INTERNATIONAL JOURNAL OF RESEARCH
In Advanced Engineering Technologies

Volume 6, Issue 2 OCT 2017

DESIGN AND ANALYSIS OF WIND TURBINE SYSTEMS WITH OPEN-CIRCUIT FAULT-TOLERANT CONTROL FOR OUTER SWITCHES OF THREE-LEVEL RECTIFIERS

[1]POTHKANURI PRANAVI, [2]SINGAM SRIDHAR
[1]M.Tech, BALAJI INSTITUTE OF TECHNOLOGY & SCIENCE
[2]Assistant Professor, BALAJI INSTITUTE OF TECHNOLOGY & SCIENCE

ABSTRACT-A three-level converter is used as the power converters of wind turbine systems because of their advantages such as low-current total harmonic distortion, high efficiency, and low collector–emitter voltage. Interior permanent magnet synchronous generators (IPMSGs) have been chosen as the generator in wind turbine systems owing to their advantages of size and efficiency. In wind turbine systems consisting of the three-level converter and the IPMSG, fault-tolerant controls for an open-circuit fault of switches should be implemented to improve reliability. This paper focuses on the open-circuit fault of outer switches (Sx1andSx4) in three level rectifiers (both neutral-point clamped and T-type) that are connected to the IPMSG. In addition, the effects ofSx1 andSx4 open-circuit faults are analyzed, and based on this analysis, a tolerant control is proposed. The proposed tolerant control maintains normal operation with sinusoidal currents under the open-circuit fault of outer switches by adding a compensation value to the reference voltages. The effectiveness and performance of the proposed tolerant control are verified by simulation and experiment

I. INTRODUCTION

The power capacity of a wind turbine system has been increasing consistently, leading to the development of generators with large power capacity [1]–[3]. There are many types of generators. Permanent magnet synchronous generators (PMSGs) have high efficiency and high reliability compared with induction generators. This is because external excitation is not required and there are no copper losses in the rotor circuits. Moreover, because of the smaller size of the PMSG, the weight of the wind turbine is reduced [4].

Among various PMSGs, interior PMSGs (IPMSGs) are especially advantageous from the standpoints of efficiency and power generation owing to the use of the reluctance torque [4]–[7]. Generators requiring high voltage need to use multilevel converter topologies to reduce the collector–emitter voltage per switch. Among multilevel topologies, three-level topologies such as the three-level neutral-point clamped (3L-NPC) and T-type topologies are applied in wind turbine systems with a wide power range. The three-level topology can easily be expanded from a two-level topology and is also easier to control compared with other multilevel topologies.

Furthermore, the three-level topology guarantees high efficiency and low-current total harmonic distortion (THD) in comparison with the two level topology [8]–[11]. The 3L-NPC topology is vulnerable to switch faults because many switches are used. Switch fault detection and tolerant control methods for switch faults should be implemented to improve the reliability of wind turbine systems. Switch faults are divided into a short-circuit fault and an open-circuit fault [12]. The short-circuit fault normally leads to a breakdown of the entire system; therefore, fault detection and tolerant control methods for the short-circuit fault require additional circuits. A back-to back converter using the 3L-NPC topology is shown in Fig. 1.

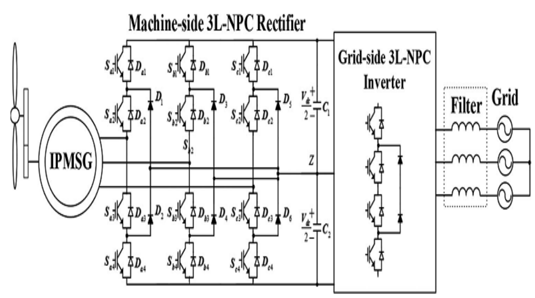


Fig. 1. Back-to-back converter using the 3L-NPC topology in wind turbine systems.

This consists of the machine-side 3L-NPC rectifier, the dc-link, and the grid-side 3L-NPC inverter. Depending on the operating conditions, tolerant controls can be applied for the rectifier or the inverter because the current paths of the rectifier and the inverter are different [9], [13]–[15]. In addition, the different structure of the three-level topologies should be considered in the tolerant controls [9], [13]. In the 3L-NPC inverter, the open-circuit fault of the inner switch causes the outer switch connected it to be infeasible; therefore, changing only the switching method does not become a solution for the open-circuit fault, and the additional devices such as fuses and switches should be added for achieving the tolerant operation under the open-circuit fault of the inner switch [16]–[18].

