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Fault Tolerant Multilevel Inverter Using Artificial Neural Network

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A B S T R A C T

Inverters have been widely used in renewable energy as a means of converting extracted power to grid standards. However, this power electronics equipment is highly vulnerable to failures due to its complex architecture and components. One of the main sources of failure is semiconductor switches that are critically sensitive to abnormal conditions such as high voltage. With the advent of multilevel inverters, this concern has been raised considerably due to the increase in the number of switches. This paper has proposed a novel method with a neural network that can detect open circuit failure of switches and replace them with some new arrangement in the inverter so that it can run effectively. Simulations with MATLAB/Simulink for a seven level inverter, illustrate that with a switch failure, the multilevel inverter can work successfully. Results also demonstrate that this method is fast and can compensate for the output in less than two cycles. Therefore, it can be used in reliable multilevel applications in which the power flow should be achieved even if a semiconductor switch is broken.

1. Introduction

Renewable energy has received wide attention in recent years. One of the key components in converting energy to standard electric energy is inverter. Inverters have also been modified to improve their output power quality. Multi-Level Inverters (MLIs) are the latest generation of inverters that have suggested better power quality and less voltage stress on switches [1]. This advantage has made MLIs an ideal candidate in other applications such as in Flexible AC Transmission Systems (FACTS) [2]. However, their reliability has been compromised due to the excessive number of semiconductor switches which are highly prone to failure[3, 4]. Although some researchers have proposed new topologies in which they have reduced the number of switches to generate the same output voltage levels, the number of utilized semiconductors are still comparable to the conventional bridge inverter [5, 6].

It is worth mentioning that the topology capability to use redundant switches in case of a failure is very critical. The MLI presented in [7, 8] has parallel

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switches in the inner switches, which provide the redundancy states for fault tolerance analysis. Therefore, the number of devices is indeed remarkably high. The inner voltage levels in the parent topology possess intrinsic redundancy [9]. Although the reference paper's main goal is to improve dependability, it neglects to consider the influence of inherent redundancy on the parent topologies' overall power loss [10, 11].

Converters can suffer from different failures i.e., open circuit (OC) and short circuit (SC) [12, 13]. Since the SC fault occurs quickly and is difficult to detect, the diagnosis and system protection of the SC fault is mainly solved by hardware circuit design. The SC fault can also be converted into an OC fault for processing by connecting the fast fuse to the circuit [14].

Therefore, new approaches have been proposed to overcome this problem by detecting faults in the switches and applying innovative scenarios to run the inverter in these conditions. One of the methods for fault detection is the Park method [15]. In this method, the average of all three phase currents is calculated. The average should be zero unless a fault occurs in the switches. The identification of the faulty power switch can be achieved by determining the interval in which the average motor supply current Park's Vector falls. Another approach is called the modified normalized DC current method, in which a less restrictive way to localize the faulty switch is employed. The normalization of the component takes place by dividing the direct component of phase current by its first harmonic absolute value. The result will be used to arrange a table based on the results for each phase. If a switch is broken, there will be a substantial change in the value by which the faulty switch can be identified [16]. An approach called the slope method proposes the slope of the trajectory in the complex plain of park transformation of phase current can be used for fault detection and identification [17]. In this method, the current polarity should be identified and the slope of the trajectory during a fault can suggest the faulty switch.

It is worth mentioning that the failure of switches will have an impact on the output voltage level. Therefore, there will be a deviation between the reference voltage and the measured one which can be used to detect the faulty switch [18]. Another approach is based on the fact that during normal operation, the voltage magnitude on lower switches is either zero or equal to bus voltage. However, during switch failure, this voltage will be about half the bus voltage. So, the failure can be recognized by measuring lower switch voltages [19].

There are several more methods for fault diagnoses. An approach based on certain logical judgment detects switch failure based on system parameters and some logical operation based on the switching sequences. This method needs some constants such as error margins, to be determined correctly so that the result becomes reliable. In addition, it is almost slow and takes about 100 ms to detect the fault [20]. Another approach uses a moving average filter to immune the diagnosis against noise. However, this method needs many sensors to measure the voltages of different capacitors in a flying capacitor topology [21].

