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# A Comprehensive Review on Switch Fault Diagnosis in Neutral-Point-Clamped (NPC) Converters

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***Abstract*—Multilevel inverters have gained popularity during the last several years. Among its beneficial features are lower switching frequencies and lower electrical limitations on power switches, which leads to higher quality output voltage. The efficiency and dependability of intensity electronic converters used in power systems may be improved by precise fault localization. A Neutral Point Clamped (NPC) three-level inverter is the most common kind of converter used to power electric engines inside the force framework. Using a constant voltage-to-recurrence ratio, this research proposes several methods for finding open-circuit deficiencies and pinpointing their locations in the NPC three-level inverter for a mobile approach. It is recommended to use an information mining algorithm to choose individual electrical periods from continuous three-stage flow data in order to analyse open-circuit failure as quickly as possible. To comprehend the state organisation, the observable characteristics of the electrical period signals are extracted, and a random timberland model is constructed. The suggested computation, in contrast to the standard method of fault assessment, identifies problem regions quickly and accurately. Tests verify the feasibility and accuracy of the suggested computation.**

***Keywords*— *Five-level Neutral-point clamped (NPC) Converter; Open-switch fault; Short-switch fault diagnosis, Photovoltaic.***

## I. Introduction

As compared to traditional two-level converters, multilevel converter topologies provide benefits such as a higher maximum DC-link voltage and improved input current harmonics. As a result, three-tier neutral-point clamped (NPC) topology systems have been the subject of a great deal of study and find widespread use across a range of sectors. Many classes may be used to organize NPC topological system research issues. Most studies focus on neutral-point voltage balancing methods [4-8] and pulse-width modulation (PWM) approaches for better performance [1-3]. The efficiency of systems based on NPC topology has been enhanced because to several research initiatives.

As the three-tier NPC structure has been adopted by so many sectors, its dependability has become a pressing concern [9]. A harmonic filter, current and voltage transducers, gate driver circuits, and power semiconductors such insulated-gate bipolar transistors make up the converter system (IGBTs). This means the system is susceptible to a wide range of errors. One of the most challenging aspects of the three-level NPC converter architecture is troubleshooting switching device, gate drive circuit, and IGBT-related failures. Short-circuit faults and open-switch faults are two subcategories of switching device problems.

Over-voltage and avalanche stress are typical causes of short-circuit defects in IGBTs [10], along with problems in the gate drive circuit. In the event of a short-circuit defect in the converter system, the power grid is promptly severed from the converter system using circuit breakers or fuses [11, 12].

There have been a number of articles that offer different fault diagnostic and tolerant control strategies to increase the system's dependability and safety under the open-switch fault state. Most studies rely on phase current measurements from sensors to pinpoint the problematic switch for diagnosing open-switch faults. Using the angle derivative of the current vector, a two-level PWM AC/DC converter system may identify an open-switch defect [13, 14]. A defective switch may be located using either a current vector pattern or an absolute normalized value of current on the d-q frame, as shown in [15, 16]. In [17-21], the authors present a technique for diagnosing a three-level NPC converter based on the current pattern's radius, residual, and form. If there is a problem with a three-level T-type rectifier, it may be determined by analyzing the current's phase angle profile [22]. Other sensor circuits may monitor pole voltage and clamped diode current to identify an open-switch fault [23, 24] in place of the phase current. Due to the high price of the sensor circuits, however, these approaches are not advised. Single or multiple open-switch failures of inner switches in three-level NPC active rectifiers may be detected using a vector trajectory of the DC-link voltage ripple, as reported in previous studies [25, 26].

Five-voltage waveforms from line to line and three-voltage waveforms from line to neutral are also possible in a NPC architecture. Four IGBTs are linked in series, with the phase outputs at the node; the DC bus input is wired to the top row of devices (Al, Bl, C1) and the bottom row (A4, B4, C4). The DC bus's ground node, shown by the symbol 10, is linked to two diodes in series for each phase. The six clamping diodes attached to the neutral bus regulate the voltage supplied to each phase leg's quartet of IGBTs. With a traditional inverter, the switches must be able to withstand the whole voltage difference between the DC buses. As the NPCI switches on each side of the neutral bus are in series and there is a real neutral point, the voltage drop (stress) across each switch is half of the voltage between the positive and negative buses. When connecting the gate and emitter terminals of two different IGBTs, each device's unique gate signal must be used as a reference. Each IGBT has a "body diode" built into its construction, and it appears as a separate component between the collector and emitter.

