Comparison of Efficiency for Voltage Source and Current Source Based Converters in 5MW PMSG Wind Turbine Systems

Tahyun Kang, Taewon Kang, Beomseok Chae, Kihyun Lee, and Yongsug Suh

Abstract

This paper provides a comparison of power converter loss and thermal description for voltage source and current source type 5 MW-class medium-voltage topologies of wind turbines. Neutral-point clamped three-level converter is adopted for a voltage source type topology, whereas a two-level converter is employed for current source type topology, considering the popularity in the industry. To match the required voltage level of 4160 V with the same switching device of IGCT as in the voltage source converter, two active switches are connected in series for the case of current source converter. Transient thermal modeling of a four-layer Foster network for heat transfer is done to better estimate the transient junction and case temperature of power semiconductors during various operating conditions in wind turbines. The loss analysis is confirmed through PLECS simulations. Comparison result shows that the VSC-based wind turbine system has higher efficiency than the CSC under the rated operating conditions.

Key words: Voltage source converter, Current source converter, Junction temperature, Wind turbine systems

1. Introduction

The demand of sustainable and renewable energy has been increased remarkably due to the energy crisis and the environmental concern. Among the renewable energy sources, especially, the wind energy capacity has been increased rapidly over the last decade. According to the recent trends, power capability of wind turbines is moving from kW class to MW class to reduce the cost of energy. As the power capability of wind turbine systems increases, in order to reduce current level, the Medium Voltage (MV) system has been adopted for power converter and generators of wind turbine. MV converter becomes more preferable due to less component count, high efficiency and simple power stage design in power converters of wind turbines.

Among various topologies of MV converter, back-to-back type three-level neutral-point clamped Voltage Source Converter (VSC) is one of popular choices in wind power systems. This converter topology has become a quite reliable industrial solution in wind turbines of MV class owing to many existing high power semiconductor switch components and modules in the market. Current source type converter has been regarded as one of many interesting circuit topologies in motor drives of MV class due to its inherent short circuit protection capability and low dv/dt characteristic of ac line voltage in a long-range cable connection. Previous literatures regarding Current Source Converter (CSC)
have focused on the design and loss analysis of current source converters\textsuperscript{[5]} in addition, most of previous work has dealt with high-power motor drive applications of current source converters\textsuperscript{[6]} \textsuperscript{[7]}. Some work has been done to apply thyristor technology to wind turbine systems\textsuperscript{[8]} However, in contrast to voltage source type converters, current source type converters, particularly those with turn-off power semiconductor switching devices, have received less attention in the field of wind turbines in spite of its many powerful advantages in MV applications.

This paper investigates the application of current source converter topology in wind power systems. This paper also includes both the quantitative and qualitative investigation on the performance comparison of current source converter and voltage source converter in a wind turbine of MV class. The wind turbine of 5MW/4160V PMSG type is chosen as a common platform for the comparison work. Back-to-back type three-level neutral-point clamped voltage source converter, which is regarded as the most popular topology choice in this power range of 5MW, and back-to-back two-level current source converter topologies are analyzed. Due to the industrial practices of simpler implementation, instead of three-level current source topology, two-level current source converter equipped with a series connection of power semiconductor switches is proposed to be the target circuit topology of current source converter in this paper. The performance of two different types of converter system is studied with respect to the loss factors and thermal behavior of power semiconductor devices.

The main objective of this paper is to provide a comparison result of system efficiency for high-power VSC and CSC of the wind turbine system. This paper is structured in five main sections. Section II describes the power semiconductor devices under comparison of 5MW PMSG Wind Turbine System (WTS). Section III discusses the model of semiconductors for calculating the losses and thermal description of the power semiconductor devices. Section IV presents simulation results of 5MW PMSG WTSs. Finally, comparison of VSC and CSC is given in Section V.

2. VSC and CSC based Wind Turbine Systems

2.1 Current Source Converter

Figure 1 shows the schematic of two-level CSC with series connection of two IGCTs, i.e. ns=2. Each leg of the CSC consists of four switches \((S_{mn}, S_{ng})\), and four reverse blocking diodes \((D_{m,n}, D_{g,n})\). The DC-Link current \(i_{dc}\) should be continuous. So zero switching state of the CSC is equivalent to shorting one of three phase legs in the converter. In general, this placement of zero state vector complicates the control of CSC compared to VSC\textsuperscript{[7]}.