Different methods and analytical techniques are also used to analyze the VSI switch fault. For example, Fast Fourier Transform (FFT) method is used to analyze the current spectrum for characteristics of an open transistor detection [22]. However, this technique needs high speed processors to calculate FFT. There are also other complex approaches, such as Wavelet-Fuzzy method and discrete wavelet–fuzzy control [23]. Wavelet transform is used to detect abnormal changes in phase current. Then, the DC offset and its polarity are calculated and fed to the fuzzy system to detect a broken switch [24]. Since wavelet is proven to have a better performance for detecting changes during failure, it is also used with neural networks to detect switch failure [25].

Artificial neural network (ANN) is considered a powerful control approach in nonlinear cases which can have training data [26]. So, ANN is adopted to detect switch failure in an inverter. This approach is achieved by training ANN with inverter parameters such as voltage and current.

In order to build a fault tolerant inverter, an effective control scenario should also be introduced to run the inverter at post fault instances. The approach is based on the inverter topology and is responsible for controlling the inverter during fault time so that the output voltage becomes the same as before or as near as possible to it [27].

This paper utilizes ANN to detect open circuit switch faults in a multilevel inverter. The main novelty of the research is applying ANN on a fault tolerant multilevel topology so that a faulty switch can be diagnosed quickly and the output can become stable fast. Unlike other mentioned approaches, this goal is achieved with less number of sensors (only output voltage) and does not need to measure the voltage at different points. In the method, PWM control of the inverter will be modified after the fault based on the detected broken switch, so that it can run with less adverse effect due to the failure. Simulations

with MATLAB/ Simulink prove the effectiveness of the approach for different fault conditions.

2. Fault tolerant topology

A proper multilevel topology should be selected so that this approach can lead to a continuous operation of the inverter. Most multilevel inverters utilize only high frequency switches in their circuit which are more expensive and prone to failure [28]. One of the latest achievements in multilevel topology is proposed in [11]. This approach separates high frequency and low frequency section switchs, culminating in a considerable reduction of high frequency switches. In addition, high frequency switches are more vulnerable to failure due to excessive switching loss and transients. Therefore, redundant switches can be assumed in this section so that the possible faults in this part can be managed. The resulting 7-level topology in which the high frequency redundant switch is introduced, is illustrated in Figure 1. According to the figure, Switches S1, S2, S3,S4, G and G2 work at high frequency, hence highly vulnerable to failure.

This topology can run even in case of an open circuit fault in switches. Therefore, this topology is adopted for fault tolerant operation of multilevel inverters.

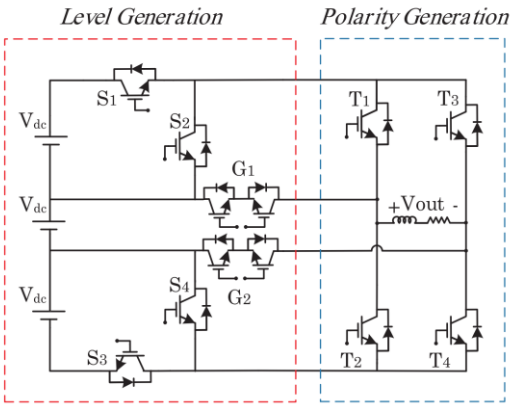

Figure 1. Redundant topology for multilevel inverter

It is pertinent to mention that this topology can be extended to higher output voltage levels.

3. PWM method

There are several modulation methods for driving an inverter which are generally categorized into high and low frequency methods. High frequency methods such as SPWM are not suitable for this purpose since they will impose considerable calculations to detect a fault in switches. Therefore, low frequency staircase (or nearest level control) method as shown in figure 2, is used in this paper [29]. In this method, limited angles (θ_1, $\theta 2$,$\theta 3$), as shown in figure 2, at which there should be a level change, are calculated. It is worth mentioning that there is another low frequency method for PWM, which is called selective harmonic elimination (SHE). It needs extensive calculations to find proper switching angles. Therefore,this method is not suitable for real time applications in which the system should respond quickly to the variations and disturbances [30].

