EFFECT OF VOLTAGE STRESS ON RELIABILITY OF THE 3-LEVEL ANPC MULTILEVEL INVERTER FOR WIND TURBINES

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Abstract

Wind power with low or no greenhouse gas emissions has been highly prevalent over the last decade. Modern renewable energy systems rely heavily on power electronic devices such as multilevel converters (MLC) to integrate renewables into the grid or provide electricity to islanding loads. These converters' power electronic switches have a high failure rate (approximately 34 percent). As a result, the reliability evaluation of these converters is vital. Most research has focused on developing a fault-tolerant, efficient and cost-effective topology that reduces components. Still, the reliability of these topologies has received relatively little attention. This paper studies the effect of voltage stress on three-level Active Neutral Point Clamped (ANPC) multilevel inverter reliability. The series redundancy is introduced in ANPC using redundant outer switches, making ANPC a fault-tolerant topology. The reliability of this fault-tolerant topology is compared with the fault-intolerant ANPC. The voltage stress factor is calculated for fault intolerant and proposed fault-tolerant ANPC topologies. Because of the reduced stress on the switches and redundant configuration of the outer switches, the proposed fault-tolerant ANPC is more reliable. The fault-tolerant topology proposed in this paper has the lowest voltage stress factor, resulting in better reliability.

Keywords: Active Neutral Point Clamped (ANPC) multilevel inverter, Fault-tolerant topology, Multilevel converters, Reliability evaluation

Introduction

Every year, the world's demand for electrical energy rises, and large-scale projects in renewable energy sources have been underway for years. The wind is one of these sources. Wind turbines ranging in output capacity from a few kW to 5MW in today's powerful turbines transform the wind's kinetic energy into electrical energy. And the goal is to increase output power even further in the future. Present wind turbines are designed to work with varying wind speeds and, as a result, variable rotor speeds. High-power inverters consisting of power electronics modules are used to achieve this. These inverters change a variable-frequency voltage into a voltage with a fixed output frequency (Mads, 2008). Due to the increase in the penetration of renewable like wind and solar, power electronic converters has drawn significant importance. In islanding mode, converters must integrate these renewable into the utility grid or deliver electric power to AC loads (Agelidis, 1998).

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As the renewable energy sources are intermittent, the power electronics converter controls the output as per the load or utility grid condition and enables the maximization of power harnessing. As the power demand increases, the best way to transfer high power is to increase the voltage level, which results in the reduction of current and power loss. The rating of power electronics devices has been matured now. Conventional power electronics converter (two-level) cannot handle high power with its rated devices (Jahns *et al*., 2001). So the industry's focus has been transferred from conventional converters to the multilevel converter. Compared to two-level-power electronic converters, MLC provides advantages such as small dv/dt stress on the equipment's, good output voltage quality and low electromagnetic interference (EMI) (Rodríguez *et al*., 2008). However, as the voltage level rises, the count value of the switches (Diode, MOSFET, IGBTs, soon) in the converter increases as well.

As per the industrial-based survey, electrolytic-capacitors and switching devices in power electronics converters are the utmost susceptible. As a result, the converter becomes the frailest element in the system, leaving the system's reliability at risk (Zhang *et al*., 2014).

As various power devices are used in multilevel inverters, any device failure will result in the loss of the drive system, forcing the inverter and the entire system to be shut down to prevent further serious damage. On the other hand, the system's reliability and sustainability are important in various serious industrial processes with high standstill costs and security concerns. Since most power electronic converters lack redundancies, any problem in components or subsystems may lead to a shut down in the system. System failures in precarious uses such as the military, economic fairs, and hospices could result in huge financial losses (Tao *et al*., 2008; Zhang *et al*., 2013)

As a result, fault-tolerant multilevel inverters have attracted a lot of attention in present times, and various authors have reported work on fault-tolerant issues for multi-level topologies (Richardeau *et al*., 2002; Turpin *et al*., 2002; A. Chen *et al*., 2004; J. Rodríguez *et al*., 2004; Kou *et al*., 2004; J.C. Lee *et al*., 2006; Li and Xu, 2006; Ceballos *et al*., 2008; Maharjan *et al*., 2010; Song and Huang, 2010; Akmaliyah, 2013) The use of a redundancy design to enhance the converter's short-circuit failure for bearanceis a good option (G. Chen *et al*., 2014). IGBTs with serial connections have a higher switching frequency and can handle higher voltages. In (Munk-Nielsen *et al*., 2009; Wang *et al*., 2013) the variation in power loss among IGBTs is serial connection and a single high voltage IGBT is explored. In high-voltage applications, adding further IGBTs in series at a suitable switching frequency minimizes power losses (G. Chen *et al*., 2014).In (Shammas *et al*., 2006), the series and parallel connections of IGBTs are examined, as well as the strategies for resolving difficulties encountered in series and parallel connections are explained. For IGBTs connected in series, many voltage balancing strategies have been proposed (Fortes *et al*., 2019; Guerrero-Guerrero *et al*., 2019; Nawaz and Khalil, 2020; Son *et al*., 2020). Numerous are grounded on active voltage control, limiting the voltage through switching transition and regulating the dynamic voltage distribution. Two ways to enhance voltage sharing among IGBT connected in series are provided, studied, and confirmed in this (Nguyen *et al*., 2010). Based on efficiency and reliability, an enhanced design (using series-connected IGBTs) for a multi-MW wind power converter is proposed in (G. Chen *et al*., 2014).

