

# Tolerance Control for the Inner Open-Switch Faults of a T-Type Three-Level Rectifier

June-Seok Lee\* and Kyo-Beum Lee†

\*†Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea

## Abstract

The T-type topology is a three-level topology that has an advantage in terms of its number of switching device and its efficiency when compared to the neutral-point clamped (NPC)-type topology. With the recent increase in the usage of the T-type topology, the interest in its reliability has also increased. Therefore, a tolerance control for a T-type rectifier is necessary to improve the reliability of applications when an open-switch fault occurs. NPC-type rectifiers cannot eliminate input current distortion completely. However, the T-type rectifier is able to restore distorted current. In this paper, a tolerance control for the  $S_{x2}$  and  $S_{x3}$  open-switch faults of a T-type rectifier is proposed where it is advantageous in terms of efficiency when compared with other tolerance controls. The performance of the proposed tolerance control is verified through simulation and experimental results.

**Key words:** Open-switch fault, Reliability, T-type rectifier, T-type topology, Tolerance control

## I. INTRODUCTION

Multi-level topologies have outstanding performance in terms of total harmonic distortion (THD) and efficiency [7]-[9]. Three-level topologies have been used in applications of wide-power range [1]-[6].

There are two types of three-level rectifier topologies. In the neutral-point clamped (NPC)-type, four switches are connected in series and two clamping diodes are connected to the neutral point. Therefore, the NPC-type rectifier can reduce the switching device's collector-emitter voltage ( $V_{CE}$ ) in half. The other type of topology is the T-type rectifier as shown in Fig. 1. Although the switches used in the T-type rectifier have a  $V_{CE}$  which is the same as that of the conventional two-level rectifier, the T-type rectifier has lower conduction and switching losses, and it does not need clamping diodes when compared to the NPC-type rectifier [7].

Research on improvements in the reliability of systems using multi-level topologies has become an important issue. Therefore, systems using switching devices need to diagnose switching device faults and to maintain their operation by

tolerance controls. Diagnosis methods for detecting the open-switch faults of NPC-type inverters and rectifiers are proposed in [8]-[11]. To detect open-switch faults, additional devices such as voltage sensors or current patterns are used.

In [12], an imperfect tolerance control for an NPC-type rectifier is proposed without additional devices. This tolerance control considers inner open-switch faults ( $S_{x2}$  and  $S_{x3}$ ) but not outer open-switch faults ( $S_{x1}$  and  $S_{x4}$ ) because the outer switches do not have an effect on rectifier operation with unity power factor [13]. These tolerance controls do not completely eliminate current distortion because of structural limitations of the NPC-type topology. In [14], there are two tolerance controls, which do not require additional devices, for the inner open-switch faults ( $S_{x2}$  and  $S_{x3}$ ) of an T-type rectifier with a high modulation index. These two methods are the replacement two-level switching (R2LS) and the maintenance three-level switching (M3LS) tolerance controls. These controls use a two-level switching method to completely restore distorted currents. They have opposite characteristic in terms of the current THD and the dc-link voltage ripple. The R2LS tolerance control maintains the two-level switching method in four of the six sectors. Therefore, the current THD in this control is higher than that of M3LS tolerance control. However, the M3LS tolerance control, which considers the neutral-point balance, has a larger dc-link voltage ripple than the R2LS tolerance control.

Manuscript received May 6, 2014; accepted Oct. 4, 2014

Recommended for publication by Associate Editor Dong-Wook Yoo.