Apart from its simplicity in calculations, it exhibits less switching loss due to its inherent low switching frequency. Therefore, this modulation method is adopted for this research. There are several approaches for applying staircase modulation.

Feed-forward method is the best method in which the step size for zero is the least. The equation for the method is used in this research as follows[29]:

$$\alpha_i = (1 / 2) * \sin^{-1}\big((2i - 1) / (m - 1)\big) \quad (1)$$

In which m is the number of levels and i is the corresponding level.

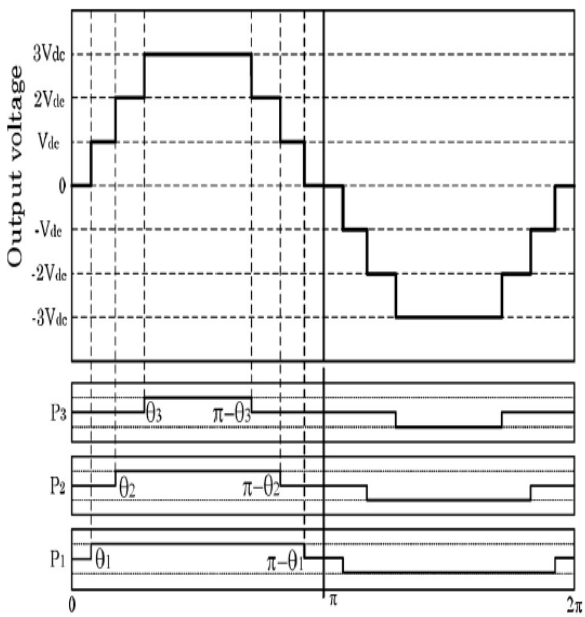

Figure 2. Staircase modulation scheme

4. Proposed method using neural networks

As stated in the previous section, there are a variety of methods to analyze the output waveforms of

inverters including: discrete Fourier transform, wavelet transform, and machine learning algorithms. In this paper, neural networks are used to analyze sampled output voltage and current of inverters. The data is sampled in different circuit situations, for example, open circuit instances in one switch, and collected relevant data are used to train the neural network.

4.1. Proposed neural network structure

In this paper, a neural network with three layers is used as depicted in figure 3. The first layer, called the input layer, contains two neurons corresponding to two input variables. The second layer, called the hidden layer, contains 20 neurons. The number of neurons in the hidden layer is determined using the following equation [31]:

$$k = \sqrt{I + O} + \theta \qquad (2)$$

In this equation, k is the number of hidden neurons, I is the number of input neurons, O is the number of output neurons, and θ is a number between 1 and 10.

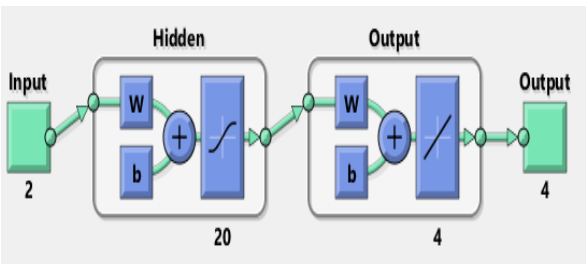

Figure 3. Details of the proposed neural network structure

Finally, the third layer, called the output layer, contains four neurons corresponding to four switches. Weights of neural networks are optimized using the Levenberg–Marquardt algorithm (LMA).

4.2. Data collection for training

Input data vectors are collected using MATLAB Simulink, as discussed in the previous section. Two input values, Δv_{rms} and v_{out}, are used in the experiments. Sample values of input features for different modulation indices are summarized in Table 1. It is pertinent to mention that each DC voltage source is 100 V. It means that with three DC sources as shown in figure 1, peak output voltage is 300V.

To improve the performance of the neural network, it needs more training data. By decreasing the simulation step size, it is possible to generate more data to train the network better.