2.2 Voltage Source Converter

Figure 2 shows the schematic of 3L-NPC VSC. Each leg of the VSC consists of two neutral-point clamped diodes \((ND_{m,n}, ND_{g,n})\), four switches \((S_{m,n}, S_{g,n})\), and four anti-parallel diodes \((D_{m,n}, D_{g,n})\). The DC-Link voltage is split into three-levels by two series connected capacitors. The middle point of two capacitors N can be defined as a neutral point. The output voltage \(v_{AN}\) has three states: \(V_{dc}/2, 0,\) and
The 5-VSC-based summarized employed reverse as devices (42L6500) and conduction -412.

Fig. 2. Back-to-back type 3L-NPC VSCs for 5MW PMSG MV wind turbines.

- $V_{dc}/2$ in each leg, which are produced by specific conduction paths depending on output current direction and output voltage polarity.[3]

2.3 Power Semiconductor Device (Press-pack IGCT, Press-pack Diode)

In this paper, VSCs and CSCs employ the same switching devices of press-pack IGCT (ABB 5SHY 42L6500) and press-pack FRD (ABB 5SDF 10H6004) devices for the sake of consistent and fair comparison of two topologies. The same type of FRD is utilized as anti-parallel diodes, neutral-point diodes, and reverse blocking diodes. The main characteristics of employed power semiconductor devices are summarized in Table I.[9][10].

2.4 System Specification

The system specifications of target CSC and VSC-based wind turbine systems as shown in Figure 1 and 2 are summarized in Table II and III, respectively. Rated operating condition for both converter system is set to the output power of 5MW and the ac line voltage of 4160V. In Table II and III, the filter networks in ac grid side and machine side of both converter system are designed to generate the ac current of same THD and power factor range for the sake of fair comparison of these two converter systems. The switching frequency adopted for the grid-side converter is set to 1020 Hz for both types of converter systems. This switching frequency is selected to be 17 times of the fundamental frequency, 60Hz.
TABLE III
SIMULATION PARAMETERS OF 5MW CSC

| Parameter                  | Symbol     | Value   | Per unit |
|----------------------------|------------|---------|----------|
| Output power               | $P_{rated-out}$ | 5 MW    | 1.0      |
| Grid frequency             | $f_{grid}$ | 60 Hz   | 1.0      |
| Grid side inductance       | $L_{grid}$ | 1.56 mH | 0.17     |
| Grid side input voltage    | $V_{L}$    | 4.16 kV | 1.0      |
| Grid side input current    | $I_{dc,input}$ | 708 A  | 1.0      |
| Switching frequency        | $f_{sc}$   | 1020 Hz | -        |
| DC-link current            | $I_{dc}$   | 997 A   | -        |
| DC-link inductance         | $L_{dc}$   | 8.3 mH  | -        |
| AC filter inductance       | $L_{f}$    | 0.98 mH | 0.11     |
| AC filter capacitance      | $C_{f}$    | 0.26 mF | 0.34     |

3.2 Switching Losses

Switching loss of power semiconductor device is determined by the total commutation time in which the device is turned on/off, and also by the voltage $v(t)$ and current $i(t)$ across the device. The energy dissipated during commutation is $E_{on}$ and $E_{off}$ for the single-pulse turn on and off, respectively, and is provided by the device manufacturers on their datasheets. The average switching power loss $P_{switching}$ over a complete fundamental period $T$ may be determined by summing all the commutations of the device during the respective interval of time. Each switching loss for turn-on and turn-off can be expressed as:

$$P_{on} = E_{on} \times f_{sw} = \frac{V_{on(measure)}}{V_{test}} \times \frac{I_{on(measure)}}{I_{test}} \times E_{on(spec)} \times f_{sw} \quad (3)$$

$$P_{off} = E_{off} \times f_{sw} = \frac{V_{off(measure)}}{V_{test}} \times \frac{I_{off(measure)}}{I_{test}} \times E_{off(spec)} \times f_{sw} \quad (4)$$

Equation (3) and (4) represent the linear approximation of actual switching loss for turn-on and turn-off based on the specific values ($E_{on(spec)}$ and $E_{off(spec)}$) provided by manufacturers. Although the switching loss can vary depending on the gate impedance, parasitic circuit elements, and snubber characteristics, this linear approximation gives a fairly good accuracy particularly at the vicinity of a manufacturer’s test point ($V_{test}$ and $I_{test}$) and snubber condition[7].