However, the open-circuit fault of the outer switch can be handled by changed the switching method in limited range [19]. In [19], the tolerant control method limits the output voltage range by half. In addition, the reactive current is injected to eliminate current distortion caused by the open-circuit fault of the outer switch [22].

when rectifiers operate at a uniquepf[4]–[7]. In such a case, an open-circuit fault of the outer switches (Sx1andSx4) causes current distortion and torque fluctuation, which can lead to vibration of the wind turbine. In this paper, the reason for the current distortion caused by the outer switches (Sx1 andSx4) is analyzed, and then, on the basis of this analysis, a tolerant control forSx1 andSx4 open-circuit faults is proposed.

III. OPEN-CIRCUITFAULTANALYSIS OFOUTERSWITCHES

There are three switching states (P, N, and O) in the 3L-NPC rectifier [9]. Six current paths can be generated depending on the current direction and the switching state, and these are shown in Fig. 2 [23]. Fig. 3 shows the input current generation process of a rectifier with unitypf.

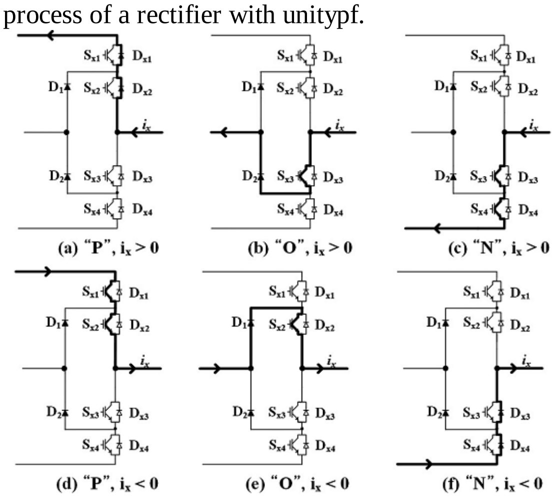


Fig. 2. Current paths depending on the current direction and the switching state.

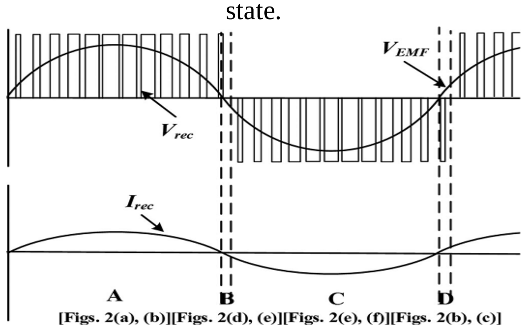


Fig. 3. Rectifier operation at unity pf.

TABLE I
CURRENTPATHCOMPOSITIONDEPENDING ON THEPART OFFIG.3

Part	V_{rec}	I_{rec}	Current path
A	Positive	Positive	(a) P switching state, (b) O switching state (valid)
B	Positive	Negative	(d) P switching state (valid), (e) O switching state
C	Negative	Negative	(e) O switching state (valid), (f) N switching state
D	Negative	Positive	(b) O switching state, (c) N switching state (valid)

The phase difference between VEMF and Vrec, which causes the current flow, is controlled to match the phase ofIrec up with the phase of the corresponding VEMF. One period of Irec can be divided into four parts depending on the polarity ofIrec and Vrec. The generated current paths are different depending on the part, and these are summarized in Table I. In parts A and C, the O switching state causes the input current flow; therefore, this is called the valid switching state. The current continuously flows through two diodes if the switching state is changed to P or N switching state in which no current flows through the switches.

In parts B and D, the P and N switching stages are the valid switching state where the current flows through the switches. When the rectifier operates with unity pf, parts A and C are large, and parts B and D are small.