Table 1. Sample values of input features.

	Δv_{rms} for m=0.1	Δv_{rms} for $m = 1$
s_1	35.52	48.28
s_2	31.7	33.7
s_3	62.25	75.78
s_4	3.07	4.26

5. Simulation results

In order to verify the approach, simulation is done in MATLAB/Simulink. The overall circuit of the fault tolerant inverter is as follows. This figure shows the topology, which is used as seven level fault tolerant inverter.

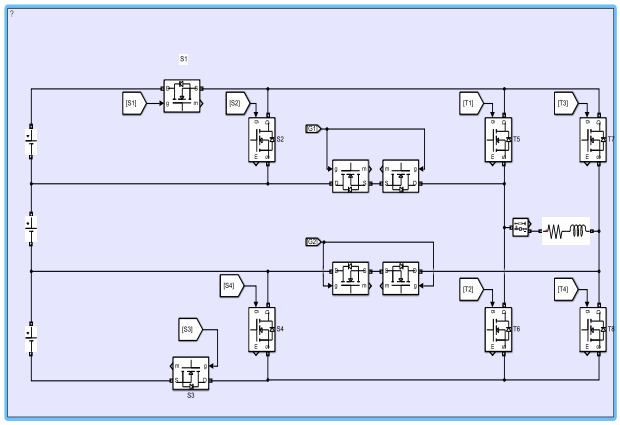

Figure 4. Simulink block diagram of the inverter

To train the neural networks, feature extraction is done in different fault scenarios. Then, it is used to identify any fault in the inverter and prompt the procedure to overcome the output voltage problem. The neural network block diagram is also depicted in figure 5.

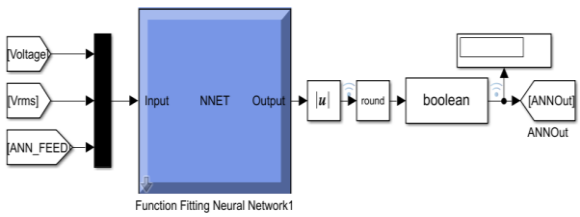

Figure 5. artificial neural network block diagram

The regression results for the training, test, validation and overall are depicted in the following diagrams. The results show that the system has been trained and validated properly and the data and the fitting curve are almost identical with negligible error.

In addition, the histogram of error in figure 7 clearly shows that the system has almost zero error in training, test and validation as the results are mostly located in the middle of the diagram which implies negligible error.

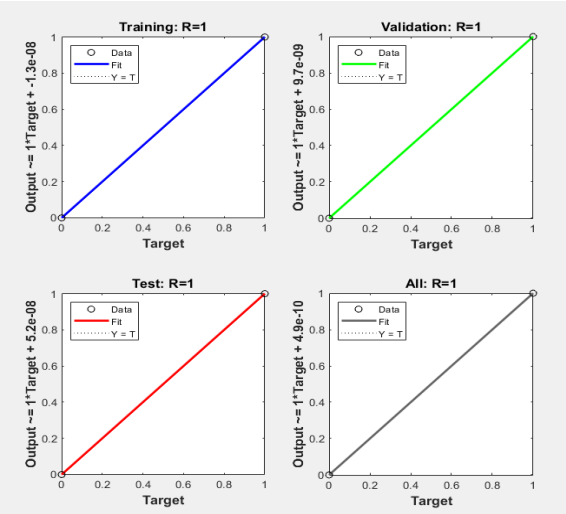

Figure 6. Error diagram for test, training , validation and overall

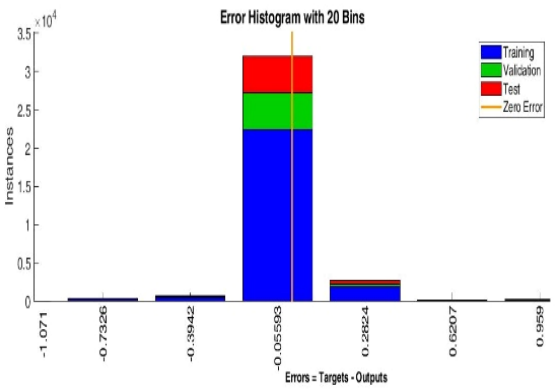

Figure 7. Histogram of errors for training, test, and validation

It is also worth mentioning that the fault detection scheme is disabled during the time that the fault is compensated. Otherwise, there will be a conflict between the fault state and the compensation state and the procedure will fail.