A multilevel inverter topology with higher reliability and lesser components is proposed in (Akbari *et al*., 2022).

In (Fahad *et al*., 2021), the multilayer inverter's (MLIs) topology reliability evaluation is carried out, which includes a comparison with previous literature regarding component requirements and reliability. In (Saketi *et al*., 2020), a novel multilevel inverter with lesser devices is proposed. This inverter can tolerate single switch and multi-switch faults while maintaining its rated voltage and power.

The authors have focussed on the design of fault-tolerant inverter topologies to improve reliability. The reliability of the MLIs is also a function of voltage stress across the switches. The effect of this voltage stress on the reliability of the multilevel inverter should also be emphasized.

The static redundancy-based fault-tolerant multilevel converters presented so far, on the other hand, did not take into account the voltage stress on the switches. Based on the literature survey, following are the objectives of the work reported.

Objectives

To study the effect of voltage stress on three-level Active Neutral Point Clamped (ANPC) multilevel inverter's reliability.

To introduce series redundancy in ANPC using redundant outer switches to make ANPC a fault-tolerant topology.

To evaluate the reliability of the proposed fault-tolerant topology and compare it with the fault intolerant ANPC.

Multilevel Converters

The conventional two-level converter cannot be used to integrate medium or higher voltages with an electric grid owing to limited reverse blocking capability of semiconductor switches. So, the multilevel converters (MLCs) are the only possible solution to replace the conventional two-level converter in medium and high voltage applications. MLC decreases the voltage stress (dv/dt) on switches by increasing the voltage levels in output waveform. The rise in the voltage level makes output waveform near to or purely sinusoidal and helps suppress the harmonic content of the output, i.e., THD is reduced, and quality is increased. Moreover, MLCs have low power loss across the semiconductor switches due to the low electromagnetic interference (EMI) (Franquelo *et al*., 2008). The basic MLCs topologies include Diode Clamped (DC) MLC, Flying-Capacitor (FC) MLC, and Cascaded H-Bridge (CHB) MLC. However, with the increase in the voltage level, the number of semiconductor switches also increases in the MLC, which increases cost and control complexity. Also, the non-fault tolerant capability of the converters results in a reduction in reliability. So, the development of MLC topologies with fault-tolerant capability and reduced stress on the semiconductor switches is the critical area of research. Several MLC topologies have been proposed so far, and further research on this is still going on. MLC was introduced with a three-level Cascaded H Bridge (CHB) converter in 1975 by R.H. Baker and L.H. Bannister by using two series-connected DC sources. Then with some modifications, Diode Clamped MLC was derived in which diode was used to clamp the neutral point. The first Diode Clamped converter was invented in 1979 by A. Nabae, I. Takahashi, and H. Akagi (Akagi, 2017). In the early 1980s, FC-MLC topology was derived by replacing the clamping diode with capacitors. FC-MLC is also called as Capacitor-Clamped MLC. In Neutral Point Clamped MLC, the loss distribution in the switching devices is non-uniform. The active switches are connected in both NPC branches to improve this unequal loss distribution, and the designed circuit is called Active Neutral Point Clamped (ANPC) MLC. This topology was first invented in the year 2001.

Figure 1 represents the classification of basic MLC topologies

The topology that has been analysed in this paper is Three-level ANPC (3L-ANPC)

The number of IGBTs in a 3L-NPC is twice that of a two-level converter. The neutral point is clamped by the two extra diodes. The zero state is provided via neutral clamping. Even though the total number of IGBTs in 3L-NPC is larger than in two-level converters with the same dc-link voltage, their voltage rating is half that of two-level converters. This topology, however, has the disadvantage of having an unequal loss distribution among its power components. To reduce the losses and have a uniform loss distribution among the components, the 3L-NPC is modified into a 3L-ANPC topology. The main difference between them is that in 3L-ANPC topology, the natural point is clamped using two additional IGBTs instead of diodes, as shown in Figure 2. Due to the use of IGBTs instead of diodes, the topology can clamp the neutral point in more than one way. The switching losses can thus be controlled by employing the proper switching strategies.