3.3 Thermal Model

The power loss modeling can be implemented based on the current and voltage values in the power devices. The thermal modeling of power devices and cooling environment for heat transfer are used to estimate the junction and case temperature of power devices[12].

The steady state average junction temperature of each power semiconductor devices can be expressed as follows[33]. $T_j$ and $P_t$ represent the junction temperature and total semiconductor device loss, respectively[32].

$$T_j [=] C = (P_t [W] \times R_{th} [\cdot C/W]) + T_o [\cdot C] \quad (5)$$

3.1 Conduction Losses

Conduction loss of each power semiconductor depends on the instantaneous on-state voltage $v_{on}(t)$ and the instantaneous switching current $i(t)$ passing through it. A forward on-state voltage of power semiconductor device, $v_{on}(t)$ can be modeled using a first-order linear approximation comprised of a threshold voltage $v_{on}$ and a series resistance $R_{on}$. And then, the total conduction loss in power semiconductors can be expressed as:

$$P_{cond} = \frac{1}{T} \int v_{on}(t) \cdot i(t) dt$$

$$= \frac{1}{T} \int (v_{on} + R_{on} \cdot i(t)) dt$$

$$= v_{on} I_{avg} + R_{on} (I)^2 \quad (2)$$

where $T$ is the fundamental period of the converter.
4. Simulation Results of VSC and CSC

Electrical and thermal behavior of the two target CSC and VSC systems in Figure 1 and 2 are simulated. The simulation is performed based on the parameters of 5MW MV VSC and CSC as specified in Table II and III. Figure 4 and 5 show the simulation waveforms of switching voltage and current in the upper-leg of phase-a in VSC and CSC under the power factor of 0.9 leading condition. In this paper, the modulation scheme of varying DC-link current depending on the power factor is adopted for CSC [32]. The both converter operates under inverter mode, i.e. power flows from the DC-link to the ac grid. Under the same operating conditions as in Figure 4 and 5, Figure 6 and 7 present the simulation waveforms of instantaneous junction temperature of switching devices in the upper-leg of phase-a in VSC and CSC. In this paper, the balanced sharing of switching voltage across two series connected devices (ns=2) in CSC is assumed. It is noted from Figure 6 and 7 that the RC Foster network thermal model in Figure 3 and its thermal impedance values in Table IV successfully exhibit the transient behavior of junction temperature with respect to the corresponding switching on and off instants. The waveforms of junction temperature in Figure 6 and 7 confirms the fact that the transient thermal modeling of switching devices is quite necessary in order to accurately investigate the transient thermal behavior of power semiconductor devices, e.g. peak temperature, repetitive temperature ripples, etc.

5. Comparison of VSC and CSC based Wind Turbine Systems

This section provides a comparison result of system efficiency for target VSC and CSC-based wind turbine systems. The conduction and switching losses of employed power semiconductor devices are calculated based on (2)–(4). In order to investigate the
전압형 및 전류형 컨버터를 적용한 5MW PMSG 풍력발전시스템의 효율 비교

Fig. 4. Waveforms of VSC switching voltage and current in the upper-leg of phase-a under 0.9 leading condition (S_{ga,1}, D_{ga,1}, S_{ga,2}, D_{ga,2}).

Fig. 5. Waveforms of CSC switching voltage and current in the upper-leg of phase-a under 0.9 leading condition (S_{ga,1}, D_{ga,1}, S_{ga,2}, D_{ga,2}).
Fig. 6. Junction temperature of switching devices in the upper-leg of phase-a under 0.9 leading condition for the VSC.