## II. LITERATURE SURVEY

In this part, we will examine and contrast a variety of defect detection and classification algorithms

In this study [5,] a novel approach to managing three-level neutral-point-clamped (NPC) rectifiers is used in order to achieve voltage equilibrium in capacitors. A model that takes into account phase-by-phase duty ratios serves as the foundation for the innovative control method. The model includes nine different duty cycle variables. Despite the peculiar wording, the control problem of currents and dc-link voltage may be described in a manner that is comparable to more conventional methods. The regulation of the capacitor voltage balance may be described using equations that are disconnected from the dynamics of the currents and the dc-link voltage. This can result in a specialized controller that does not affect the dynamics that came before it. The formulation of the recommended strategy already includes an element of the modulation stage. Examines and contrasts two controllers. This problem can be circumvented, according to the new controller that has been proposed, by accomplishing the same level of performance with fewer commutations.

It is possible, with the appropriate variable adjustments, to express dc-link voltage and active and reactive power management concerns in a manner that is comparable to other conventional approaches. As a result of the elimination of a crucial part of the modulation process, the voltage balance controller may be constructed quickly. As a result of this, the approach that was offered may be interpreted as a control method, with a portion of the modulation step integrated in the control formulation (ICM). Even if the recommended control rule is easier to implement than modified versions of space vector modulation (SVM) [16] that further handle capacitor voltage imbalance, it still has advantages over CB-PWM. The modulation step has been made simpler without compromising the adaptability of SVM

The author of this work [1] proposes fault diagnosis and tolerance control methodologies for an open-switch failure in a three-phase three-level NPC PWM active rectifier. They are presented in the context of the study. A three-level NPC dynamic rectifier that has an open-switch deficiency will create information stage current mutilation as well as a DC-interface capacitor voltage wave. The proper identification of the source of the problem and the implementation of lax control procedures are essential in order to forestall more dissatisfaction and corrector system corruption. This study examined the effect that a single open-switch failure has on the NPC PWM dynamic rectifier and offered a deficiency conclusion approach that makes use of the DC interface voltage and the information lattice voltage. This study provides a deficit forgiving control approach with the goal of minimising the open-switch impact by providing a reward for a misshaped reference voltage. The results of the trial provide support for the proposed deficiencies analysis and laxity control processes.

An approach that is based on phase current time series measurements has been proposed in this work [2] under a variety of different operating conditions (motor speed, load, and environment noise). The processes of fault identification and classification are investigated, and the usefulness of the selected criteria is established. For the purpose of increasing performance in defect identification, we make use of the first four statistical moments, extracted features, and the Cumulative Sum technique (CUSUM). For the study on categorization, we recommend combining statistical moments with Kullback-Leibler divergence, which may identify changes that are only beginning to take place. PCA is used in the classification process. Faults may be efficiently categorized using a 2D framework under the operational conditions that were taken into consideration for each fault duration that was specified.

The solution that has been proposed is straightforward, and it lessens the dv/dt as well as the total harmonic distortion in the ac output voltages. NPC inverters are used often in grid-connected systems as well as high-power industrial applications. Some examples of these applications are high-voltage dc transmission, static VAR compensators, and high-power adjustable-speed motor drives.

 

The NPC inverter has a greater number of switches than the two-level inverter. There is a greater likelihood of malfunctions with NPC inverter switches.

A system shut down is not required in the event of an open-circuit malfunction. It's possible that it will make some noise and vibrate. Faults in open switches that are not handled might cause secondary problems in other parts of the system. It is very important to monitor switching device faults; hence, the present research provides a technique for detecting and localizing an open-switch fault in a single switch for a grid-connected NPC inverter. This is because monitoring switching device faults is extremely important.