In this paper, the other case (Case II), which is the reactive current injection for IPMSG, is also considered. Fig. 4 shows that the input current generation process of the rectifier for Cases I and II. There are two phase differences: the phase difference (ϕZ) between VEMF and Vrec explained in [22], and the phase difference (ϕpf) between Iref and VEMF caused by thepf.InFig.4, part B (or part D) consists ofϕZ andϕpf, and their lengths increase. This means that the current can be more distorted by the open-circuit fault of the outer switches compared to when ϕZ alone is considered

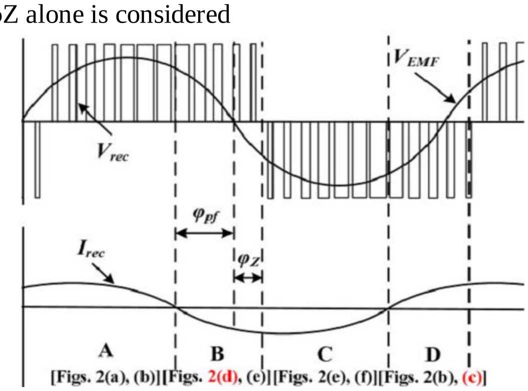


Fig. 4. Rectifier operation at anypf.

Case I can be ignored becauseϕZ is determined depending on the operating condition of the rectifier and the PMSG. However, becauseϕpf is determined by thepf, Case II should be considered when the IPMSG is employed. The current distortion caused by the open-circuit fault of the outer switches is shown in Fig. 5 for variouspfs. Owing to the infeasible open-circuit fault switch, the current becomes zero during the range consisting ofϕZandϕpf.TheSx1open-circuit fault makes the current path of Fig. 2(d) infeasible.

The current path of Fig. 2(d) belongs to part B; therefore, theSx1 opencircuit fault causes distortion in the negative current as shown in Fig. 5(a) and (c). On the contrary, the Sx4 open-circuit fault leads to distortion in the positive current as shown in Fig. 5(b) and (d) because the current path of Fig. 2(c) related to theSx4 open-circuit fault belongs to part D. The lowpfhas a largeϕpf. Therefore, the rectifier operation at a lowpfleads to a large zero-current range when the opencircuit fault of the outer switch occurs. As a result, the zerocurrent range increases, as the pf decreases.

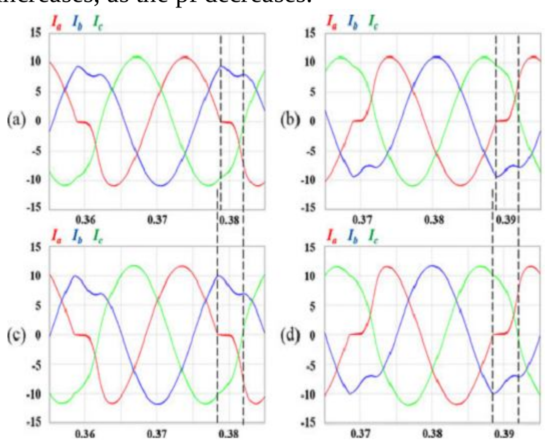


Fig. 5. Current distortion depending on the open-circuit fault and thepf:(a) 0.95pf, Sx1 open-circuit fault, (b) 0.95pf, Sx4 open-circuit fault, (c) 0.9pf, Sx1 open-circuit fault, and (d) 0.9pf,Sx4 open-circuit fault

The analysis related to the open-circuit fault of the outer switches can be applied to the T-type topology. The effects of open-circuit faults of the outer switches on the current are the same in both the NPC rectifier and the T-type rectifier [13], [22]. Therefore, the current distortion caused by open-circuit faults of the outer switches in the NPC rectifier is the same as that in the T-type rectifier.

III.TOLERANT CONTROL FOROPEN-CIRCUIT FAULT OF OUTER SWITCHES

An existing tolerant control method for the open-circuit fault of the outer switches isreactive current injection [22]. This method changes the phase ofIrecso that it corresponds with the phase ofVrec. This means that parts B and D are eliminated. However, this tolerant control method has the disadvantage of low-power generation efficiency of the generator because the PMSG has efficient operating condition which depends on the pfof the rectifier. The proposed tolerant control does not change the pf of the rectifier. The rectifier voltage (Vrec) without the current path related to the open-circuit fault switch is generated by changing the reference voltages. To explain the proposed tolerant control, theSx1open-circuit fault is used as an example.