Fig. 7. Junction temperature of switching devices in the upper-leg of phase-a under 0.9 leading condition for the CSC.
Fig. 8. Loss distribution in upper-leg two switches (S_{g_1}, S_{g_2}) and three diodes (D_{g_1}, D_{g_2}, ND_{g_1}) of VSC (pf=0.9 leading).

Fig. 9. Loss distribution in upper-leg two switches (S_{g_1}, S_{g_2}) and three diodes (D_{g_1}, D_{g_2}, ND_{g_1}) of VSC (pf=1.0).

Fig. 10. Loss distribution in upper-leg two switches (S_{g_1}, S_{g_2}) and three diodes (D_{g_1}, D_{g_2}, ND_{g_1}) of VSC (pf=0.9 lagging).

Fig. 11. Loss distribution in upper-leg two switches (S_{g_1}, S_{g_2}) and two diodes (D_{g_1}, D_{g_2}) of CSC (pf=0.9 leading).

Fig. 12. Loss distribution in upper-leg two switches (S_{g_1}, S_{g_2}) and two diodes (D_{g_1}, D_{g_2}) of CSC (pf=1.0).

Fig. 13. Loss distribution in upper-leg two switches (S_{g_1}, S_{g_2}) and two diodes (D_{g_1}, D_{g_2}) of CSC (pf=0.9 lagging).
characteristics of loss distribution under various operating conditions of different power factor, three different power factor conditions are selected in the loss comparison: 0.9 leading, 1.0, and 0.9 lagging. The loss distribution among switching devices in the upper-leg of phase-a under these three different power factor conditions are presented in Figure 8 through 13. Figure 8-10 correspond to loss distribution of VSC while Figure 11-13 correspond to those of CSC.

The numerical data of junction temperature presented in Figure 8-13 are obtained using the steady-state thermal model as depicted in (5). It is noted from Figure 8 and 11 that the steady-state values of junction temperature are close to average values of temperature profiles illustrated in Figure 6 and 7 whose operating conditions are same as those of Figure 8 and 11, respectively. In general, the steady-state value of junction temperature obtained from (5) corresponds to the average value of instantaneous junction temperature waveform measured from Foster RC network within relevant time scales of thermal dynamics.

It is noted from Figure 4 and 6 that, in the case of VSC, the loss is concentrated at the switching device of $S_{k,i}$ and Diode $ND_{k,i}$, i.e. the outer switching device and neutral-point clamped diode. Therefore, these devices have relatively high junction temperature. On the other hand, in the case of CSC, the loss is evenly distributed over the switching devices and diodes as shown in Figure 5 and 7. This evenly distributed loss and junction temperature profile among the devices in the case of CSC, as compared to that of VSC, is mainly due to the balanced sharing of switching voltage across two series connected devices. Therefore, when the voltage sharing becomes uneven across series connected devices, the loss distribution also becomes uneven which is the usual case in industry practices.

The total losses and efficiency of VSC and CSC-based grid-side converter in wind turbine systems are illustrated in Figure 14. As in Figure 8-13, the total losses and its efficiency are given under three different operating conditions: 0.9 leading, 1.0, and 0.9 lagging power factor. It is noted from Figure 14 that, although the loss is evenly distributed over the switching devices and diodes in CSC, the total losses of CSC is higher than those of VSC. The main reason for this higher loss of CSC is that CSC has four semiconductor junction drops in the current path of upper-leg of each phase while VSC has only two semiconductor junction drops in the current path of upper-leg of each phase. Therefore, CSC has almost twice large conduction loss as that of VSC. On the other hand, the switching loss portions of VSC and CSC are within the same order of magnitude due to the equal sharing of switching voltage across two series connected devices in CSC. These characteristics are apparent in the conduction and switching loss data shown in Figure 8-13. In Table V, the efficiency data measured from the simulation models described in Figure 1 and 2 are compared to efficiency data specified in the data sheet of the state-of-the-arts MV converters of similar types[16][17][18]. It is assumed that both the machine side converter and the grid side converter in the back-to-back configuration of VSC and CSC consume same amount of power loss in power semiconductor devices. In addition, the efficiency data are obtained from the simulation model of VSC and CSC under the operating condition of unity power factor at the grid side. The auxiliary loss factors such as snubber loss, filter loss, and DC-link loss are not taken into consideration for the efficiency data of simulation model in Table V. Therefore, including the effect of these auxiliary loss factors, the efficiency data from the simulation model of VSC and CSC would reach the level of the values of practical converter systems.