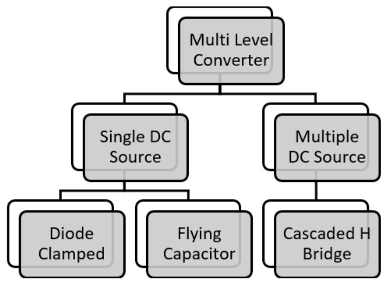

Figure 1. Classification of Basic MLC Topologies

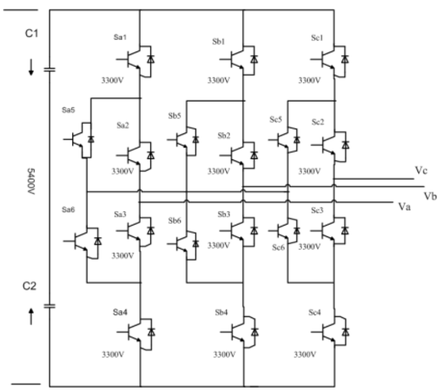

Figure 2. Three-Level ANPC Topology

Three-level ANPC inverter

The three-level ANPC (Floricau *et al*., 2009) is imitative of the three-level-NPC topology. The clamp diodes are connected in antiparallel by two active switches. Six bi-directional switches proficient of handling a voltage of +Vdc represent the three ANPC structure. Every switch (S) is built up of transistor (T) and an antiparallel diode (D). Switching states of ANPC topology are listed in Table 1, which shows that the number of states of

Table 1. Switching States of three-level ANPC Topology

Output Voltage	Switch States					
	S_1	S_2	S_3	S_4	S_5	S_6
$+V_{dc}$	ON	OFF	ON	OFF	ON	OFF
0	OFF	ON	OFF	ON	ON	OFF
0	OFF	ON	OFF	ON	ON	OFF
0	ON	OFF	ON	OFF	OFF	ON
0	ON	OFF	ON	OFF	OFF	ON
$-V_{dc}$	OFF	ON	OFF	ON	OFF	ON

zero voltages states in ANPC is increased compared to the number of zero voltage states in NPC topology. Different zero states can be employed to spread losses more equally across the semiconductors. The objective is not only to reduce overall converter losses but to evenly dispense them. Distribution of switching losses is determined by commutations from and to zero states.

Reliability of Multilevel converters

Multi-level inverters have recently engrossed considerable attention in areas of high-power applications. To improve the overall power efficiency, multilevel inverters perform power conversion in multilevel voltage steps. Multilevel inverters have become incredibly popular in present as a result of benefits.

The quantitative study focuses on the failure rate model for main elements in power electronics circuits like semiconductor devices, capacitors, etc. IGBT, MOSFET, and diode are the most widely used semiconductor devices. In order to determine if a design meets certain criteria, a quantifiable valuation of dependability for power electronic converters is required. It may also be used to compare various topologies, control methods, and equipment's. Furthermore, precise reliability prediction provides significant direction to system operation and maintenance management. Models are used in all types of reliability analysis, whether at the equipment or system level. A system-level-reliability model depicts efficient inter-dependencies clearly and offers an outline for calculating quantifiable system reliability evaluations to aid in the strategy trade-off method. There have been various techniques proposed to measure the reliability metrics of power electronic converters.

Series Redundancy

Traditional two-level inverters have certain disadvantages in running at high frequency in high-power applications, owing to switching losses and power device rating limitations. A series and parallel combination of power switches is an option to attain the power handling voltages and currents.

From a redundancy perspective, the series connection of IGBTs in a multilevel inverter has some benefits. If one device in a series group fails and short circuits, the remaining devices will sustain the inverter working as long as the individual devices' voltage ratings are not exceeded. If a parallel device is short-circuited, the short-circuited device can clamp all paralleled devices, leaving the remaining paralleled IGBTs useless.

Adding series components in multilevel inverter leg improves the reliability. Consequently, if one component fails, it will not lead to the loss of other components and, ultimately, the whole system. The only factor that limits the number of series components is cost. The reliability function for a device having series redundancy with n components is given in (1)

$$R(t) = 1 - (1 - e^{-\lambda t})^n \quad (1)$$

A more significant number of series components, according to Equation (1), results in reliability values that are nearer to 1.

When the frequency exceeds a few hundred Hz, two lower-rated IGBTs in series have lower losses than one double rating device (Mads, 2008). This is because the IGBT's internal capacitance does not follow the voltage rating of the device linearly. This result means that two IGBTs in series will work at a higher switching frequency than one IGBT with a higher voltage rating for a given loss.

Since the average on-state voltage drop for the series string is more significant than for a single device, the conduction losses increase. However, as lower-rated IGBTs have lower junction capacitances, switching losses are reduced significantly, and overall losses are reduced as compared to using less high-rated IGBTs in series.

The features of equipment's of the same type, on the other hand, are not similar. Voltage sharing can be done in a variety of ways. The passive RC snubber is the first approach, which works by increasing the slope of V_{ce} and thereby balancing the voltages. The active gate control and the Zener clamped snubber are the other approaches, and they operate by clamping any overvoltage seen in V_{ce}. In the serial operation of power units, the passive snubber circuit (Withanage and Shammas, 2012) is commonly used.

Failure Rate of components

Several reliability models are available as literature for the failure rate models of the power electronics components. The most widely accepted model to predict the reliability of the power electronic components is Military-Handbook-217F (Equipment, 1991). MILHDBK-217F is a database that covers a wide range of component types. Its aim is to provide a standardized database for predicting component reliability in the absence of extensive component reliability experience.