A. Compensation Voltage (Vcomp) Calculation

Three-phase reference voltages (Vx,ref, x=a, b, c)are expressed as

$$\begin{aligned} V_{a,ref} &= V_{mag}\cos(2\pi f_s t) \\ V_{b,ref} &= V_{mag}\cos(2\pi f_s t - 2\pi/3) \\ V_{c,ref} &= V_{mag}\cos(2\pi f_s t + 2\pi/3) \end{aligned} \quad (1)$$

Where Vmag is the magnitude of the reference voltages, and fs is the fundamental frequency. The offset voltage (Voffset) is added to each reference voltage to expand the range of the modulation index(Ma = √ 3× Vmag/Vdc). Voffset and the changed reference voltages (Vx,ref,offset,x=a, b, c) are expressed as

$$V_{offset} = -\left(\mathrm{V_{ref,max}} + \mathrm{V_{ref,min}}\right)/2 \quad (2)$$

$$\begin{aligned} V_{a,ref,offset} &= V_{a,ref} + V_{offset} \\ V_{b,ref,offset} &= V_{b,ref} + V_{offset} \\ V_{c,ref,offset} &= V_{c,ref} + V_{offset} \end{aligned} \quad (3)$$

Where Vref,max and Vref,min are the maximum and minimum values ofVa,ref,Vb,ref, andVc,ref. The reference voltages of (3) are compared with the carrier signals to generateVrec. When theSx1 open-circuit fault occurs, the current path of Fig. 2(d) should be eliminated to prevent current distortion; therefore, the reference voltage should be changed to generate Vrec without the current path of Fig. 2(d). In the proposed tolerant control, a reference voltage of a phase containing theSxopen-circuit fault is changed to zero as shown in Fig. 6. As a result, the current path of Fig. 2(d) disappears because the O switching state is only used in part B. To make the reference voltage zero,|Vcomp| is assigned the magnitude of the reference voltage (Vx,ref,offset) containing the open-circuit fault, and Vcompcan be expressed as

$$V_{comp} = -V_{x,ref,offset}\ (x = a\ phase\ containing\ open\ circuited\ fault\ switch) \quad (4)$$

The proposed tolerant control is implemented by adding Vcomp to the reference voltages (Vx,ref,offset, x=a, b, c). The new reference voltages (Vx,ref,tolerance, x=a, b, c) of the proposed tolerant control are expressed as

$$\begin{aligned} V_{a,ref,tolerance} &= V_{a,ref,offset} + V_{comp} \\ V_{b,ref,tolerance} &= V_{b,ref,offset} + V_{comp} \\ V_{c,ref,tolerance} &= V_{c,ref,offset} + V_{comp} \end{aligned} \quad (5)$$

B. Compensation Range for AddingVcomp

By addingVcomp to each reference voltage, the use of the current path related to the open-circuit fault switch will be precluded. To achieve this perfectly,Vcompis added for the suitable range and position. The compensation range, which is part B or part D of Fig. 4, consists ofϕZandϕpf. ϕZcan be calculated with the equivalent circuit of the PMSG and the three-level rectifier [22].ϕZ, which is the phase difference betweenVEMFand Vrec, is expressed as

$$\varphi_z = \tan^{-1}\left(\frac{-|I_{rec}|*2\pi f_S L}{V_{EMF}-|I_{ref}|R}\right) \quad (6)$$

whereRandLare the equivalent resistance and inductance of the PMSG, and fs is the fundamental frequency representing the angular frequency of the PMSG. ϕpf, which is the phase difference between VEMFandIrec, is related to the pf. ϕpf can be calculated by thepfand this is expressed as

$$\varphi_{pf} = \cos^{-1}(pf) \quad (7)$$

If the d–q control theorem is used,ϕpf can be calculated as

$$\varphi_{pf} = \cos^{-1}\left(\frac{I_{qe}}{\sqrt{I_{qe}^2+I_{de}^2}}\right) \quad (8)$$

Where Ide indicates thed-axis current related to the flux andIqe indicates the q-axis current related to the torque, and these are values in the d–q synchronous rotating frame. ϕZandϕpf, which are calculated from (6) and (8), are located near the zero-crossing point ofVEMFas shown in Fig. 6. Therefore, the compensation position for addingVcomp is defined on the basis of VEMF's angle (θEMF).

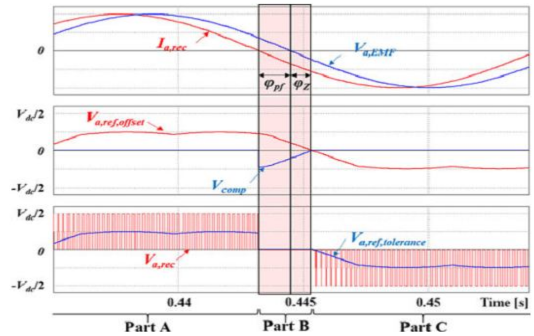


Fig. 6. Change of reference voltages in the proposed tolerant control for the Sx1 open-circuit fault (0.95pf).

