Magnetic Design of Flyback Type Snubber for IGCT Applications

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ABSTRACT

Abstract– 10kV IGCT has been recently developed and has the potential to push wind turbine systems to higher power and voltage rating. Converters employing IGCTs need snubber and OVP circuit to limit the rate of current's rising and peak over voltage across IGCT during turn on and off state, respectively. The conventional RCD snubber which is used in such power converter dissipates a significant amount of power. In order to reduce the amount of energy lost by conventional RCD snubber, this paper proposes flyback type snubber comprising two coils wound on a magnetic core. The flyback snubber not only meets all of the IGCTs characteristics during on and off-state but also significantly saves the power loss. Modern magnetic model using permeance-capacitance analogy leads to more accurate loss analysis of flyback type di/dt snubber circuit in 3-level NPC type back-to-back VSC. In turns, the comparison between conventional and flyback type snubber yield the effectiveness of proposed snubber in wind turbine systems.

1. INTRODUCTION

During the recent years, the installed wind power capacity has increased significantly, and an interesting area for further development is offshore wind farms. The back-to-back connected power electronic converters in medium-voltage (MV) level 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 [1]. As the most commercialized ML converter, PMSG (Permanent Magnet Synchronous Generator) wind turbine system with a back-to-back 3L-NPC VSC is presented in Fig. 1 [2], [3].

Power semiconductors have experienced a rapid technical improvement toward higher blocking voltages and current ratings, more reliable packages, and extended safe operating areas (SOAs) [4]. Recently, the integration of newly developed 10kV IGCT and diode (Fig. 2) is a very attractive solution for 3L-NPC VSCs since the expense for the mechanical construction and cooling can be substantially reduced.

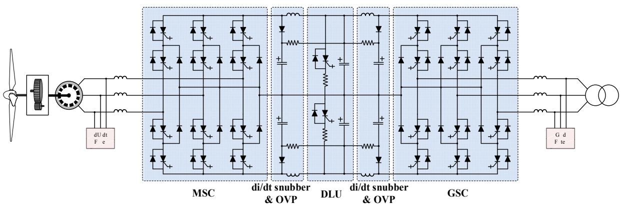


Fig. 1. 3L-NPC back-to-back configuration for multi-MW PMSG MV wind turbines

Fig. 2. Press-pack type IGCT (left) and Diode (right) for MV wind turbines

This medium voltage drive employing 10kV IGCTs needs a di/dt limiting inductor to meet the required di/dt characteristics during switching on transients. Consequently, this di/dt limiting inductor usually necessitates an additional over voltage protection (OVP) snubber or clamp circuitry as shown in Fig. 1. This snubber circuitry imposes certain power loss on 3L-NPC VSCs. There have been several kinds of active RCD snubber for GTO device trying to meet both wide Safe Operating Area (SOA) and low loss [5]-[8]. However those snubber circuitries add device count and circuit complexity.

In this paper a new flyback-type di/dt snubber circuit which is simpler and more efficient than conventional RCD snubber for 10kV IGCT in MV wind turbines is proposed. This flyback-type di/dt snubber adopts a flyback type transformer. In addition to effectiveness in restricting the di/dt characteristics, this flyback-type di/dt snubber circuit reduces the power loss caused by OVP circuit.

2. CONVENTIONAL SNUBBER CIRCUIT FOR IGCT

It is shown that the use of 10kV IGCTs enables a reduction of the total number of the main power components by 41 - 71% compared to a series connection of 4.5kV or 5.5kV IGCT devices. Major operating characteristics of 10kV IGCT and diode are summarized in Table 1.