The handbook includes a wide range of different components and is generally accepted. So, for failure rate calculations in this paper, MIL-HDBK-217F is used. Since this research aims to find out the effect of stress on reliability, any trusted and available data source can be used. It has been confirmed from the field experience that the capacitor and power electronic switches are the most failure-prone components. Hence, in this paper, only the capacitor and power electronic switches are considered, and other systems such as control, gate drivers, etc., are not considered.

Furthermore, the power electronic switches that have been used are insulated-gate bipolar transistors (IGBT's). Other types of switches can be considered in the same way. The failure rate parameters of IGBT are taken from (Handbook and Fiabilite, 2000).The power electronic devices failure rate is affected by a variety of factors, including operational voltage, current, technical characteristics of the devices, atmospheric conditions, and thermal stress. The constraints are expressed in form of various acceleration factors for the calculation of failure rates. The consideration of these acceleration factors makes the failure rate calculation more accurate. The failure rate of micro-electronic part is expressed in (2)

$$\lambda_{electronicpart} = \lambda_b \prod_{i=1}^{k} \pi_k \quad (2)$$

Where k is the number of acceleration factors that upset the failure rate

λ_b = Basic failure rate

Failure Rate of capacitor

The failure rate of capacitor part is expressed in (3)

$$\lambda\_Cap = \lambda_0 \pi_T \pi_C \pi_V \pi_{SR} \pi_Q \pi_E \text{ Failures/106hours} \quad (3)$$

λ_{Cap}= failure rate of capacitor

λ_0= basic failure rate

Π_T= temperature factor

π_C = Capacitance factor

π_V= voltage stress factor

π_{SR}=Series resistance factor

π_Q= quality factor

π_E= environmental factor

An aluminium electrolyte capacitor is most commonly used in DC-link applications due to its low cost. In this paper, for illustrative purposes, a dry electrolytic capacitor is considered.

The failure rate parameters assumed for capacitor are given below

λ_0= basic failure rate = 0.00012

Temperature rating = 120°C

π_T= $\exp\left(-4062\left(\frac{1}{T_a+273} - \frac{1}{298}\right)\right)$

Π_C=$C^{0.23} = 7.09$

Π_V=$\left(\frac{S}{0.6}\right)^5 + 1$ = 1.4 at S=80%

π_{SR}= 1

π_E = 1 for G_B

π_Q= 10

Failure Rate of diodes

The failure rate of diodes is expressed in (4)

$$\lambda_d = \lambda_0 \pi_T \pi_{CCF} \pi_S \pi_Q \pi_E \text{ Failures/}10^6 \text{ hours} \quad (4)$$

π_{CCF}= Contact construction factor

Fast recovery power rectifier is considered

λ_0= 0.025

$\Pi_T = \exp\left(-3091\left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right)$

$T_J = T_C + \theta_{JC} \times P_D$

$T_C = T_A + \theta_{CA} \times P_D$

π_S= 0.054

π_S= $V_S^{2.43}$

V_S = Voltage stress ratio = $\frac{Voltageapplied}{Voltagerated}$

Voltage is diode reverse voltage

π_C = 1 for metallurgically bonded

π_Q = 8 (plastic)

π_E = 1 for G_B

Failure Rate of IGBT

The MILHDBK-217F does not cover the failure rate model of IGBT. The failure rate parameters are given in the public database in(Equipment, 1991). In this paper, the parameters for failure rate calculation of IGBT will be used from(Handbook and Fiabilite, 2000). The failure rate of IGBT is expressed in (5)

$$\lambda_{IGBT} = \lambda_0 \pi_T \pi_S \pi_Q \pi_E \text{ Failures/}10^9 \text{ hours} \quad (5)$$

Where λ_0 = failure rate reference, at T_j= 100°C

$\Pi_T = \exp\left(-4640\left(\frac{1}{373} - \frac{1}{T_j+273}\right)\right)$

λ_0 depends on the device package and its technological class

T_j = Junction temperature (in °C)

$\pi_S = 0.22\, e^{1.7\frac{V_{ceoff-state}}{V_{cerated}}}$

π_E = Environmental factor = 1

π_Q= Quality factor = 8

Table 2. Assumed values for various failure rate parameters for different components.