The results of faults at different switches are depicted in the following diagrams. Firstly, the modulation index is considered m=0.8, and the results of open circuit fault at t=0.1 in switches S2 and S4 and S1 are depicted as follows.

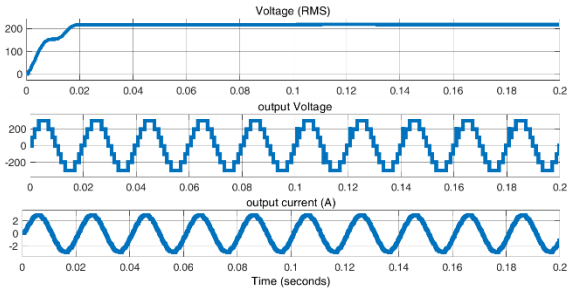

Figure 8. Output voltage of fault tolerant inverter when S2 is open circuited and m=0.8

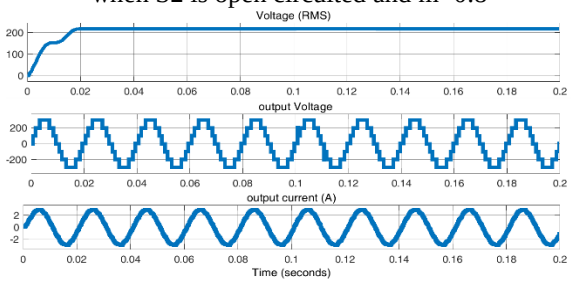

Figure 9. Output voltage of fault tolerant inverter when S4 is open circuited and m=0.8

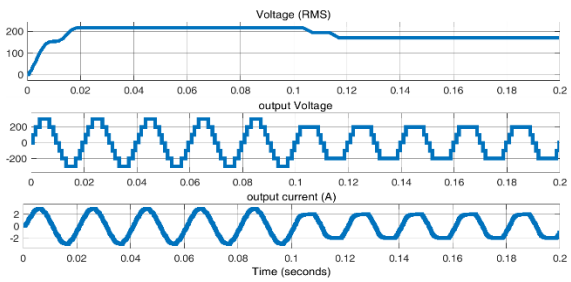

Figure 10 Output voltage of fault tolerant inverter when S1 is open circuited and m=0.8

In order to investigate the performance of the inverter in another modulation index, the fault is applied in modulation index m=0.4. The results show the effectiveness of the inverter in fault instances.

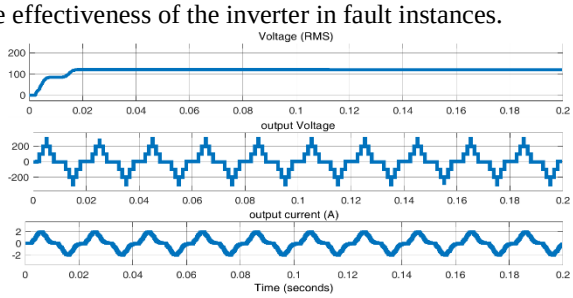

Figure 11. Output voltage of fault tolerant inverter when S2 is open circuited and m=0.4

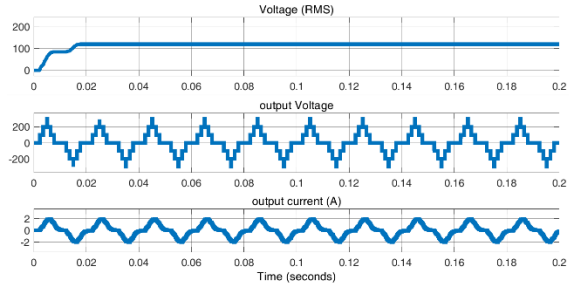

Figure 12. Output voltage of fault tolerant inverter when S4 is open circuited and m=0.4