†Corresponding Author: kyl@ajou.ac.kr

Tel: +82-31-219-2487, Fax: +82-212-9531, Ajou University

\*Dept. of Electrical and Computer Eng., Ajou University, Korea



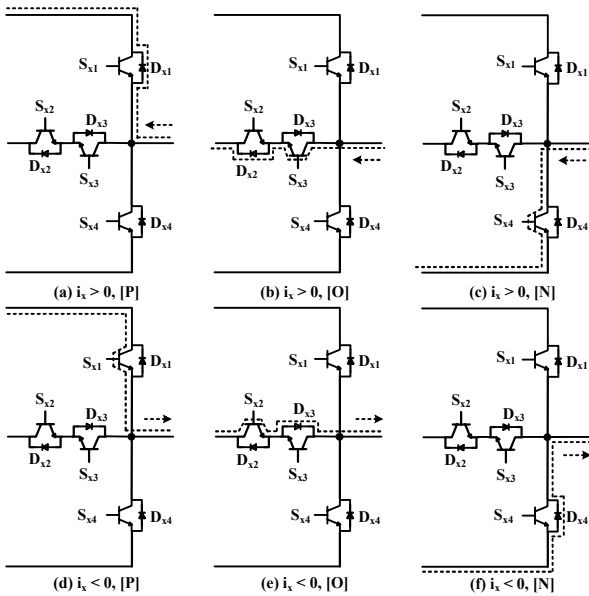
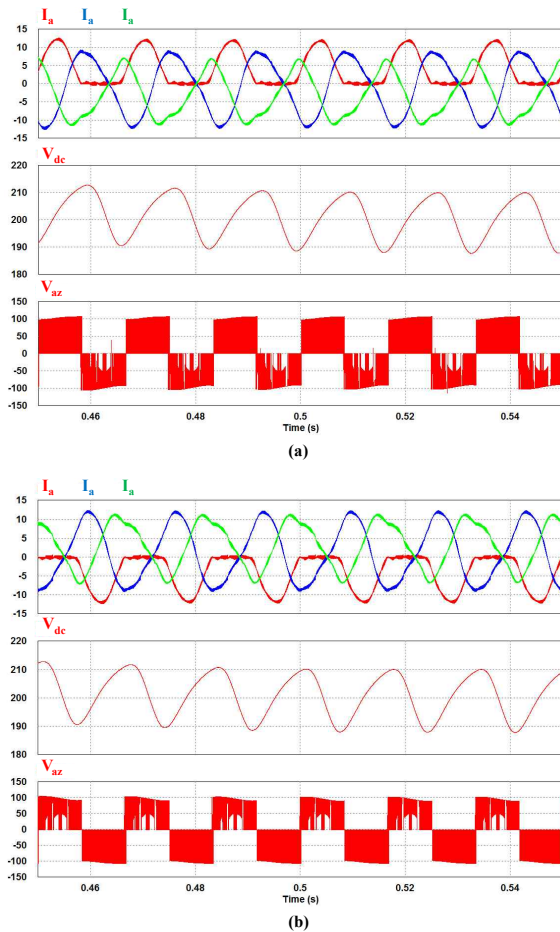


Fig. 3. Current paths depending on operating state and current.

Fig. 4. Rectifier waveforms: (a)  $S_{a2}$ . (b)  $S_{a3}$  open-switch fault.

fatal effect on the a-phase input current. In the negative part of the a-phase current, as shown in Fig. 4(a), the valid operating state “O”, shown in Fig. 3(e), becomes infeasible.

Therefore, the negative part of the a-phase current cannot be generated and the dc-link voltage has ripple. Like an  $S_{a2}$  open-switch fault, an  $S_{a3}$  open-switch fault has a fatal effect on the positive part of the a-phase current.

### III. PROPOSED TOLERANCE CONTROL FOR THE INNER OPEN-SWITCH FAULTS OF T-TYPE RECTIFIERS

The proposed tolerance control does not use the “O” operating vectors of a phase which contains an open-switch fault. Furthermore, in the proposed tolerance control, the two-level switching method is applied for a phase containing an open-switch fault and two pole voltages ( $V_{bz}$  and  $V_{cz}$ ) are maintained to three levels ( $V_{dc}/0$ ,  $0$ ,  $-V_{dc}/2$ ) at a high modulation index. As a result, the proposed tolerance control is advantageous in terms of efficiency when compared with the other tolerance controls using the two-level switching method. In this section, an  $S_{a2}$  open-switch fault is considered as the fault case. The proposed tolerance control is developed based on the nearest space-vector PWM (SVM) method. Fig. 5 shows the infeasible vectors when an  $S_{a2}$  open-switch fault occurs.

#### A. Tolerance Operation at a High Modulation Index

An  $S_{a2}$  open-switch fault leads two medium-vectors (OPN, ONP), five small-vectors (OPO, OPP, OOP, OON, ONO) and one zero-vector (OOO) being infeasible when the a-phase current is negative. At a high modulation index, which is shown in the white part of Fig. 5, the OPN, ONP, OPO, OPP, OOP, OON, and ONO vectors should be changed to other feasible vectors during negative current.

In sectors III and IV, the infeasible P-type small-vectors OPO, OPP, and OOP are changed to the N-type small vectors NON, NOO, and NNO. The increased use of N-type small vectors in sectors III and IV can cause a neutral-point unbalance. Therefore, in sectors I and VI, the N-type small-vectors OON, ONN, and ONO are changed to the P-type small-vectors PPO, POO, and POP. When an  $S_{a2}$  open-switch fault occurs, the changing vector methods in sectors I, III, IV, and VI are the same as those of the M3LS tolerance control in [14]. The M3LS tolerance control uses two-level switching in sectors II and V. However, the two-level switching increases the switching loss of the three-phase switches.