Component	Failure rate	Factors
IGBT	$\boldsymbol{\lambda_{IGBT} = \lambda_0 \pi_T \pi_S \pi_Q \pi_E}$ **Failures/10^9 hour**	$\lambda_0 = \mathbf{0.75}$ $\pi_T = \exp\left(-3480\left(\frac{1}{373} - \frac{1}{T_j + 273}\right)\right)$ **= 0.1672 (T_j= 40°C)** $\pi_S = 0.22\, e^{1.7 \frac{V_{ceoff-state}}{V_{cerated}}}$ $\pi_E = \mathbf{1}$ $\pi_Q = \mathbf{8}$
Diode	$\lambda_d = \lambda_0 \pi_T \pi_{CCF} \pi_S \pi_Q \pi_E$ Failures/10^6 hours	$\lambda_0 = \mathbf{0.025}$ π_S= 0.56 π_S= $V_S^{2.43}$ V_S = Voltage stress ratio = $\frac{Voltageapplied}{Voltagerated}$ $\pi_T = \exp\left(-3091\left(\frac{1}{T_j+273} - \frac{1}{298}\right)\right)$ = 2.2 (50°C) $T_J = T_C + \theta_{JC} \times P_D$ $\boldsymbol{T_C = T_A + \theta_{CA} \times P_D}$ $\pi_{CCF} = \mathbf{1}$ $\pi_E = \mathbf{1}$ ***and*** $\pi_Q = \mathbf{8}$
Capacitor (Aluminum Electrolytic)	$\lambda_{Cap} = \lambda_0 \pi_T \pi_{CF} \pi_V \pi_{SR} \pi_Q \pi_E$ Failures/10^6 hours **Temperature rating = 120^{0C}** **Capacitance = 5000μF** **S = 80%**	$\lambda_0 = \mathbf{0.00012}$ π_T= $\exp\left(-4062\left(\frac{1}{T_a+273} - \frac{1}{298}\right)\right)$ $\pi_T = \mathbf{2.9}$ $\pi_C = \boldsymbol{C^{0.23}} = \mathbf{7.09}$ $\pi_V = \left(\frac{\boldsymbol{S}}{\mathbf{0.6}}\right)^{\mathbf{5}} + \mathbf{1} = \mathbf{8.6}$ $\pi_{SR} = \mathbf{1}$, $\pi_E = \mathbf{1}$ $\pi_Q = \mathbf{10}$

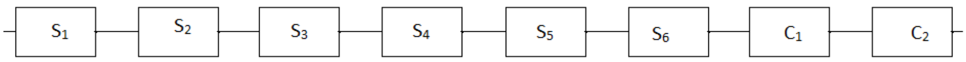

Figure 3. RBD of single leg of ANPC

Reliability Evaluation and Comparison

Three-level ANPC topology (shown in Figure 2) has four switches only in a single leg. To get the desired performance of the converter, all these components are necessary. Hence, the RBD is a series connection of all these components for this topology, reported in Figure 3.

The reliability of the three-level ANPC is evaluated using the failure rates in section 3. Four cases are taken to examine the impact of voltage stress on reliability of ANPC. The first step involved in the reliability evaluation is the RBD representation of these topologies. In case I, the reliability and stress factor (π_S) of ANPC are calculated. In case II, a pair of low-rated IGBTs in series are used instead of single high-rated outer switches S_1 and S_4. A pair of high-rated switches connected in series replaces the single high-rated outer switches S_1 and S_4 in case III to introduce series redundancy and develop a fault-tolerant topology. The failure rates of both the redundant components are assumed to be the same (λ), i.e., voltage-independent.

In case IV (voltage-dependent), when both components are operating, they have the same failure rate, which is symbolized by λ_1. If one of the two components fails, the other will continue to function with λ_2. The value of λ_2 will be greater than the value of λ_1 due to the increase in stress when one component fails.

Case I

The reliability of the three-level ANPC is evaluated using Reliability Block Diagram shown in Figure 3. The failure rates are calculated using the Military-Handbook-217F (Equipment, 1991) and are given in Table 2.

One leg of ANPC topology consists of six IGBTs and two capacitors. The converter will fail if any one of the switches fails.

Case II

The outer high rated switches S_1 and S_4 (3300V) are replaced by a pair of low rated switches (1700V) to analyse the impact of voltage stress on overall reliability, and shown in Figure 4. However, the failure (short circuit) of any pair of switches will cause the system to fail, making it a fault intolerant topology. This arrangement will decrease the losses, also this article emphasis on the effect of voltage stress on the devices. The stress factor will increase, which will reduce the overall reliability and is quantified under the results section. The reliability block diagram for this case is shown in Figure 5.