Most manufacturing operations might be more productive if they were less expensive to make. This is accomplished by boosting the output of all electrical machinery and equipment and expanding the size of existing installations. There are two routes to this boost in strength: By 1) creating a multilayer inverter and 2) constructing high-voltage semiconductors with voltage blocking capabilities of 3,300, 4,500, and 6,500 volts. The medium-voltage (MV) network may now be connected directly to the power converter. Just one structure, the voltage-source two-level inverter, is widely used at low voltage. At higher voltages, though, things change dramatically. Figure 2.1 shows how the market and uses for industrial MV drives are split across a number of different topologies. It is feasible to utilise either direct converters (cycloconverters) or indirect converters (with a dc connection of either current or voltage) for high-power applications.

In recent years, the nominal voltage and power ratings of self-commutated converters have increased dramatically thanks to the continuous development of high-voltage insulated-gate bipolar transistors (IGBTs) and integrated-gate commutated thyristors (IGCTs) and the application of these power semiconductors in several multilevel voltage-source converter (VSC) topologies. Thyristor-based converters have been mostly phased out in favour of pulsewidth modulation (PWM) VSCs. Reasons for this include the system's many benefits, such as its ride through capability, its ability to eliminate line harmonics, its longer working range, its changeable power factor at the point of common coupling, and its radically enhanced dynamic performance

In terms of architecture, voltage-source multilevel inverters are often categorized into neutral point clamped (NPC), flying capacitor (FLC), and cascade H-bridge designs. The NPC inverter, first developed 25 years ago, is the most extensively used high-power converter across all industries. It typically operates at 2.3 to 4.16 kV, but may go up to 6 kV in certain circumstances.

There are two broad categories into which the diagnostic methods described in the literature fall. Several techniques proposed by authors [12], [16] require measuring the voltage and/or current at each switch. The current and voltage sensors included into the gate drivers may be used for this purpose. This means that no extra hardware is required. In these cases, you may learn if a switch failed in a short or open circuit. For instance, if the voltage across a single switch is zero in all circumstances, regardless of the condition of the gate signal, this indicates a short-circuit problem at that switch. On the other hand, some approaches rely on output phase voltage or current measurements [7], [8] to provide a solution. After a problem, the phase voltage or current recorded in the defective leg is off from what would normally be seen. To ascertain which insulated-gate bipolar transistor (IGBT) has failed, an error signal is created and analysed

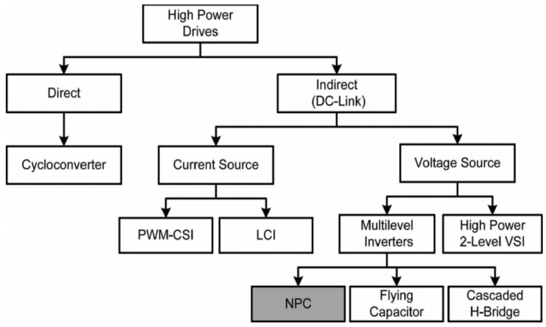


Figure 1: Classification of Inverter topologies used for High power applications

### A. *Summary of Literature Review*

The NPC inverter is already widely used in high-power applications and may be regarded a fully developed architecture. Redundant states definitively resolve the issue of capacitor voltage balancing, which was formerly seen as a shortcoming of this design

For operating with low switching frequency, as required by this architecture, the most popular modulation algorithms have been classical pulsewidth modulation, SVM, and SHE. Also popular is hysteresis control, which employs slower switching rates. The ANPC is used to remedy the issue of passive NPC's uneven loss distribution throughout its semi-conductors. DTC and field-oriented control are two of the most common methods used to regulate speed. Predictive control's ease of implementation and excellent performance make it a compelling option for future advancement. With their small size, high efficiency, and reliable operation, NPC inverters are quickly finding new uses

## III. FAULTS DIAGNOSIS METHODOLOGY

Several methods of NPC converter diagnostics are discussed in this section. There are two main categories into which the many approaches presented in the literature may be categorized. Some solutions are built on a three-pronged architecture, for example. The fundamental benefit of these approaches is their ease of implementation. Yet, the converters' poor performance in imperfect situations is a consequence of their simplicity. Nonetheless, there are several options based on four-legged topologies. Despite the increased complexity of the converter architectures in these scenarios, they are nonetheless able to function normally after a failure, providing the same level of performance as they did before the incident. Topologies of primary importance are discussed here.