Sector II is divided into four parts as shown in Fig. 5. In sector II-A, there are infeasible OPN and OPO vectors. The OPN vector can be changed to NPN and PPN vectors, and the PPO vector can be also changed to a PPO vector as shown in Fig. 6. As a result, the NPN, PPN, and PPO vectors retain the b- and c- phase pole voltages  $V_{bz}$  and  $V_{cz}$ . However, the a-phase pole voltage  $V_{az}$  has  $V_{dc}/2$  and  $-V_{dc}/2$  without 0. The changing vector is easily performed by recalculating the switching time of the newly selected NPN, PPN, and PPO



TABLE II  
PROPOSED TOLERANCE CONTROL AT HIGH MODULATION INDEX:  
S<sub>A2</sub> OPEN-SWITCH FAULT

Sector	Tolerance principle
I	OON→PPO, ONN→POO
II	Using NON, PPO, NPN and PPN -A, -B → $T_{a,on,TC} = T_{a,on} / 2$ -C, -D → $T_{a,on,TC} = (T_{a,on} + T_s) / 2$
III	OPO→NON, OPP→NOO
IV	OPP→NOO, OOP→NNO
V	Using NNO, POP, NNP and PNP -A, -B → $T_{a,on,TC} = T_{a,on} / 2$ -C, -D → $T_{a,on,TC} = (T_{a,on} + T_s) / 2$
VI	ONN→POO, ONO→POP

$$T_{a,on,TC} = \frac{1}{2}(T_{a,on} + T_s). \quad (4)$$

Likewise, in sector V, equations (2) and (4) are applied according to parts of sector V.

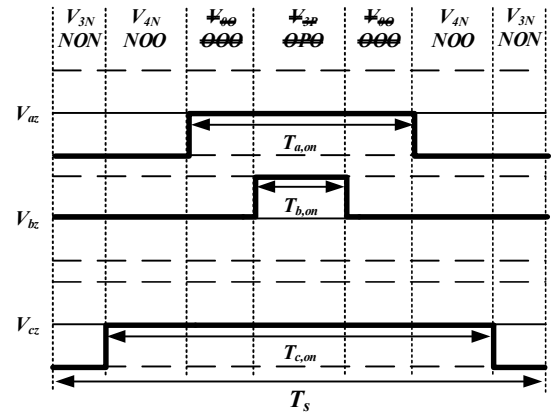
Consequently, the proposed tolerance control always keeps  $V_{bz}$  and  $V_{cz}$  as three levels and it makes the level of  $V_{az}$ , which contains the faulty switch, two in sectors II and V when an S<sub>A2</sub> open-switch fault occurs. The whole principle of the tolerance control method at a high modulation index is shown in Table II.

### B. Tolerance Operation at a Low Modulation Index

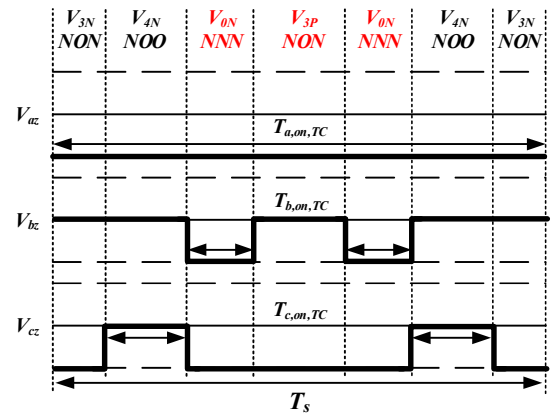
Like the method mentioned in section III-A, the proposed tolerance control at a low modulation index, which is shown in the blue part of Fig. 5, changes the infeasible vectors to other vectors. This principle is also different depending on the sectors.

In sectors III and IV, the infeasible P-type small-vectors OPO, OPP, and OOP are changed to the N-type small-vectors NON, NOO, and NNO. Moreover, the zero-vector OOO cannot be used. Therefore, it should be substituted with PPP and NNN.

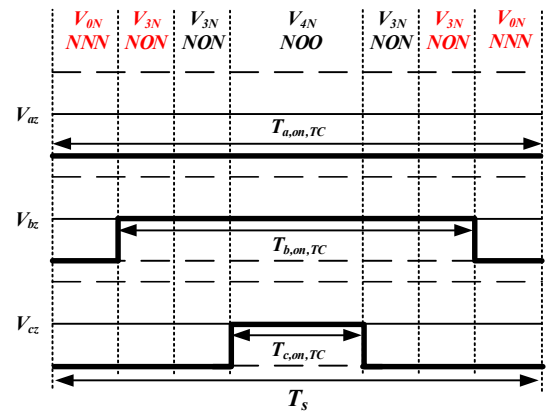
Fig. 9(a) shows the switching sequence in sector III-1 when the rectifier operates normally without any faults. This switching sequence consists of the NON, NOO, OOO and OPO vectors. The OPO and OOO vectors are infeasible. The P-type small-vector OPO can be replaced with NON, and the OOO zero-vector can be replaced with the NNN zero-vector as shown in Fig. 9(b). The switching sequence in Fig. 9(b) causes switching to occur two times in the b- and c- phases. Therefore, the switching sequence should be changed to NNN-NON-NOO-NON-NNN, as shown in Fig. 10, if the SVM method is used. Its switching sequence can be performed by adding the offset value as shown in Fig. 9(c). This is expressed as:



(a) Normal switching



(b) Vector change



(c) Tolerance switching

Fig. 9. Tolerance control in sector III-1.