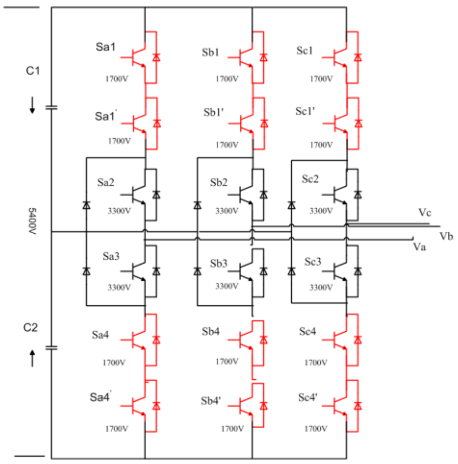

Figure 4. Topology for case II

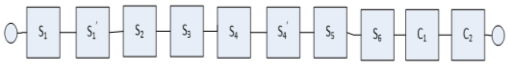

Figure 5. RBD for case II

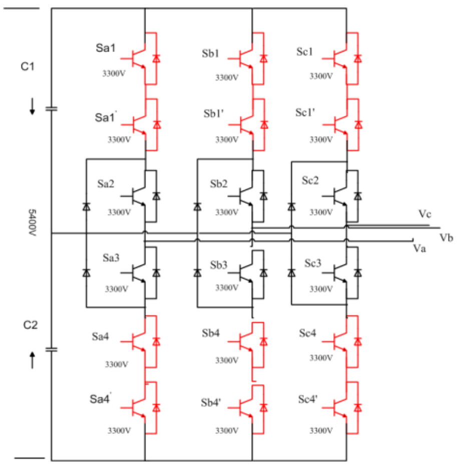

Figure 6. Topology for case III

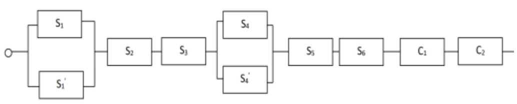

Figure 7. RBD for case III

Case III

In this case, the outer high-rated switches $S_1$and S_4 are replaced by a pair of switches of the same rating, as shown in Figure 6. This arrangement makes this topology fault-tolerant by making the pair of high-rated switches redundant. A disadvantage of this topology is the increase in power loss and cost. However, with introduction of redundant switches and the reduction in the stress of the redundant switches increases the reliability of this topology. This arrangement is ideal for mission-critical a system where cost is not a constraint. The failure rate of both the redundant switches is presumed to be same, i.e., the arrangement is voltage-independent. The reliability block diagram of this topology is shown in Figure 7.

Case IV

This case is similar to case III, but the failure rates of redundant switches are voltage-dependent. When both components are Operating, they have the same failure rate, which is denoted by $\lambda_{1.}$ If one of the two components fails, the other will continue to function with λ_2. The value of λ_2 will be greater than the value of λ_1 due to the increase in stress when one of the switches fails.

Results

From the failure rates and the reliability block diagram, the reliability of all four cases is evaluated. It is plotted against time to study the effect of voltage stress on the reliability of the active neutral point converter. Figure 8 and Figure 9 shows the reliability of all four cases in the single and three-phase modes. It is clear from the graphs that the reliability of case III is the highest, followed by case IV. CaseI has the lowest reliability. Case III possesses the highest reliability among all four cases due to redundancy and reduction in the voltage stress on the redundant switches. Figure 10 shows the reliability of case 3 in single-phase and three-phase modes. It is clear from the graph that the reliability of ANPC in three-phase mode is greater than the reliability of ANPC in single-phase mode due to the 2 out of 3 redundancies in three-phase mode.

The value of stress factor (π_S) of outer IGBTs (S_1 and S_4) is evaluated using equation (11) for ‘all the four cases and is given in Table 3. Case I has a stress factor of 0.8841, which is reduced to 0.8486 in case 2 due to low-rated series IGBT switches. The stress factor is reduced to 0.4410 in case III and case IV due to high-rated switches, which reduce the stress on the switches.

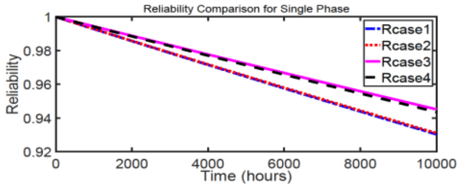

Figure 8. Reliability comparison of four cases in single-phase mode

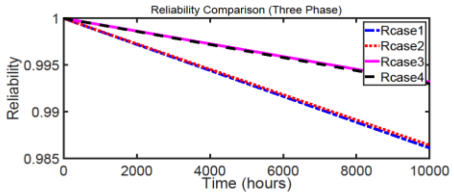

Figure 9. Reliability comparison of four cases in a three-phase mode

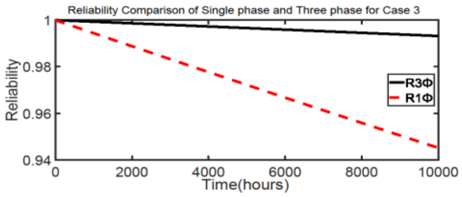

Figure 10. Reliability comparison of single-phase and three-phase modes for case 3

Table 3. Voltage Stress Factor (π_S) for the four cases

Case	Stress factor (π_S)
Case 1	0.8841
Case 2	0.8486
Case 3	0.4410
Case 4	0.4410

Conclusion

The failure rate of power electronic switches is high (approximately 34 percent). Hence, determining the converters' reliability is essential. A large number of studies have focused on developing a reliable, cost-effective, and fault-tolerant topology, as well as reducing components. Despite this, the reliability of these topologies has gained little consideration. The effect of voltage stress on the reliability of three-level Active Neutral Point Clamped (ANPC) multilevel inverters is investigated in this article. In ANPC, redundant outer switches are used to add series redundancy, rendering it a fault-tolerant topology. This fault-tolerant topology is compared to the fault-intolerant ANPC in terms of reliability. Because of the decreased stress on the switches and the redundant configuration of the outer switches, the proposed fault-tolerant ANPC is more reliable.

The voltage stress factor is calculated for both the fault intolerant and proposed fault-tolerant ANPC topology. The fault-tolerant topology presented in this paper has the lowest voltage stress factor, resulting in increased reliability.

