800A)	9 9 J (2 8kV / 2400A)
E_{off}	44 J (4kV / 3800A)	10 7 J (2 8kV / 2400A)
$R_{th(j-c)}$	8 5 K/kW	5 2 K/kW
$R_{th(c-h)}$	3 K/kW	3 K/kW
$R_{th(h-a)}$	6 K/kW	6 K/kW

Table II. Characteristic values of IGBT module.

	IGBT Module (ABB 5SNA 0750G650300)	
	IGBT	Diode
Symbol	Value	Value
V_{TO}	2 0 V	2 5 V
R_T	2 5 mΩ	1 3 mΩ
E_{on}	6 4 J (3 6kV / 750A)	-
E_{off}	5 3 J (3 6kV / 750A)	2 7 J (3 6kV / 750A)
$R_{th(j-c)}$	11 K/kW	21 K/kW
$R_{th(c-h)}$	9 K/kW	18 K/kW
$R_{th(h-a)}$	10 K/kW	10 K/kW

3. Simulation

The simulation is performed based on the parameters of 5MW MV 3L-NPC VSC as specified in Table III.

Table III. Simulation parameters of 5MW MV 3L-NPC VSC.

5MW Wind Turbine MV PCS		
Parameter	**Symbol**	**Value**
Output power	$P_{rated\text{-}out}$ [MW]	5
Frequency	f_s [Hz]	60
Grid side inductance	L_{grid} [mH]	1
Grid side capacitance	C_{grid} [mF]	0 4
Grid side input voltage	V_{LL} [kV]	4 16
Grid side input current	$I_{AC\ input}$ [A]	708
Switching frequency	$f_{ARU\ PWM}$ [Hz]	1020
DC-link voltage	$V_{DC\text{-}link}$ [kV]	7

A. *Switching Status of NPC 3-level VSC*

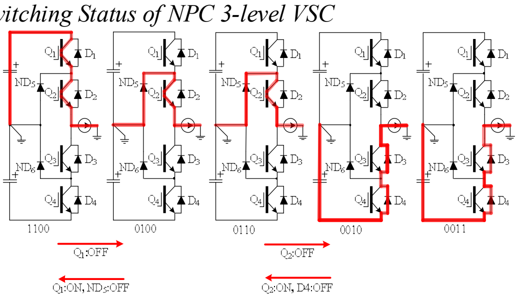

Fig. 3 Switching on/off loss under the positive input current (i_c>0).

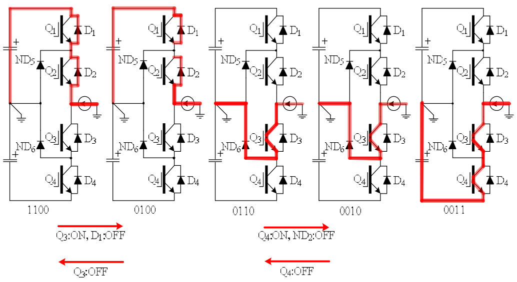

Fig. 4 Switching on/off loss under the negative input current (i_c<0).

Figure 3 and 4 describe the switching modulations in a phase-leg of 3L NPC VSC. The conduction and switching loss distribution in each switching devices, free-wheeling diodes, and neutral point diodes are readily understood from the schematics.

B. *Simulation Results*

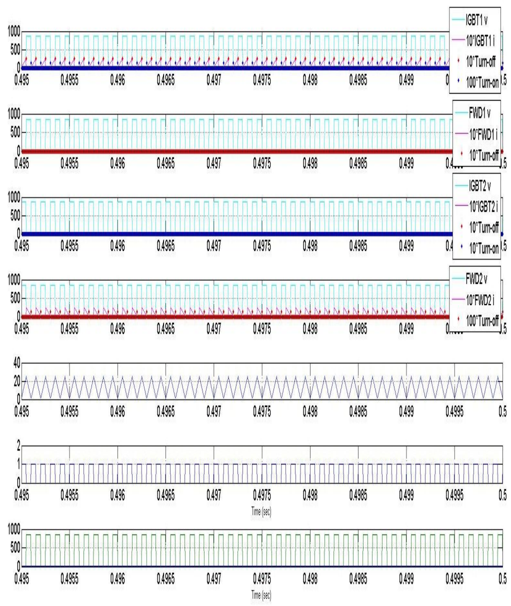

Fig. 5 Waveforms of voltage and current in each phase-leg.