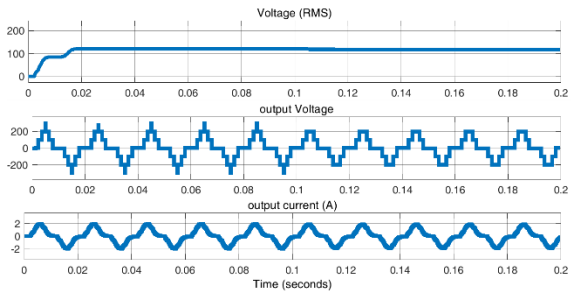

Figure 13. Output voltage of fault tolerant inverter when S1 is open circuited and m=0.4

The results in different modulation indexes and switches clearly illustrate the effectiveness of the proposed method. In comparison with other fault tolerant methods, this method only needs to measure the output voltage of the inverter unlike the method in which all separate voltage cells (3 cell in this system) should be measured [32]. Therefore, the proposed method has less number of measurement units and is also faster. Another special merit of the approach is its fast response compared to other methods. One of the fastest methods claims to achieve the fault tolerant procedure could work within two cycles (40 ms) [32]. In addition, some researchers have investigated different detection methods with new machine learning techniques in conjunction with digital wavelet transform (DWT) such as decision tree (DT) and support vector machine (SVM). The research illustrated that the fastest method took 0.433 seconds to detect open circuit faults [33].

It is worth mentioning that the transient time in the proposed method is 30ms which is much less than other methods.

6. Conclusion

This paper proposed a fault tolerant multilevel inverter in which open circuit switch fault can be detected and compensated. Therefore, the inverter can run successfully in case a switch is broken. In order to verify the method, three switches were intentionally open circuited in different scenarios at different modulation indexes. The proposed system successfully detected the failure and retrieved the output voltage. Furthermore, results show that this method can detect the faulty switch and compensate the output faster than available methods. This approach can be used in applications such as renewable energy in which the reliability of multilevel inverters is of paramount importance and they should run constantly even if a switch is broken. Electric planes can also use this technique to avoid electric propulsion failure due to inverter switch failure. This approach can also be implemented on different topologies and circuits.

Nomenclature

α_i	Output level change angle (kJ/K)
K	Number of hidden neurons
m	Modulation index
t	time (S)
ANN	Artificial neural network
FACTS	Flexible AC Transmission System
MLI	Multi- Level Inverter
VSI	Voltage Source Inverter
PWM	Pulse Width Modulation
SPWM	Sinusoidal Pulse Width Modulation
OC	Open Circuit
SC	Short Circuit

References

1. Najafi, E. and A. Yatim, Design and implementation of a new multilevel Inverter topology. IEEE Transactions on Industrial Electronics, 2011. **PP**(99): p. 1-1.DOI: 10.1109/tie.2011.2176691.
2. Hasanzadeh, S., et al., Power Quality Enhancement of the Distribution Network by Multilevel STATCOM-Compensated Based on Improved One-Cycle Controller. IEEE Access, 2022. **10**: p. 50578-50588.DOI: 10.1109/ACCESS.2022.3172144.