Fig. 7 shows three-phase VEMFsandθEMF. θEMFis acquired from the encoder or position sensor. Six zero-crossing points are expressed for every 60°, which are matched to each open-circuit fault as shown in Fig. 7. Consequently,θEMFrepresenting each zero-crossing point is a criterion for addingVcomp. For example, when the Sa1 opencircuit fault occurs,Vcompshould be added for the compensation range from(0 ◦−ϕpf)to (0 ◦+ϕZ)which is based on 0°.By considering all open-circuit faults, Table II shows the compensation ranges for eliminating the current distortion depending on the position of the open-circuit fault

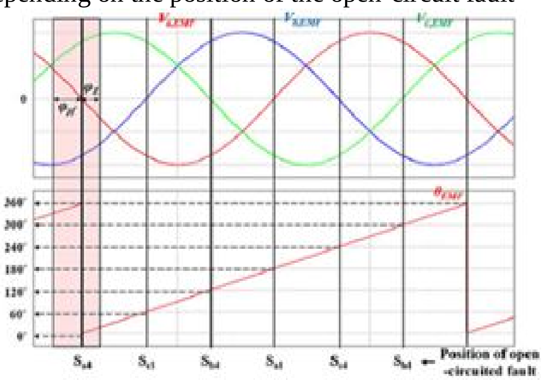


Fig. 7. Compensation position on the basis ofVEMF's angle (θEMF).

Table II
compensation range depending on the position of the open-circuit fault

Position of open-circuit fault	Compensation range
S_{a1}	$(0^\circ - \varphi_{pf}) \sim (0^\circ + \varphi_Z)$
S_{c4}	$(60^\circ - \varphi_{pf}) \sim (60^\circ + \varphi_Z)$
S_{b1}	$(120^\circ - \varphi_{pf}) \sim (120^\circ + \varphi_Z)$
S_{a4}	$(180^\circ - \varphi_{pf}) \sim (180^\circ + \varphi_Z)$
S_{c1}	$(240^\circ - \varphi_{pf}) \sim (240^\circ + \varphi_Z)$
S_{b4}	$(300^\circ - \varphi_{pf}) \sim (300^\circ + \varphi_Z)$

C. Considering Neutral-Point Voltage Balance

The compensation voltage which is one of the offset voltages can cause neutral-point voltage unbalance becauseVcomp calculated from (4) is a one-sided voltage .

Fig. 8 shows the concept of proposed tolerant control considering the neutral-point voltage balance when the Sa1 open-circuit fault occurs. In Fig. 8, Vcomp is added for the compensation range[(0 ◦−ϕpf)∼(0 ◦+ϕZ)]which corresponds to the position for theSa1 open-circuit fault; in addition,Vcomp is also added for the diametrically opposite compensation range [(180 ◦−ϕpf)∼(180 ◦+ϕZ)], which is the range for the Sa4 open-circuit fault. The final principles of the proposed tolerant control with the neutral-point voltage balance are summarized in Table III.

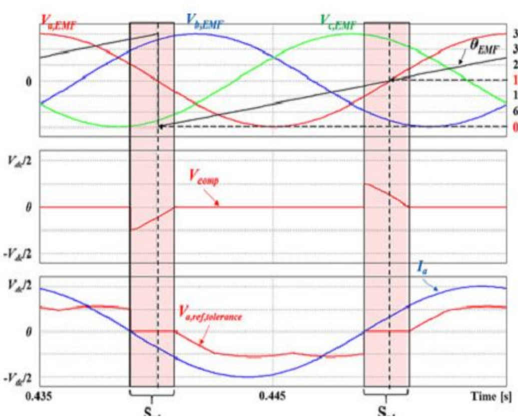


Fig. 8. Proposed tolerant control considering neutral-point voltage balance under theSa1 open-circuit fault

Table III

principle of the proposed tolerant control depending on the position of the open-circuit fault