 

### A. Fault Diagnosis Methods

There are two broad categories into which the diagnostic methods described in the literature fall.

1) Several techniques proposed by authors [12], [16] require measuring the voltage and/or current at each switch. The current and voltage sensors included into the gate drivers may be used for this purpose. This means that no extra hardware is required. In these cases, you may learn if a switch failed in a short or open circuit. For instance, if the voltage across a single switch is zero in all circumstances, regardless of the condition of the gate signal, this indicates a short-circuit problem at that switch.

2) On the other hand, some approaches rely on output phase voltage or current measurements [7], [8] to provide a solution. After a problem, the phase voltage or current recorded in the defective leg is off from what would normally be seen. To ascertain which insulated-gate bipolar transistor (IGBT) has failed, an error signal is created and analyzed.

### B. Hardware Solutions

1) Three-Legged Topologies: Solution I In [10], the authors present a fairly straightforward fault-tolerant solution for a NPC converter that can handle short-circuit failures. As no additional power components are required for this design, the fault-tolerant converter may look just like a regular one (Figure 3.1). The redundancy of voltage vectors in NPC converters allows for fault-tolerant operation. This section provides explanations of several possible failure circumstances in this topology. For instance, phase a cannot provide level "1" if the switch Sa4 fails in short circuit. As Sa4 is now closed, the corresponding voltage vectors in this figure have been eliminated. Yet, the converter keeps running thanks to the built-in redundancy of its voltage vectors. Nonetheless, the entire dc-link voltage must be tolerated by the switches. The converter's design approach need to include in this aspect.

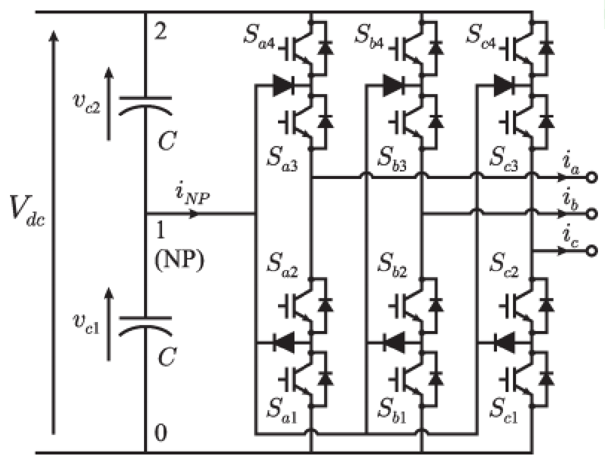

Figure 2: NPC Converter

But, phase 'a' is unable to provide level "0" if switches Sa3 and Sa4 fail in short circuit. Some voltage vectors (those located on the outside boundaries of the vector diagram) are off-limits in this scenario. As the reference vector in a steady state defines a circle on the plane, the maximum modulation index is cut in half (it is assumed that the maximum modulation index under normal operation mode is equal to one). In [11], the authors offer a similar method for a five-level converter.

The second solution, shown in Figure 3.2 [12], is an effort to provide the aforementioned topology with open-circuit fault tolerance capabilities. The NPC converter's fundamental design thus incorporates three sets of thyristors. When either of the converter's switches open, these new components will make the connection from the defective leg to the NP.

The problems and possible solutions presented in [13]–[15] are similar. Whether the defect is an open circuit or a short circuit, the bad leg may always be linked to the NP of the converter. Thus, there is no need to enlarge the semiconductors so that they can survive over-voltages. However, this means that the maximum modulation index will always be cut in half when a problem is present. There are a variety of modulation techniques available today.