$$\begin{aligned} T_{a,on,TC} &= T_{a,on} + (-T_{a,on}) \\ T_{b,on,TC} &= T_{b,on} + (T_s - T_{a,on}) \\ T_{c,on,TC} &= T_{c,on} + (-T_{a,on}) \end{aligned} \quad (5)$$

The positive voltage  $V_{bz}$  in Fig. 9(a), is changed to a negative voltage as shown in Fig. 9(c).  $V_{az}$  and  $V_{cz}$  are maintained as negative voltages. Consequently, when the sign of  $V_{xz}$  is changed,  $-T_{a,on}$  is added to  $T_{x,on}$  for  $V_{xz}$ .  $T_s - T_{a,on}$  is added to  $T_{x,on}$  for  $V_{xz}$  when the sign of  $V_{xz}$  is not changed. This method is applied in sectors III and IV.

TABLE III  
PROPOSED TOLERANCE CONTROL AT LOW MODULATION INDEX:  
S<sub>A2</sub> OPEN-SWITCH FAULT

Sector	Tolerance principle
	OON→PPO, ONN→POO, OOO→PPP
I	-1→ $T_{a,on,TC} = T_{a,on} + (T_s - T_{a,on})$ $T_{b,c,on,TC} = T_{b,c,on} + (-T_{a,on})$
	-2→ $T_{a,b,on,TC} = T_{a,b,on} + (T_s - T_{a,on})$ $T_{c,on,TC} = T_{c,on} + (-T_{a,on})$
II	Two-level switching method
	OPO→NON, OPP→NOO, OOO→NNN
III	-1→ $T_{a,c,on,TC} = T_{a,c,on} + (-T_{a,on})$ $T_{b,on,TC} = T_{b,on} + (T_s - T_{a,on})$
	-2→ $T_{a,on,TC} = T_{a,on} + (-T_{a,on})$ $T_{b,c,on,TC} = T_{b,c,on} + (T_s - T_{a,on})$
	OPP→NOO, OOP→NNO, OOO→NNN
IV	-1→ $T_{a,on,TC} = T_{a,on} + (-T_{a,on})$ $T_{b,c,on,TC} = T_{b,c,on} + (T_s - T_{a,on})$
	-2→ $T_{a,b,on,TC} = T_{a,b,on} + (-T_{a,on})$ $T_{c,on,TC} = T_{c,on} + (T_s - T_{a,on})$
V	Two-level switching method
	ONN→POO, ONO→POP, OOO→PPP
VI	-1→ $T_{a,c,on,TC} = T_{a,c,on} + (T_s - T_{a,on})$ $T_{b,on,TC} = T_{b,on} + (-T_{a,on})$
	-2→ $T_{a,on,TC} = T_{a,on} + (T_s - T_{a,on})$ $T_{b,c,on,TC} = T_{b,c,on} + (-T_{a,on})$

For neutral-point balancing control, the N-type small vectors are changed to P-type small-vectors and the zero-vector OOO is changed to the zero-vector PPP in sectors I and VI. In sectors I and V, the two-level switching method is used. The whole principle of the tolerance control method at a low modulation index is shown Table III.

#### IV. SIMULATION RESULTS

Simulations were performed using PSIM. The simulation circuit is the same as the one shown in Fig. 1. The simulation parameters are shown in Table IV.

Fig. 10 shows the three-phase currents, dc-link voltage, and line-to-line voltage of the rectifier when the proposed tolerance control is applied at a high modulation index ( $V_{\text{line-to-line}}$  is 126 V<sub>rms</sub> and the load is 33 Ω). Due to an inner open-switch fault, the current containing an open-switch fault becomes zero for a half period and the dc-link voltage has a large ripple. After 0.6 s, which means that the proposed tolerance control is applied, the three-phase currents are

TABLE IV  
SIMULATION AND EXPERIMENT PARAMETERS

Parameters	Value	Parameters	Value
V <sub>line-to-line,rms</sub>	126 / 63 V <sub>rms</sub>	dc-link voltage	200 V
Grid frequency	60 Hz	dc-link capacitor	1100 uF
L-filter	1.5 mH	Load	33 / 67 Ω