3. Falck, J., et al., Reliability of Power Electronic Systems: An Industry Perspective. IEEE Industrial Electronics Magazine, 2018. **12**(2): p. 24-35.DOI: 10.1109/MIE.2018.2825481.
4. Cheng, Y., et al., Open-circuit fault diagnosis of traction inverter based on compressed sensing theory. Chinese Journal of Electrical Engineering, 2020. **6**(1): p. 52-60.DOI: 10.23919/CJEE.2020.000004.
5. Beigi, L.M.A., et al. A new multilevel inverter topology with reduced number of power switches. in 2012 IEEE International Conference on Power and Energy (PECon). 2012.DOI: 10.1109/PECon.2012.6450277.
6. Zolfaghar, M., E. Najafi, and S. Hasanzadeh. A modified diode clamped inverter with reduced number of switches. in 2018 9th Annual Power Electronics, Drives Systems and Technologies Conference (PEDSTC). 2018.DOI: 10.1109/PEDSTC.2018.8343771.
7. Aly, M., E.M. Ahmed, and M. Shoyama, A New Single-Phase Five-Level Inverter Topology for Single and Multiple Switches Fault Tolerance. IEEE Transactions on Power Electronics, 2018. **33**(11): p. 9198-9208.DOI: 10.1109/TPEL.2018.2792146.
8. Jalhotra, M., et al. Fault Tolerance and Energy Sharing Analysis of a Single Phase Multilevel Inverter Topology. in IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society. 2018.DOI: 10.1109/IECON.2018.8591853.
9. Sadanala, C., S. Pattnaik, and V.P. Singh, Fault tolerant architecture of an efficient five-level multilevel inverter with overload capability characteristics. IET Power Electronics, 2020. **13**(2): p. 368-376.DOI: https://doi.org/10.1049/iet-pel.2019.0736.
10. Soni, N., et al. A Simple Fault Tolerant Multilevel Inverter Topology. in 2018 8th IEEE India International Conference on Power Electronics (IICPE). 2018.DOI: 10.1109/IICPE.2018.8709448.
11. Choupan, R., et al., A new structure for multilevel inverters with fault-tolerant capability against open circuit faults. Electric Power Systems Research, 2019. **168**: p. 105-116.DOI: https://doi.org/10.1016/j.epsr.2018.11.013.
12. Gorla, N.B.Y., et al., A Novel Open-Circuit Fault Detection and Localization Scheme for Cascaded H-Bridge Stage of a Three-Stage Solid-State Transformer. IEEE Transactions on Power Electronics, 2021. **36**(8): p. 8713-8729.DOI: 10.1109/TPEL.2019.2918148.
13. Chai, M., N.B.Y. Gorla, and S.K. Panda, Fault Detection and Localization for Cascaded H-Bridge Multilevel Converter With Model Predictive Control. IEEE Transactions on Power Electronics, 2020. **35**(10): p. 10109-10120.DOI: 10.1109/TPEL.2020.2978670.
14. Oliveira, A.B.d.M., R.L. Moreno, and E.R. Ribeiro, Short-Circuit Fault Diagnosis Based on Rough Sets Theory for a Single-Phase Inverter. IEEE Transactions on Power Electronics, 2019. **34**(5): p. 4747-4764.DOI: 10.1109/TPEL.2018.2861564.
15. Mendes, A.M.S. and A.J.M. Cardoso. Voltage source inverter fault diagnosis in variable speed AC drives, by the average current Park's vector approach. in IEEE International Electric Machines and Drives Conference. IEMDC'99. Proceedings (Cat. No.99EX272). 1999.DOI: 10.1109/IEMDC.1999.769220.
16. Rothenhagen, K. and F.W. Fuchs. Performance of diagnosis methods for IGBT open circuit faults in voltage source active rectifiers. in 2004 IEEE 35th Annual Power Electronics Specialists Conference (IEEE Cat. No.04CH37551). 2004.DOI: 10.1109/PESC.2004.1354769.
17. Peuget, R., S. Courtine, and J.P. Rognon, Fault detection and isolation on a PWM inverter by knowledge-based model. IEEE Transactions on Industry Applications, 1998. **34**(6): p. 1318-1326.DOI: 10.1109/28.739017.
18. Ribeiro, R.L.d.A., et al., Fault detection of open-switch damage in voltage-fed PWM motor drive systems. IEEE Transactions on Power Electronics, 2003. **18**(2): p. 587-593.DOI: 10.1109/TPEL.2003.809351.
19. Yu, O.S., N.J. Park, and D.S. Hyun. A Novel Fault Detection Scheme for Voltage Fed PWM Inverter. in IECON 2006 - 32nd Annual Conference on IEEE Industrial Electronics. 2006.DOI: 10.1109/IECON.2006.347541.
20. Zhang, G. and J. Yu, Open-circuit fault diagnosis for cascaded H-bridge multilevel inverter based on LS-PWM technique. CPSS Transactions on Power Electronics and Applications, 2021. **6**(3): p. 201-