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References

Agelidis, M.C. and V.G. (1998). Martina Calais Vassilios G. Agelidis. IEEE International Symposium on Industrial Electronics. Proceedings. ISIE'98 (Cat. No.98TH8357)., 1:224-229. https://doi.org/doi: 10.1109/ISIE.1998.707781

Akagi, H. (2017). Multilevel Converters: Fundamental Circuits and Systems. Proceedings of the IEEE. https://doi.org/10.1109/JPROC.2017.2682105

Akbari, A., Ebrahimi, J., Jafarian, Y., and Bakhshai, A. (2022). A Multilevel Inverter Topology with an Improved Reliability and a Reduced Number of Components. IEEE J. of Emerging And Selected Topics In Power Electronics., 10(1):553-563. doi: 10.1109/jestpe.2021.3089867

Akmaliyah, M. (2013). Fault-Tolerant Operation of a 150KW 3-Level Neutral-Point-Clamped PWM Inverter in a Flywheel Energy Storage System. J. of Chemical Information and Modeling., 53(9):1,689-1,699.

Ceballos, S., Member, S., Pou, J., Robles, E., Gabiola, I., Zaragoza, J., Villate, J.L., and Boroyevich, D. (2008). Three-Level Converter Topologies with Switch Breakdown Fault-Tolerance Capability. IEEE Transactions on Industrial Electronics., 55(3):982-995.

Chen, A., Hu, L., Chen, L., Deng, Y., Yao, G., and He, X. (2004). A multilevel converter topology with fault tolerant ability. Conference Proceedings. IEEE Applied Power Electronics Conference and Exposition - APEC., 3(2):1,610-1,616. https://doi.org/10.1109/apec.2004.1296080

Chen, G., Zhang, J., Zhu, M., Dai, N., and Cai, X. (2014). Optimized design for multi-MW wind power converter based on efficiency and reliability. Int. Power Electronics Conference, IPEC-Hiroshima - ECCE Asia., 1,769-1,774. https://doi.org/10.1109/IPEC.2014.6869823

Equipment, E. (1991). Reliability Prediction of Electronic Equipment (Military Handbook). Department of Defense of the USA., 205.

Fahad, M., Alsultan, M., Ahmad, S., Sarwar, A., Tariq, M., and Khan, I. (2021). Reliability Analysis and Fault-Tolerant Operation in a Multilevel Inverter for Industrial Application. Electronics., 11(1):98. doi: 10.3390/electronics11010098

Floricau, D., Popescu, C. L., Popescu, M. O., Floricau, E., and Spataru, L. (2009). A comparison of efficiency for three-level NPC and active NPC voltage source converters. CPE 2009 - 6th International Conference-Workshop -

Compatability and Power Electronics., 331-336. https://doi.org/10.1109/CPE.2009.5156055

Fortes, G.O., Mendes, M.A.S., and Cortizo, P.C. (2019). Integrated solution for driving series-connected IGBTs and its natural intrinsic balancing. Energies., 12(12):1-15. https://doi.org/10.3390/en12122406

Franquelo, L.G., Rodriguez, J., Leon, J.I., Kouro, S., Portillo, R., and Prats, M.A.M. (2008). The age of multilevel converters arrives. IEEE Industrial Electronics Magazine. https://doi.org/10.1109/MIE.2008.923519

Guerrero-Guerrero, A.F., Ustariz-Farfan, A.J., Tacca, H.E., and Cano-Plata, E.A. (2019). Self-feeder driver for voltage balance in series connected IGBT associations. J. of Power Elec., 19(1):68-78. https://doi.org/10.6113/JPE.2019.19.1.68

Handbook, R.D., and Fiabilite, R.D.E.D.D.E. (2000). UTE C 80-810 July 2000 UNION TECHNIQUE DE L' ELECTRICITE. July.

Jahns, T.M., Blasko, V., and Member, S. (2001). Recent Advances in Power Electronics Technology for Industrial and Traction Machine Drives., 89(6):963-975.

Kou, X., Corzine, K.A., and Familiant, Y.L. (2004). A unique fault-tolerant design for flying capacitor multilevel inverter. IEEE Transactions on Power Electronics., 19(4):979-987 https://doi.org/10.1109/TPEL.2004.830037

Lee, J.C., Kim, T.J., Kang, D.W., and Hyun, D.S. (2006). A control method for improvement of reliability in fault tolerant NPC inverter system. PESC Record - IEEE Annual Power Electronics Specialists Conference. https://doi.org/10.1109/PESC.2006.1711954

Lee, J.D., Kim, T.J., Lee, J.C., and Hyun, D.S. (2007). A novel fault detection of an open-switch fault in the NPC inverter system. IECON Proceedings (Industrial Electronics Conference)., 1:1,565-1,569. https://doi.org/10.1109/IECON.2007.4460204

Li, S., and Xu, L. (2006). Strategies of fault tolerant operation for three-level PWM inverters. IEEE Transactions on Power Electronics., 21(4):933-940. https://doi.org/10.1109/TPEL.2006.876867

Mads Chr, Pilgaard Vaerens, J.S. (2008). Three-Level Inverter for Medium Level Voltage Using Series Connected IGBTs. In Master Thesis.: Vol. Spring. Alborg University.