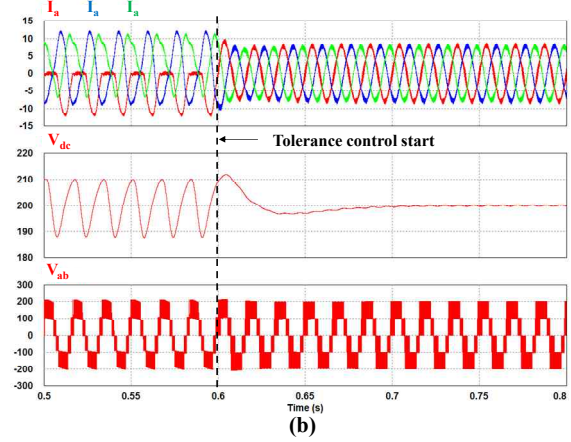
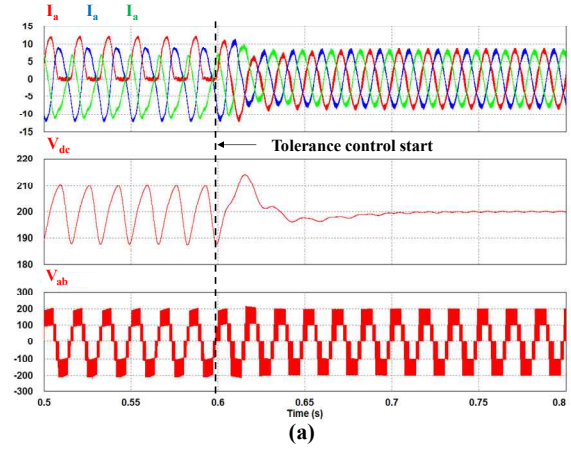


Fig. 10. Performance of tolerance control at high modulation index. (a) S<sub>A2</sub> open-switch fault. (b) S<sub>A3</sub> open-switch fault.

restarted as a sinusoidal waveform and the dc-link voltage ripple is eliminated. Additionally, the line-to-line voltage ( $V_{ab}$ ) between the a- and b- inputs of the proposed tolerance control is different from that of the conventional SVM method [15].

Fig. 11 shows the three-phase pole voltages and currents of the proposed tolerance control at a high modulation index.  $V_{bz}$  and  $V_{cz}$  maintain three levels. However,  $V_{az}$  has only  $V_{dc}/2$  in sectors I and VI or  $-V_{dc}/2$  in sectors III and IV. This is the same as that of the two-level switching method in sectors II and V. Therefore, the a-phase current ripple increases in sectors II and V due to the high dV/dt of the two-level

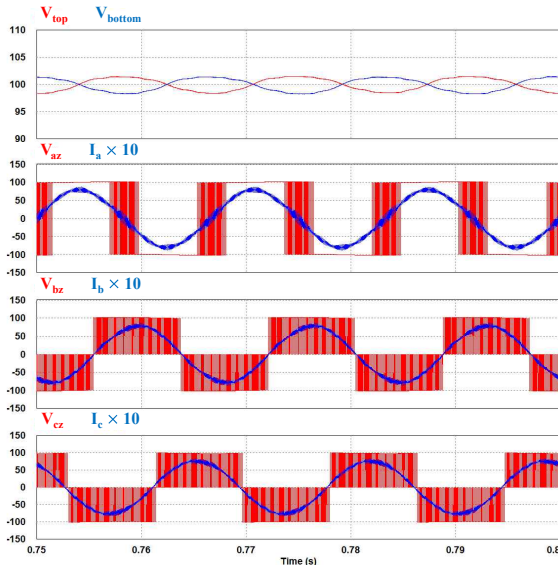


Fig. 11. The neutral-point and three-phase pole voltages of the proposed tolerance control at high modulation index.

switching method. The proposed tolerance control only uses P-type small vectors for the two sectors and N-type small vectors for the other two sectors. Therefore, the neutral-point voltages ( $V_{top}$  and  $V_{bottom}$ ) have a low frequency ripple which is the same as the fundamental frequency of the input current as shown in Fig. 11.

Fig. 12 shows the three-phase currents, dc-link voltage, and line-to-line voltage of the rectifier when the proposed tolerance control is applied at a low modulation index ( $V_{line-to-line}$  is  $63 V_{rms}$  and the load is  $67 \Omega$ ). Similar the case of a high modulation index, the current containing an open-switch fault becomes zero for a half period and the dc-link voltage has a large ripple. After the tolerance control is applied, the three-phase currents are restarted as a sinusoidal waveform and the ripple of the dc-link voltage is eliminated. Additionally, the line-to-line voltage ( $V_{ab}$ ) between the a- and b- inputs of the rectifier has  $V_{dc}$  and 0 or  $-V_{dc}$  and 0 in sectors II and V when the two-level switching method is applied.

Fig. 13 shows the three-phase pole voltages and currents of the proposed tolerance control at a low modulation index. In sectors II and V, the three-phase pole voltages have  $V_{dc}/2$  or  $-V_{dc}/2$ . Therefore, the current ripple of the three-phase increases in sectors II and V due to a high  $dV/dt$ . The switching operation of the remaining sectors is the same as that in the case of a high modulation index. At a low modulation index, the neutral-point voltages has a low frequency ripple which is the same as the fundamental frequency of the input current

## V. EXPERIMENTAL RESULTS

Experiments are conducted to verify the validity of the proposed tolerance control. Fig. 14 shows the hardware setup