208.DOI: 10.24295/CPSSTPEA.2021.00018.
21. Fard, M.T., et al., Fast online diagnosis of open-circuit switching faults in flying capacitor multilevel inverters. Chinese Journal of Electrical Engineering, 2020. **6**(4): p. 53-62.DOI: 10.23919/CJEE.2020.000030.
22. Bilal Djamal Eddine, C., et al., A Comparative Study on Some Fault Diagnosis Techniques in Three-Phase Inverter Fed Induction Motors, in Fault Detection and Diagnosis, V. Constantin, Editor. 2018, IntechOpen: Rijeka. p. Ch. 4.DOI: 10.5772/intechopen.79960.
23. Alapati, S.M. and V. Singh. A Novel Approach for Fault Diagnosis of Multilevel Inverter Using Dwt and Fuzzy Logic Algorithm. in 2021 2nd International Conference on Smart Electronics and Communication (ICOSEC). 2021.DOI: 10.1109/ICOSEC51865.2021.9591900.
24. Mamat, M.R., M. Rizon, and M.S. Khanniche, Fault Detection of 3-Phase VSI using Wavelet-Fuzzy Algorithm. American Journal of Applied Sciences, 2006. **3**(1).DOI: 10.3844/ajassp.2006.1642.1648.
25. Charfi, F., F. Sellami, and K. Al-Haddad. Fault Diagnostic in Power System Using Wavelet Transforms and Neural Networks. in 2006 IEEE International Symposium on Industrial Electronics. 2006.DOI: 10.1109/ISIE.2006.295798.
26. Mohsenzadeh, M.M., et al., Flashover voltage and time prediction of polluted silicone rubber insulator based on artificial neural networks. Electric Power Systems Research, 2023. **221**: p. 109456.DOI: https://doi.org/10.1016/j.epsr.2023.109456.
27. Ning, Y., et al. Open-circuit fault-tolerant control of power switch for two-level three-phase motor inverter. in 2023 IEEE PELS Students and Young Professionals Symposium (SYPS). 2023.DOI: 10.1109/SYPS59767.2023.10268141.
28. Kumar, M.S., V.B. Borghate, and S. Sabyasachi. A Generalized Fault Tolerant Multilevel Inverter for Switch Open-Circuit Faults. in 2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES). 2018.DOI: 10.1109/PEDES.2018.8707742.
29. E., A.M. and I. C. Staircase Modulation for Thirteen level cascaded H Bridge Inverter with Different Staircase Wave Generation Techniques. in the International Conference on Systems, Energy & Environment (ICSEE). 2021.DOI: 10.2139/ssrn.3798296.
30. Shang, F., et al. Optimization Modulation Method of Seven-level SHEPWM Inverter Based on TSA-PSO. in 2023 3rd International Conference on Electrical Engineering and Mechatronics Technology (ICEEMT). 2023.DOI: 10.1109/ICEEMT59522.2023.10262982.
31. Uzair, M. and N. Jamil. Effects of Hidden Layers on the Efficiency of Neural networks. in 2020 IEEE 23rd International Multitopic Conference (INMIC). 2020.DOI: 10.1109/INMIC50486.2020.9318195.
32. Stonier, A.A. and B. Lehman, An Intelligent-Based Fault-Tolerant System for Solar-Fed Cascaded Multilevel Inverters. IEEE Transactions on Energy Conversion, 2018. **33**(3): p. 1047-1057.DOI: 10.1109/TEC.2017.2786299.
33. Achintya, P. and L.K. Sahu. Open Circuit Switch Fault Detection in Multilevel Inverter Topology using Machine Learning Techniques. in 2020 IEEE 9th Power India International Conference (PIICON). 2020.DOI: 10.1109/PIICON49524.2020.9112870.