4. Comparison of Loss in High Power Semiconductor

Table IV. Loss distribution of high power semiconductor devices.

ABB IGCT 6.5kV/3800A (5SHY 42L6500)					
Parameter		**Q1**	**Q2**	**Q3**	**Q4**
	I_{rms}[A]	79 0	436 6	433 2	95 0
	I_{AVG}[A]	13 6	191 1	187 3	17 0
Conduction loss	P_{con}[W]	29 0	466 1	457 2	37 0
Turn-on loss	(P_{on})	11 4	217 1	224 8	49 7
Turn-off loss	(P_{off})	686 5	4604 9	4731 8	1278 5
Total power loss	(P_{total})	726 9	5288 1	5413 8	1365 2
Junction temperature	T_j[℃]	52 7	132 5	134 7	63 9

ABB 6.5kV/1500A IGBT module (5SNA 0750G650300)					
Parameter		**Q1**	**Q2**	**Q3**	**Q4**
	I_{rms}[A]	79 0	436 6	433 2	95 0
	I_{AVG}[A]	13 6	191 1	187 3	17 0
Conduction loss	P_{con}[W]	10 8	180 4	177 0	13 8
Turn-on lossW	(P_{on})	44 3	841 1	870 9	192 7
Turn-off loss	(P_{off})	155 2	1040 9	1069 6	289 0
Total power loss	(P_{total})	210 3	2062 4	2117 5	495 5
Junction temperature	T_j[℃]	46 3	101 9	103 5	54 9
ABB 6.5kV/1500A Diode (5SNA 0750G650300)					
Parameter		**D1**	**D2**	**D3**	**D4**
	I_{rms}[A]	594 4	549 4	545 0	545 0
	I_{AVG}[A]	254 7	254 7	255 0	254 5
Conduction loss	P_{con}[W]	255 9	255 9	255 0	255 0
Turn-on loss	(P_{on})	-	-	-	-
Turn-off loss	(P_{off})	367 5	-	-	354 7
Total power loss	(P_{total})	623 4	255 9	255 0	609 7
Junction temperature	T_j[℃]	70 5	52 5	52 5	69 9

IXYS 4.5kV/4800A Press-pack IGBT (T2400GB45E)					
Parameter		**Q1**	**Q2**	**Q3**	**Q4**
	I_{rms}[A]	79 0	436 6	433 2	95 0
	I_{AVG}[A]	13 6	191 1	187 3	17 0
Conduction loss	P_{con} [W]	29 5	513 7	504 2	38 0
Turn-on loss	P_{on} [W]	60 0	1140 5	1180 9	261 3
Turn-off loss	P_{off} [W]	275 3	1846 5	1897 3	512 6
Total power loss	P_{total} [W]	364 8	3500 7	3582 4	811 9
Junction temperature	T_j[℃]	45 2	89 7	90 9	51 5

5. Conclusion

This paper compares 6.5kV/3800A IGCT press-pack (ABB), 6.5kV/1500A IGBT module (ABB), and 4.5kV/4800A IGBT press-pack (IXYS) for 5MW permanent magnet synchronous generator medium voltage wind turbine employing a back-to-back 3-level NPC voltage source converter. The switching frequency is set to 1020Hz, and grid side input voltage is 4.16kV. The press-pack IGBT of 4.5kV has been found to have the lowest device losses, i.e. highest efficiency, among three candidates. However, total price of power semiconductor including gate drivers and gate units in case of press-pack IGBT is higher than that of 6.5kV press-pack IGCT by 37%. Considering the loss and cost benchmarking result of three MV high power semiconductors, a further utilization of press-pack IGCTs is expected for MW wind turbines.

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