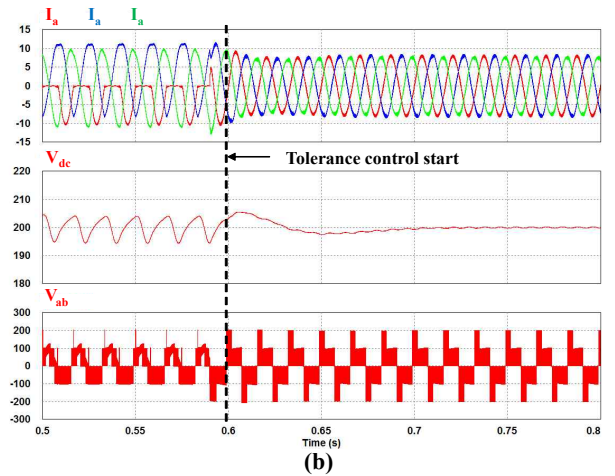
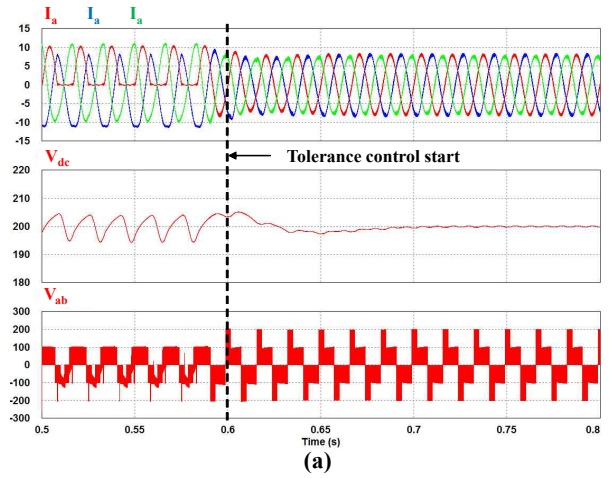


Fig. 12. Performance of tolerance control at low modulation index: (a)  $S_{a2}$  open-switch fault (b)  $S_{a3}$  open-switch fault.

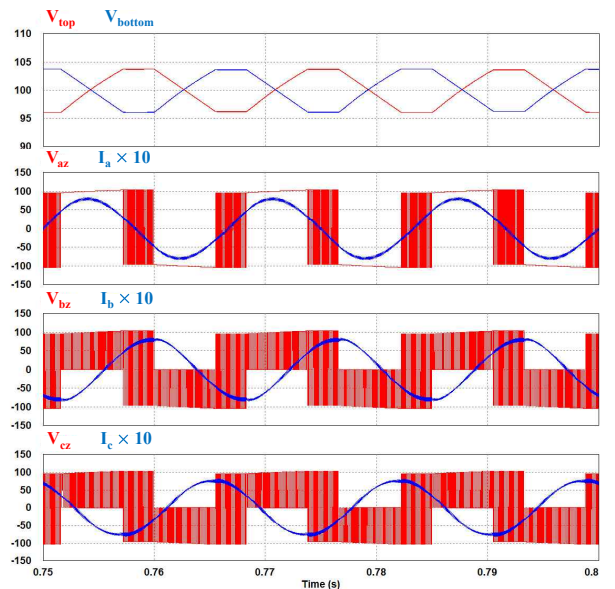


Fig. 13. Neutral-point and three-phase pole voltages of proposed tolerance control at low modulation index.

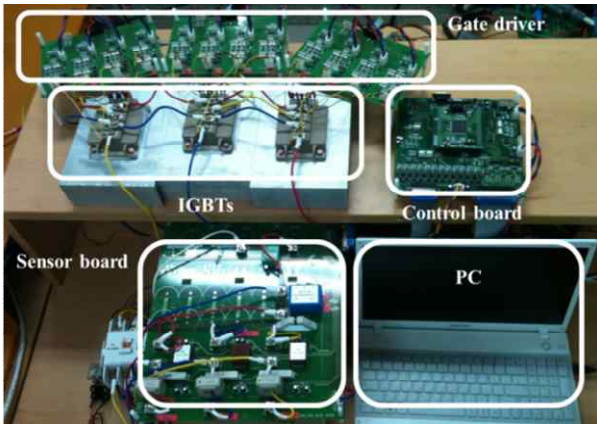


Fig. 14. Experiment setup of T-type rectifier.