It is expected that the three-level structure of CSC has a more meaningful and relevant loss data in this comparative investigation in regard of the VSC of three-level topology. In addition, several loss factors other than semiconductor losses such as snubber loss, filter loss, and DC-link loss may have a significant impact on the comparison of VSC and CSC-based wind turbine systems. These aspects of system behavior will be reported in future publications.

6. Conclusion

This paper investigates the performance of VSC and CSC in PMSG type wind turbine of 5MW/4160V. In order to effectively compare the performance of two converter topologies, this paper calculates and compares the efficiency of two different types of WTS. Along with efficiency, the detailed loss distribution of each functional block of the entire WTS is presented. The loss analysis is confirmed
through PLECS simulations in both of VSC and CSC. The loss calculation method proposed in this paper can determine relatively accurate switching losses in semiconductor devices on the basis of simulated switching waveforms. The simulation result shows that VSC–based wind turbine system has a higher efficiency than that of CSC. This superior characteristic of VSC is attributed to the fact that CSC has the double the semiconductor junction drops in the device series connection structure (ns=2) of two-level topology in contrast to three-level structure of VSC.

**TABLE V**

EFFICIENCY COMPARISON OF SIMULATION MODEL AND STATE–OF–THE–ARTS MV CONVERTERS [9–13][14]

| Converter Type | Efficiency of State–of–the–arts MV Converters | Efficiency Measured from Simulation Model |
|----------------|-----------------------------------------------|------------------------------------------|
| VSC            | 98% (PCS 6000, ABB)                           | 98.4% (Simulation Model in Fig. 2)       |
|                | 99% (MV7000, GE)                             |                                          |
| CSC            | 97.5% (Powerflex 7000, Rockwell Automation) | 98.2% (Simulation Model in Fig. 1)       |

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2010–0028509) & (No. 2014R1A2A1A11053678).

**References**

[1] H. J. Lee and S. K. Sul, “Wind power collection and transmission with series connected current source converters,” in *Proc. 14th EPE*, pp. 1–10, Aug. 30–Sep. 1, 2011.

[2] J. Sayago, T. Bruckner, and S. Bernet, “How to select the system voltage of MV drives: A comparison of semiconductor expenses,” *IEEE Trans. Ind. Electron.*, Vol. 55, No. 9, pp. 3381–3390, Sep. 2008.

[3] K. Lee, K. Jung, Y. Suh, C. Kim, H. Yoo, and S. Park, “Comparison of high power semiconductor devices losses in 5MW PMSG MV wind turbines,” *IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 2511–2518, Mar. 2014.

[4] O. S. Senturk, L. Helle, S. Munk-Nielsen, and P. Rodriguez, “Power capability investigation based on electro–thermical models of press–pack IGBT three–level NPC and ANPC VSCs for multimegawatt wind turbines,” *IEEE Trans Power Electron.*, Vol. 27, No. 7, pp. 3196–3206, Jul. 2012.

[5] F. Pilsecker, R. Alvarez, and S. Bernet, “Design and losses of PWM current source converters,” in *Proc. IEEE Int Conf Ind Technol.*, pp. 737–744, 2010.

[6] E. P. Wiechmann, P. Aqueveque, R. Burgos, and J. Rodriguez, “On the efficiency of voltage source and current source inverters for high–power drives,” *IEEE Trans Ind Electron.*, Vol. 55, No. 4, pp. 1771–1782, Apr. 2008.

[7] Y. Suh, J. K. Steinke, and P. K. Steimer, “Efficiency comparison of voltage–source and current–source drive systems for medium–voltage applications,” *IEEE Trans. Ind. Electron.*, Vol. 54, No. 5, pp. 2521–2531, Oct. 2007.