Position of open-circuit fault	V_{comp}	Compensation range
S_{a1} or S_{a4}	$-V_{a,\mathrm{ref,offset}}$	$(0^\circ - \varphi_{pf}) \sim (0^\circ + \varphi_Z)$
S_{c4} or S_{c1}	$-V_{c,\mathrm{ref,offset}}$	$(60^\circ - \varphi_{pf}) \sim (60^\circ + \varphi_Z)$
S_{b1} or S_{b4}	$-V_{b,\mathrm{ref,offset}}$	$(120^\circ - \varphi_{pf}) \sim (120^\circ + \varphi_Z)$
S_{a4} or S_{a1}	$-V_{a,\mathrm{ref,offset}}$	$(180^\circ - \varphi_{pf}) \sim (180^\circ + \varphi_Z)$
S_{c1} or S_{c4}	$-V_{c,\mathrm{ref,offset}}$	$(240^\circ - \varphi_{pf}) \sim (240^\circ + \varphi_Z)$
S_{b4} or S_{b1}	$-V_{b,\mathrm{ref,offset}}$	$(300^\circ - \varphi_{pf}) \sim (300^\circ + \varphi_Z)$

D. Limitation of Proposed Tolerant Control

Vx,ref,tolerance cannot exceed a limitation voltage (Vlimit)which is restricted by the dc-link voltage (Vdc). Therefore, Vcomp is limited as follows

$$V_{comp} < V_{limit} - V_{ref,max} \qquad (9)$$

Where Vlimit isVdc/2. On the basis of (9), the applicable operation range of the proposed tolerant control is determined depending on Ma and thepf.Fig.9showsVx,ref,toleranceandVcompof the proposed tolerant control depending on the pf when Ma is 0.5. In Fig. 9,Vcomp leads to Va,ref, tolerance with zero value in the corresponding compensation range. Moreover, the peak value of Vc,ref, tolerance increases owing to Vcomp .

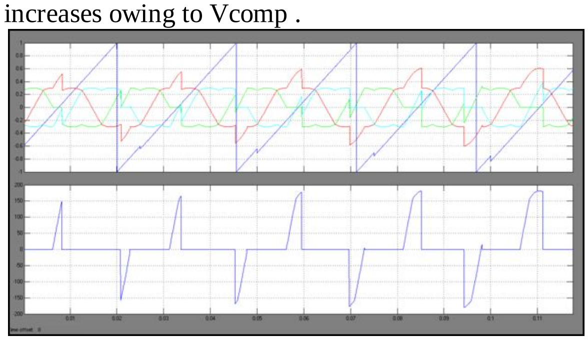


Fig.9.Vx,ref,tolerance(x=a,b,c) and Vcomp depending on the pf when Ma is 0.5.

As the pf decreases, this peak value increases; however, it does not exceed Vlimit . Consequently, whenMais smaller than 0.5,Vcompcan be added regardless of the pfbecauseVc,ref,tolerance cannot exceedVlimit. When Ma is larger than 0.5, the applicablepfrange is determined byMa. This is because a lowMa provides a large margin forVcomp; however, a largeVcompcannot be acceptable for highMa. Fig. 10 shows the applicablepfrange for various values ofMa. The shaded part of Fig. 10 represents the applicable operation range. The proposed tolerant control is feasible over the entire factor range when Ma is smaller than 0.5. By increasing Ma from 0.5, the applicable operation range decreases.

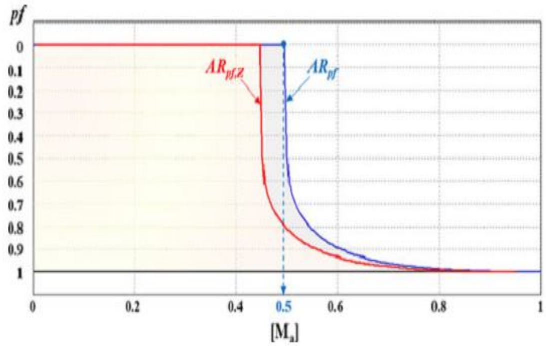
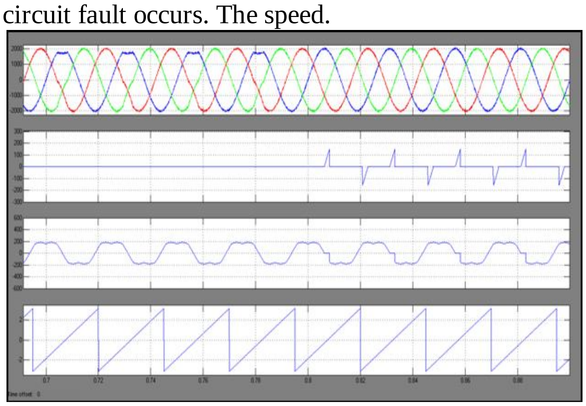


Fig. 10. Applicable pfrange of the proposed tolerant control depending onMa.