Table 1. Characteristics of 10kV Press-pack type IGCT and Diode for 7MW MV 3L-NPC VSCs

DEVICE	BLOCKING VOLTAGE	I_{TGQM} / $I_{F(AV)M}$	V_{TO} (Max.)	R_T (Max.)	E_{on} (Max.)	E_{off} (Max.)	Meas. condition	T_{vj_max}	$R_{th(j-c)}$	$R_{th(c-h)}$	$R_{th(h-a)}$
IGCT	10 kV	2000A	2.7V	1.2mΩ	3.4J	34 J	6kV/2000A	125℃	8.5K/kW	3K/kW	6K/kW
DIODE	10 kV	1700A	2.7V	2.7mΩ	-	17.6 J	6kV/1700A	125℃	6K/kW	3K/kW	6K/kW

Converters employing IGCTs need a di/dt limiting inductance to meet the required di/dt characteristics during switching on transients. The di/dt limiting inductor (Li) stores magnetic energy when the IGCT is conducting and this energy needs to be dissipated somewhere, otherwise it will oscillate between C_{Cl} and Li. Therefore, a clamp resistor (R_{Cl}) is also required to dissipate this energy. The clamp diode (D_{Cl}) prohibits the snubber capacitor (C_{Cl}) from discharging through IGCT. The inclusion of the clamp circuit increases the component count per building block, which is considered to be one of the disadvantages of using IGCT.

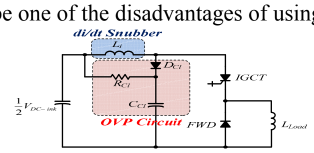


Fig. 3. di/dt snubber and OVP clamp circuit for IGCT in the upper-half part of 3L-NPC VSCs

At the instant of switching off, the stored magnetic energy from the on-state current of the IGCT is given by;

$$E_{L_i} = \frac{1}{2} L_i \cdot i(t)^2 \tag{1}$$

This stored energy is mainly dissipated in the snubber resistor (R_{Cl}) or fed back to charge the dc link capacitor ($C_{DC\text{-}link}$). In this paper, the total stored energy in the di/dt limiting inductor is assumed to be snubber circuit power loss. Therefore, snubber circuit power loss (P_{Cl}) can be expressed as;

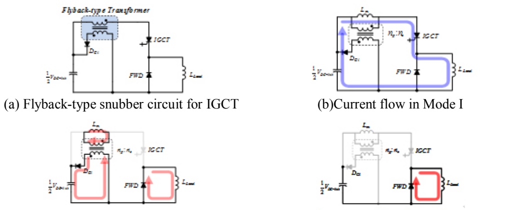
$$P_{cl} = \left(\sum_{k=1}^{n} E_{L_i} \right) \times f_{sw} = \left\{ \frac{1}{2} L_i \sum_{k=1}^{n} i_k(t)^2 \right\} \times f_{sw} \tag{2}$$

3. FLYBACK-TYPE SNUBBER CIRCUIT FOR IGCT

The proposed flyback-type di/dt snubber configuration is shown in Fig. 4(a). Single-phase leg circuit in the upper-half part of 3-level NPC converter is considered for the sake of simple analysis.

Figure 4(b)-4(d) illustrate the current flow path for each operating mode of flyback-type di/dt snubber circuit. There are three operating modes during one switching period of single IGCT in Fig. 4.

The voltage at the primary side of flyback-type transformer is obtained as;



(a) Flyback-type snubber circuit for IGCT (b)Current flow in Mode I

(c) Current flow in Mode II (d) Current flow in Mode III

Fig. 4. Flyback-type snubber circuit for IGCT in the upper-half part of 3L-NPC VSCs

$$V_{flyback\ TR} = \frac{n_p \times \frac{1}{2} V_{DC-link}}{n_s} \quad (3)$$

The peak voltage across IGCT becomes as the following.

$$V_{IGCT} = \frac{V_{DC-link}(n_p + n_s)}{2n_s} \quad (4)$$

4. Magnetic Modeling of Flyback Transformer

The permeance-capacitance analogy implemented in PLECS tool provides a powerful modeling domain for magnetic circuits. The structure of the magnetic circuit can be derived easily from the core geometry. The non-linear characteristic of the core material can be modeled using the variable permeance component [9]. Figure 5 shows the magnetic model of flyback type snubber for 10KV IGCT using PLECS magnetic simulation tool.