Maharjan, L., Yamagishi, T., Akagi, H., and Asakura, J. (2010). Fault-tolerant operation of a battery-energy-storage system based on a multilevel cascade PWM converter with star configuration. IEEE Transactions on Power Electronics., 25(9):2,386-2,396. https://doi.org/10.1109/TPEL.2010.2047407

Munk-Nielsen, S., Vaerens, M.C.P., and Sundvall, J. (2009). Three level MV converter using series connected IGBT's. 2009 13th European Conference on Power Electronics and Applications., EPE '09:1-7.

Nawaz, M.Z., and Khalil, M. (2020). Techniques for Connecting IGBT Modules and Loss Mitigation: A Survey. SPCE Portland 2020 - IEEE Symposium on Product Compliance Engineering, Proceedings, November. https://doi.org/10.1109/SPCE50045.2020.9296164

Nguyen, T. Van., Jeannin, P., Vagnon, E., Frey, D., Nguyen, T. Van., Jeannin, P., Vagnon, E., Frey, D., Series, J.C., Nguyen, T., Jeannin, P., Vagnon, E., Frey, D., and Crebier, J. (2010). Series connection of IGBT. APEC 2010, Feb 2010, Palm Springs, United States., p. 2,238-2,244.

Richardeau, F., Baudesson, P., and Meynard, T.A. (2002). Failures-tolerance and remedial strategies of a PWM multicell inverter. IEEE Transactions on Power Electronics., 17(6):905-912. https://doi.org/10.1109/TPEL.2002.805588

Rodríguez, J., Pontt, J., Musalem, R., and Hammond, P. (2004). Operation of a medium-voltage drive under faulty conditions 8.14. Conference Proceedings - IPEMC 2004: 4th International Power Electronics and Motion Control Conference., 2(4):799-803.

Rodríguez, Jose, Leon, J.I., Kouro, S., Portillo, R., and Prats, M.A.M. (2008). The Age of Multilevel Converters Arrives. June., 28-39.

Saketi, S., Chaturvedi, P., Yadeo, D., and Atkar, D. (2020). Loss study and reliability analysis of a new reconfigurable fault-tolerant multilevel inverter topology. IET Power Electronics., 13(18):4,291-4,303. doi: 10.1049/iet-pel.2020.0913

Shammas, N.Y.A., Withanage, R., and Chamund, D. (2006). Review of series and parallel connection of IGBTs. IEE Proceedings - Circuits Devices and Systems., 153(1):34-39.

Son, M., Lee, T., Kwon, S., and Cho, Y. (2020). Impact of snubber parameters on voltage sharing in series-connected insulated gate bipolar transistors. J. of Power Elec., 20(4):1,002-1,014. https://doi.org/10.1007/s43236-020-00094-8

Song, W., and Huang, A.Q. (2010). Fault-tolerant design and control strategy for cascaded H-bridge multilevel converter-based STATCOM. IEEE Transactions on Industrial Electronics., 57(8):2,700-2,708. https://doi.org/10.1109/TIE.2009.2036019

Tao, H., Duarte, J.L., and Hendrix, M.A.M. (2008). Line-interactive UPS using a fuel cell as the primary source. IEEE Transactions on Industrial Elec., 55(8):3,012-3,021. https://doi.org/10.1109/TIE.2008.918472

Turpin, C., Baudesson, P., Richardeau, F., Forest, F., and Meynard, T.A. (2002). Fault management of multicell converters. IEEE Transactions on Industrial Electronics., 49(5):988-997. https://doi.org/10.1109/TIE.2002.803196

Wang, Y., Chen, G., and Wang, F. (2013). A novel hybrid three-level NPC topology with digital driven serial connected IGBTs for medium voltage multi-MW wind power converter. Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC., 2,807-2,810. https://doi.org/10.1109/APEC.2013.6520695

Withanage, R., and Shammas, N. (2012). Series connection of Insulated Gate Bipolar Transistors (IGBTs). IEEE Transactions on Power Electronics., 27(4):2,204-2,212. https://doi.org/10.1109/TPEL.2011.2167000

Zhang, W., Xu, D., Enjeti, P.N., Li, H., Hawke, J.T., and Krishnamoorthy, H.S. (2014). Survey on fault-tolerant techniques for power electronic converters. IEEE Transactions on Power Electronics., 29(12):6,319-6,331. https://doi.org/10.1109/TPEL.2014.2304561

Zhang, W., Xu, D., Li, X., Xie, R., Li, H., Dong, D., Sun, C., and Chen, M. (2013). Seamless transfer control strategy for fuel cell uninterruptible power supply system. IEEE Transactions on Power Electronics., 28(2):717-729. https://doi.org/10.1109/TPEL.2012.2204777