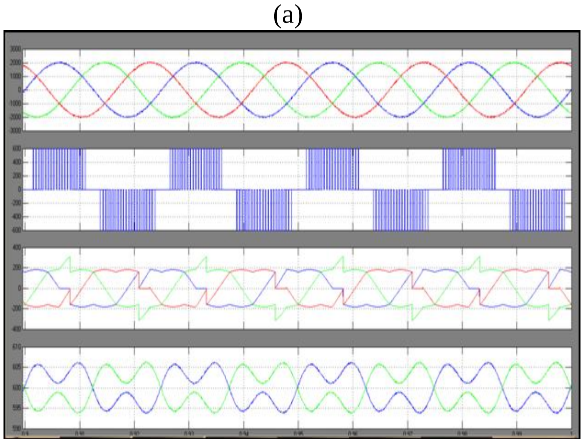
In Fig 10.the applicable operation range shown as ARpf is largest when only thepfrelated to ϕpf is taken into account. However, a largeϕZmeans that large portion of the compensation range is reserved forϕZ, and the rest can be used to compensate ϕpf.

IV. SIMULATIONRESULTS

The simulation is performed using the PSIM tool. The 3L-NPC rectifier of the back-to-back converter with 2.5-MW IPMSG is only considered in the simulation. Fig. 11 shows the simulation results of the proposed tolerant control when the Sa1 open-circuit fault occurs. The speed.



(a)



(b)

Fig. 11. Simulation results with the proposed tolerant control under the Sa1 open-circuit fault (600 rpm,Ma =0.35,0.95pf).

Table IV
ipmsg parameters insimulation

Rated power	2.5 MW
Number of pole	8
Rated voltage (line-to-line)	760 V_{rms}
Rated current	1902 A_{rms}
Rated speed	1650 rpm
Resistance	0.4567 mΩ
q-inductance	0.0982 mH
d-inductance	0.0725 mH

As a result, the a-phase pole voltage (Van) is clamped to 0 at their ranges as shown in Fig. 11(b) and the current distortion is eliminated completely.

In addition, the two dc-link capacitor voltages are balanced. The proposed tolerant control is effective for thepftransition operation of the rectifier. Fig. 12 shows the results when the proposed tolerant control is applied and thepfis changed from 0.95 to 0.9.

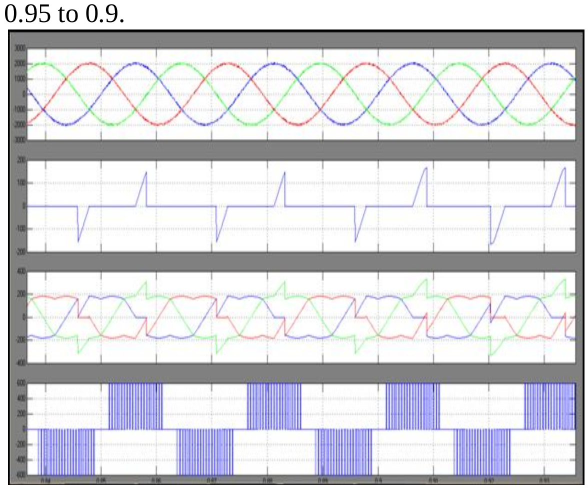


Fig. 12. Simulation results with the proposed tolerant control under theSa1 open-circuit fault (600 rpm,Ma =0.35, pf-transition from 0.95 to 0.9).

Fig. 13 shows the performance of the proposed tolerant control under the Sa1 open-circuit fault at different speed (1000 rpm) of the PMSG whenMa is 0.59. Similar to Fig. 11, the distorted currents are corrected after the proposed tolerant control is applied. However, the peak value of Vc,ref, tolerance is close to Vlimit(Vdc/2)at 0.95pf, which is different from what is shown in Fig. 11. This is because Maof Fig. 13 has a smaller.