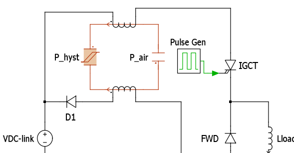


Fig. 5. PLECS magnetic model of FTS

Table 2. Magnetic Specification

Parameter	Value
Cross sec area	1e-2(m^2)
Length of flux path	0 99(m)
Coercitive field strength H_C	50(A/m)
Remanence flux density B_r	0 51(T)
Sat field strength H_{sat}	900(A/m)
Sat flux density B_{sat}	1 2(T)
Sat rel permeability $\mu_{r\ sat}$	10
Air gap distance	1mm

Table 2 shows all designing parameters from a flyback transformer manufacturer. Among all of the losses related to magnetic components, hysteresis loss is more dominant. According to the simulation result, the hysteresis loss is 1.5kW for the flyback transformer. Adding the eddy current and copper loss might increase the overall loss slightly. The super core silicon steel material like JNHF core is ideal for producing the minimum amount of magnetic loss.

5. Simulation Results of Snubber Circuit for 10kV IGCT

The operation of proposed flyback-type di/dt snubber circuit is verified through the simulation using PLECS tool. Detailed simulation condition for the proposed circuit in Fig. 4(a) is summarized in Table 3.

Table 3. Simulation Parameters of Flyback-type di/dt Snubber Circuit

Parameter	Symbol	Value
DC-link voltage	$V_{DC-link}$	11 2 kV
Switching frequency	$f_{GSC\ PWM}$	1020 Hz
Magnetizing inductance	L_m	13 6 uH
Turn ratio (Primary winding/ Secondary winding)	n (=n_p/n_s)	1/8

The waveforms of voltage and current of IGCT during the IGCT's switching transient process are shown in Fig. 6. The voltage overshoot peak (V_{DSP}) of IGCT can be adjusted by selecting the proper turn ratio of flyback-type transformer. The waveforms of voltage and current of clamp diode during switching transients are also given in Fig. 7.

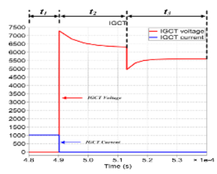


Fig. 6. Voltage and current waveforms of IGCT during each operating mode

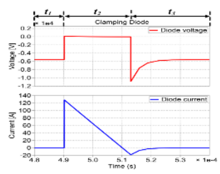


Fig. 7. Voltage and current waveforms of clamp diode during each operating mode

In this paper, the loss analysis is performed to compare the loss factors due to the proposed and conventional snubber circuits, respectively. The simulation is performed based on the parameters of 7MW MV 3L-NPC VSCs as specified in Table 4.

Table 4. System Specifications of 7MW MV 3L-NPC VSCs

Parameter	Symbol	Value	Per unit
Output power	$P_{rated-out}$	7 MW	1 0
Grid frequency	f_{grid}	60 Hz	1 0
Grid side inductance	L_{grid}	2 5 mH	0 17
Grid side input voltage	V_{ll}	6 9 kV	1 0
Grid side input current	$I_{AC\ input}$	854 A	1 0
Switching frequency	$f_{GSC\ PWM}$	1020 Hz	-
DC-link voltage	$V_{DC-link}$	11 2 kV	-
AC filter inductance	L_f	2 3 mH	0 16
AC filter capacitance	C_f	0 22 mF	0 45
di/dt limiting inductance	L_i	13 6 μH	-

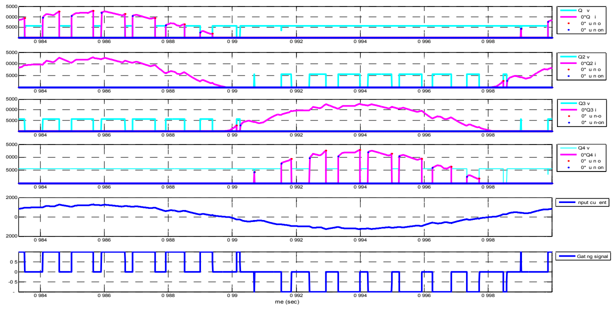


Fig. 8. Waveforms of switching and current in each phase-leg of 10kV IGCTs (pf=0 9)