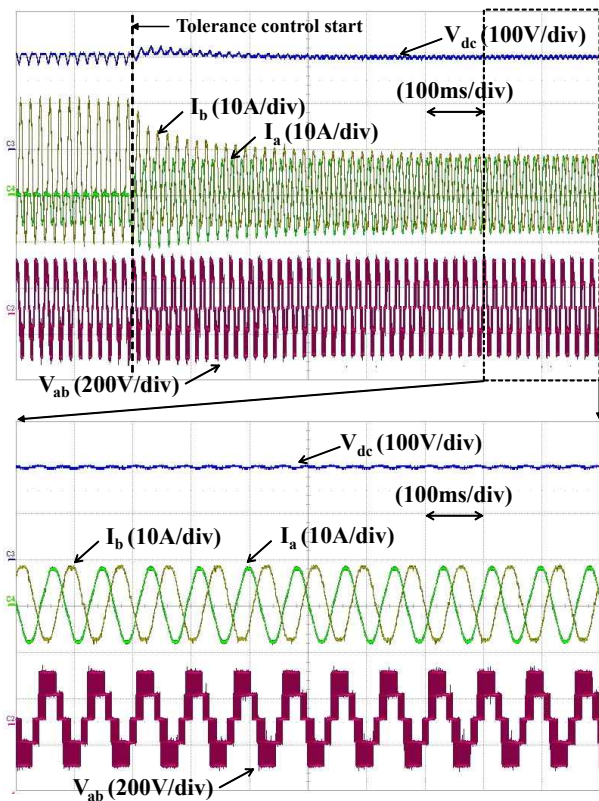


Fig. 15. Experimental results of tolerance control at high modulation index when  $S_{a2}$  open-switch fault occurs.

which consists of a control board, sensors, gate drivers, and T-type IGBT modules. This module is 4MBI300VG-120R-50 from Fuji. The parameters for the experiments are the same as those used in the simulations.

Fig. 15 shows the performance of the proposed tolerance control at a high modulation index ( $V_{\text{line-to-line}}$  is  $126 V_{\text{rms}}$  and the load is  $33 \Omega$ ) when an  $S_{a2}$  open-switch fault occurs. Due to the  $S_{a2}$  open-switch fault, the positive a-phase current ( $I_a$ ) becomes zero and the dc-link voltage has a large ripple. After the proposed tolerance control for a high modulation index is applied, the a- and b-phase currents ( $I_a$  and  $I_b$ ) are restored as the sinusoidal waveforms and the dc-link voltage ripple

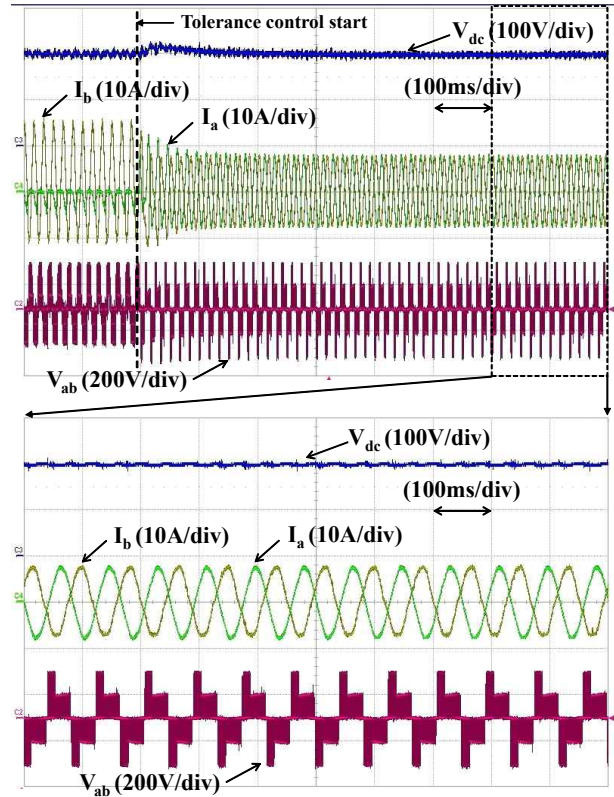


Fig. 16. Experimental results of tolerance control at low modulation index when  $S_{a2}$  open-switch fault occurs.

decreases as shown in Fig. 15. In the experimental results, the  $V_{ab}$  of the proposed tolerance control, which is different from the  $V_{ab}$  of the conventional SVM in two sectors, is the same as that in simulation.

Fig. 16 shows the experimental results of the proposed tolerance control for a low modulation index when an  $S_{a2}$  open-switch fault occurs. Like the results at a high modulation index, the current distortion is eliminated and the dc-link ripple decreases. The  $V_{ab}$  of the proposed tolerance control for a low modulation index has  $V_{dc}$  and  $-V_{dc}$  in spite of the low modulation index. This is the same result as the simulation.

## VI. CONCLUSION

This paper proposes a tolerance control based on the nearest SVM methods for the  $S_{x2}$  and  $S_{x3}$  open-switch faults of a T-type rectifier. The proposed tolerance control does not need additional devices and restores the distorted input currents caused by  $S_{x2}$  and  $S_{x3}$  open-switch faults. In addition, it guarantees the operation at the whole modulation index with inner open-switch faults. In comparison with the R2LS and M3LS tolerance controls, the switching loss is decreased at a high modulation index because only the input voltage of the phase containing an open-switch fault has two levels in two sectors. The performance of the proposed tolerance control is verified by the simulation and experimental results.



## ACKNOWLEDGMENT

This work was supported by the 20134030200310 of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea government Ministry of Knowledge Economy.

This work was supported by KETEP (G031462812) which is funded by MKE (Ministry of Knowledge Economy).