[8] P. Tenca, A. A. Rockhill, T. A. Lipo, and P. Tricoli, “Current source topology for wind turbines with decreased mains current harmonics, further reducible via functional minimization,” *IEEE Trans. Power Electron.*, Vol. 23, No. 3, pp. 1143–1155, May 2008.

[9] “Asymmetric integrated gate–commutated thyristor 5SHY 42L6500,” Datasheet, Doc. No. 5SYA124/–03 Dec. 12, ABB Switzerland Ltd., Online: www.abb.com.

[10] “Fast recovery diode 5SDF 10H6004,” Datasheet, Doc. No. 5SYA1109–03 Jan. 10, ABB Switzerland Ltd., Online: www.abb.com.

[11] L. Clotea and A. Porcos, “Power losses evaluation of two and three–level NPC inverters considering drive applications,” in *Proc. OPTIM*, pp. 929–934, 2012.
[12] K. Ma and F. Blaabjerg, "Thermal optimized modulation methods of three-level neutral-point-clamped inverter for 10MW wind turbines under low-voltage ride through," *IET Power Electronics*, Vol. 5, No. 6, pp. 920–927, 2011.

[13] ABB Application Note: ‘Applying IGBTs’, May 2007.

[14] H. Wang, A. M. Khambadkone, and X. Yu, "Control of parallel connected power converters for low voltage microgrid – Part II: dynamic electrothermal modeling," *IEEE Trans. on Power Electronics*, Vol. 25, No. 12, pp. 3071–2080, Dec. 2010.

[15] J. Dai, D.D. Xu, B. Wu, "A novel control scheme for current-source-converter-based PMSG wind energy conversion systems," *IEEE Trans. on Power Electronics*, Vol. 24, No. 4, pp. 963–972, Apr. 2009.

[16] ABB Switzerland Ltd, http://www.abb.com

[17] GE U.S.A. Ltd, http://www.gepowerconversion.com

[18] Rockwell Automation U.S.A Ltd, http://www.rockwellautomation.com

**Tahyun Kang** was born in Gunsan, Korea, in 1982. He received his B.S. in Electrical Engineering from Chonbuk National University, Jeonju, Korea, in 2013, where he is currently working toward his M.S. in Electrical Engineering. His current research interests include the power conversion system of high power for renewable energy sources and medium electric drive system.

**Taewon Kang** received the B.Sc. and M.Sc. degrees in electrical engineering from Chonbuk National University, Jeonju, Korea, in 2010 and 2013, respectively. Currently, he is working toward the Ph.D. degree in Chonbuk National University. His research interests include PEBB, DC-DC converter, EV and traction charging system.

**Beomseok Chae** was born in Korea, in 1985. He received his B.S. in Electrical Engineering from Chonbuk National University, Jeonju, Korea, in 2013, where he is currently working toward his M.S. in Electrical Engineering. His current research interests include the EV charger systems and power conversion system topologies.

**Kihyun Lee** was born in the Republic of Korea, in 1982. He received his B.S. degree in Electronic Engineering from Chonbuk National University, Jeonju, Korea, in 2008, where he is presently working towards his M.S. degree in Electrical Engineering. From 2008 to 2012, he was a Research Engineer in the High Power

Discrete Division of KODENSHI AUK Co., Korea. His current research interests include high power conversion systems for renewable energy sources and medium electric drive systems.

**Yongsug Suh** was born in Seoul, Korea. He received his B.S. and M.S. in Electrical Engineering from Yonsei University, Seoul, Korea, in 1991 and 1993, respectively, and his Ph.D. in Electrical Engineering from the University of Wisconsin, Madison, WI, USA, in 2004. From 1993 to 1998, he was an Application Engineer in the Power Semiconductor Division of Samsung Electronics Co. From 2004 to 2008, he was a Senior Engineer in the Power Electronics and Medium Voltage Drives Division of ABB, Turgi, Switzerland. Since 2008, he has been with the Department of Electrical Engineering, Chonbuk National University, Jeonju, Korea, where he is currently an Associate Professor. His current research interests include the power conversion systems of high power for renewable energy sources and medium voltage electric drive systems.