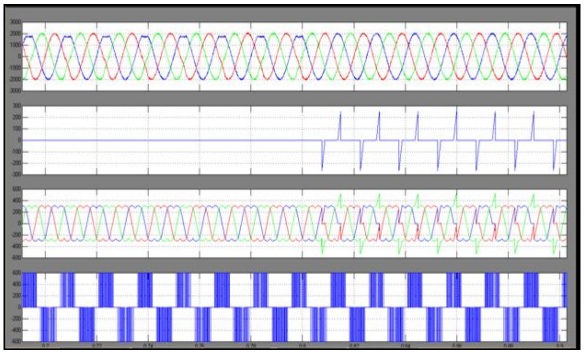


Fig. 13. Simulation results with the proposed tolerant control under theSa1 open-circuit fault (1000 rpm,Ma =0.59,0.95pf)

Table V shows the current THD results before and after the proposed tolerant control is applied. The current THD is increased by theSa1 open-circuit fault; however, owing to the proposed tolerant control, the current THD is restored as good as normal state without any open-circuit fault.

VI. CONCLUSION

This paper proposes a tolerant control for the open-circuit fault of the outer switches in three-level rectifiers (both 3L-NPC and T-type topologies) used in wind turbine systems. The reason why the tolerant control for the open-circuit fault of the outer switches in three-level rectifiers is necessary is presented, together with the supporting circuit analysis. On the basis of the analysis, a tolerant control for each open-circuit fault is proposed that takes into account the neutral-point voltage balance. This control is implemented by adding a compensation voltage (Vcomp) to the reference voltages for the corresponding compensation ranges depending on the position of the open-circuit fault. Furthermore, this control can be used in both the 3L-NPC and T-type rectifiers and guarantees normal operation without a change of the pf in the applicable operation range shown in Fig. 10 depending on the modulation index (Ma) and the pf. Although the operating range of the proposed tolerant control is subject to a limitation, considering that wind turbine systems do not always operate with the rated wind speed and that the operating pf of the rectifier with an IPMSG is not too low, the proposed tolerant control is clearly effective. The performance and effectiveness of the proposed tolerance control are proved through simulations.

REFERENCES

[1] A. Isidori, F. M. Rossi, F. Blaabjerg, and K. Ma, "Thermal loading and reliability of 10-MW multilevel wind power converter at different wind roughness classes,"IEEE Trans. Ind. Appl., vol. 50, no. 1, pp. 484–494, Jan./Feb. 2014.

[2] H. G. Jeong, K. B. Lee, S. Chio, and W. Choi, "Performance improvement of LCL-filter-based grid-connected inverters using PQR power transformation,"IEEE Trans. Power Electron., vol. 25, no. 5, pp. 1320–1330, May 2010.

[3] S. Li, T. A. Haskew, R. P. Swatloski, and W. Gathings, "Optimal and direct-current vector control of direct-driven PMSG wind turbines,"IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2325–2337, May 2012.

[4] W. Qiao, L. Qu, and R. G. Harley, "Control of IPM synchronous generator for maximum wind power generation considering magnetic saturation," IEEE Trans. Ind. Appl., vol. 45, no. 3, pp. 1095–1105, May/Jun. 2009.

[5] S. Morimoto, H. Nakayama, M. Sanada, and Y. Takeda, "Sensorless output maximization control for variable-speed wind generation system using IPMSG," IEEE Trans. Ind. Appl., vol. 41, no. 1, pp. 60–67, Jan./Feb. 2005.

[6] Y. Zhao, W. Qiao, and L. Wu, "An adaptive quasi-sliding-mode rotor position observer-based sensorless control for interior permanent magnet synchronous machines,"IEEE Trans. Power Electron., vol. 28, no. 12, pp. 5618–5629, Dec. 2013.

[7] P. B. Reddy, A. M. EL-Refaie, and K. K. Huh, "Effect of number of layers on performance of fractional-slot concentrated-windings interior permanent magnet machines,"IEEE Trans. Power Electron., vol. 30, no. 4, pp. 2205–2218, Apr. 2015.

[8] 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.

[9] 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.

[10] U. M. Choi, J. S. Lee, and K. B. Lee, "New modulation strategy to balance the neutral-point voltage for three-level neutral-clamped inverter systems," IEEE Trans. Energy Convers., vol. 29, no. 1, pp. 91–100, Mar. 2014.