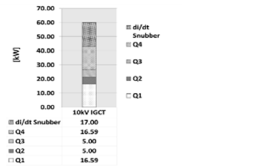


Fig. 9. Total loss distribution in 10kV IGCTs of 7MW MV 3L-NPC VSCs (three legs)

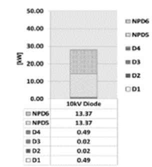


Fig. 10. Total loss distribution in 10kV diodes of 7MW MV 3L-NPC VSCs (three legs)

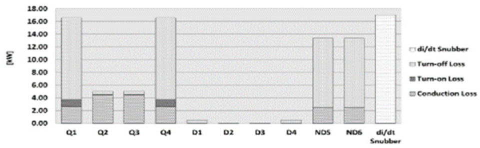


Fig. 11. Total loss distribution of each power semiconductor device (pf=0 9 leading, three legs)

6. Conclusion

In this paper flyback-type di/dt snubber circuit for 7MW PMSG wind turbine employing a 3L-NPC back-to-back voltage source converter is presented. As compared to the conventional snubber circuitry for IGCT-based converters, the proposed flyback-type di/dt snubber circuit using flyback-type transformer has such good features as a fewer number of snubber component and improved efficiency. The 10kV IGCT for the line voltage classes of 6 - 7.2kV MV 3L-NPC VSCs is investigated and basic operation of the flyback-type di/dt snubber circuit is discussed. The switching frequency is set to 1020Hz under the grid side input voltage of 6.9kV. Modern magnetic model using permeance-capacitance analogy leads to more accurate loss analysis of flyback type di/dt snubber circuit in 3-level NPC type back-to-back VSC. The proposed flyback-type di/dt snubber can save the loss (34kW, 0.49%) of conventional snubber circuit in 7MW back-to-back 3L-NPC VSCs at most without considering the core losses newly incurred by the flyback-type di/dt snubber.

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References

[1] B. Wu, High-Power Converters and AC Drives, Piscataway, NJ, IEEE Press, 2006, ISBN 978-0-471-731-9.

[2] A. Nabae, I. Takahashi, and H. Akagi, "A new neutral point clamped PWM inverter," IEEE Trans. Ind. Applicat., vol. IA–17, pp. 518-523, Sept./Oct. 1981.

[3] Information about ACS1000 medium voltage drive product at http //www.abb.com/motor&drives.

[4] F. Filsecker, R. Alvarez, and S. Bernet, "Comparison of 4.5-kV press-pack IGBTs and IGCTs for medium-voltage converters," IEEE Trans. Ind. Electron., vol. 60, no. 2, pp. 440-449, Feb. 2013.

[5] A. Nagel, S. Bernet, T. Brückner, P.K. Steimer, and O. Apeldoorn, "Characterization of IGCTs for series connected operation," in Conf. Rec. IEEE-IAS Annu.

[6] L. Q. Yuan, Z. M. Zhao, and Y. H. Li, "The optimization of snubbers for IGCT-based voltage source inverters," in Proc. 29th Annual. Conf. IEEE IECON, 2003, pp. 679-682.

[7] C. G. Steyn, "Analysis and optimization of regenerative linear snubber," IEEE Trans. Power Electron., vol. 4, no. 3, pp. 362-370, Jul. 1989.

[8] A. Zuckerberger, E. Suter, C. Schaub, A. Klett, and P. Steimer, "Design, simulation and realization of high power NPC converters equipped with IGCTs," in Proc. 33rd IAS Annual Meeting, vol. 2, pp.865-872, 1998.

[9] J. Allmeling, W. Hammer, and J. Schonberger, "Transient Simulation of Magnetic Circuits Using the Permeance-Capacitance Analogy," in Proc. IEEE 13th Workshop on COMPEL, 2012, pp.1-6.