## REFERENCES

- [1] S. Alepuz, A. Calle, S. Busquets-Monge, S. Kouro, and B. Wu, "Use of stored energy in PMSG rotor inertia for low-voltage ride-through in back-to-back NPC converter-based wind power systems," *IEEE Trans Ind. Electron.*, Vol. 60, No. 5, pp. 1787-1796, May 2013.
- [2] R. C. Portillo, M. M. Prats, J. I. León, J. A. Sánchez, J. M. Carrasco, E. Galván, and L. G. Franquelo, "Modeling strategy for back-to-back three-level converter applied to high-power wind turbines," *IEEE Trans. Ind. Electron.*, Vol. 53, No. 5, pp.1483-1491, Oct. 2006.
- [3] Y. S. Park, S. K. Sul, and C. H. Lim, "Asymmetric control of DC-link voltages for separated MPPTs in three-level inverters," *IEEE Trans. Power Electron.*, Vol. 28, No. 6, pp.2760-2769, Jun. 2013.
- [4] J. S. Lee, and K. B. Lee, "New modulation techniques for a leakage current reduction and a neutral-point voltage balance in transformerless photovoltaic systems using a three-level inverter," *IEEE Trans. Power Electron.*, Vol. 29, No. 4, pp. 1720-1732, Apr. 2014.
- [5] J. D. Barros, J. F. A. Silva, and É. G. A. Jesus, "Fast-predictive optimal control of npc multilevel converters," *IEEE Trans. Ind. Electron.*, Vol. 60, No. 2, pp. 619-627, Feb. 2013.
- [6] U. M. Choi and K. B. Lee, "Neutral-point voltage balancing method for three-level inverter systems with a time-offset estimation scheme," *Journal of Power Electronics*, Vol. 13, No. 2, pp. 243-249, Mar. 2013.
- [7] M. Schweizer and J. W. Kolar, "Design and implementation of a highly efficient three-level T-type converter for low-voltage applications," *IEEE Trans. Power Electron.*, Vol. 28, No. 2, pp.899-907, Feb. 2013.
- [8] U. M. Choi, H. G. Jeong, K. B. Lee, and F. Blaabjerg, "Method for detecting an open-switch fault in a grid-connected NPC inverter system," *IEEE Trans. Power Electron.*, Vol. 27, No. 6, pp. 2726-2739, Jun. 2012.
- [9] H. K. Ku, W. S. Im, J. M. Kim, and Y. S. Suh, "Fault detection and tolerant control of 3-phase NPC active rectifier," in *Proc. ECCE*, pp. 4519-4524, 2012.
- [10] W. S. Im, J. S. Kim, J. M. Kim, D. C. Lee, and K. B. Lee, "Diagnosis methods for IGBT open switch fault applied to 3-phase AC/DC PWM converter," *Journal of Power Electronics*, Vol. 12, No. 1, pp. 120-127, Jan. 2012.
- [11] U. M. Choi, K. B. Lee, and F. Blaabjerg, "Diagnosis and tolerant strategy of an open-switch fault for T-type three-level inverter systems," *IEEE Trans. Ind. Appl.*, Vol. 50, No. 1, pp. 495-508, Jan./Feb. 2014.
- [12] J. S. Lee, K. B. Lee, and F. Blaabjerg "Open-switch fault detection method of an NPC converter for wind turbine systems," in *Proc. ECCE*, pp. 1696-1701, 2013.
- [13] K. A. Corzine and J. R. Baker, "Reduced-parts-count multilevel rectifiers," *IEEE Trans. Ind. Electron.*, Vol. 49, No. 4, pp. 766-774, Aug. 2002.
- [14] J. S. Lee and K. B. Lee, "An open-switch fault detection method and tolerance controls based on SVM in a grid-connected T-type rectifier with unity power factor," *IEEE Trans. Ind. Electron.*, Vol. 61, No. 12, pp. 7092-7014, Sep. 2014.
- [15] J. H. Seo, C. H. Choi, and D. S. Hyun, "A new simplified space-vector PWM method for three-level inverters," *IEEE Trans. Power Electron.*, Vol. 16, No.4, pp. 545-550, Jul. 2001.



**June-Seok Lee** received his B.S. and M.S. degrees in Electronic Engineering from Ajou University, Suwon, Korea, in 2011 and 2013, respectively, where he is currently working toward his Ph.D. degree. His current research interests include grid-connected systems, multilevel inverters and reliability.



**Kyo-Beum Lee** received his B.S. and M.S. degrees in Electrical and Electronic Engineering from Ajou University, Suwon, Korea, in 1997 and 1999, respectively. He received his Ph.D. degree in Electrical Engineering from Korea University, Seoul, Korea in 2003. From 2003 to 2006, he was with the Institute of Energy Technology, Aalborg University, Aalborg, Denmark. From 2006 to 2007, he was with the Division of Electronics and Information Engineering, Chonbuk National University, Jeonju, Korea. In 2007, he joined the Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea. His current research interests include electric machine drives, electric vehicles, and renewable power generation.