To operate the converter even if one of the legs is defective. According to the space-vector theory, only voltage vectors within the shaded region may be created in order to produce sinusoidal three-phase voltages. Moreover, certain approaches have been developed from the viewpoint of carrier-based pulse width modulation (PWM). The primary goal of these techniques is to produce a series of voltages with a 60-degree phase difference.

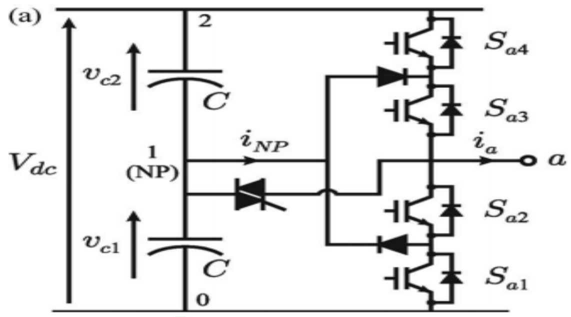

Figure 3: NPC fault-tolerant converter leg

Third, another approach is described in [16] that can handle both open and short circuit failures. This approach makes use of the supplementary IGBTs proposed in the proposed topology described in [17]. By creating new redundant switching states, these extra switches are employed to equalize power losses across devices under typical operating settings. This allows for a massive boost in output power. When a switch in one leg fails, the other leg's extra switching states may be used to continue the circuit. The additional switches are used to link the defective phase to the converter's NP. The authors use a PWM modulation technique using a collection of modulation signals once the converter has been reprogrammed. As the power semiconductors in this architecture won't be subjected to any overvoltages, they won't need to be oversized like they would be in other systems. Nevertheless, under fault conditions, the maximum modulation index is cut in half.

Fourth, in fault operation mode, the modulation index must be lowered in all of the aforementioned solutions. Because of this, grid-connected applications are not a good fit for such solutions. In [18], the authors make an effort to find a solution. Fast fuses and thyristors are included in the basic architecture, as can be shown. In the event of a malfunction, the current will recirculate via the clamping diodes, therefore these fuses will protect the dc-bus capacitors from being shorted out. In addition, semiconductors must be used that will always cause a short circuit in the event of a malfunction. Many companies now sell these IGBTs to consumers (using press-pack technology). As an alternative, a pair of thyristors might be connected in parallel with each IGBT and triggered to create a short circuit in the event of an IGBT failure.

### *C. Modulation and Control Strategies for Three-Level NPC Inverters*

The basic voltage-age delivered by the three-level inverter may be regulated in three different ways. These are some of the approaches:

Space vector modulation (SVM), carrier-based PWM, and selective harmonic elimination are the three methods (SHE).

The inputs of either the motor side inverter or the side active front end (AFE) may be modulated and controlled in the same way.

Three-level NPC inverters apply the control mechanisms shown briefly in Figure 3.3:

Direct torque control (DTC), predictive torque control (PTC), and linear controller using pulse width modulators (PWM).

Figure 3.4 depicts the traditional linear current control approach. This common and useful strategy must regulate the load voltage at its most basic level. Thus, a carrier-based or SVM modulator is required.

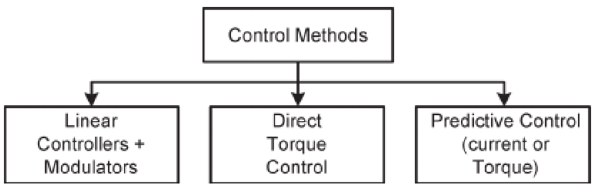


Figure 6: Control methods for three-level NPC inverters

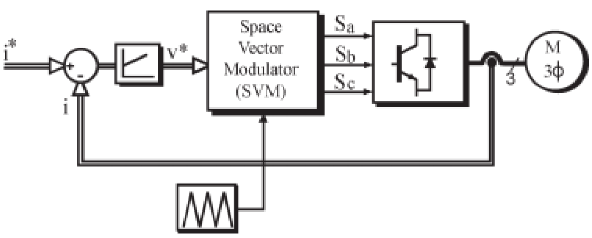


Figure 4: Linear current control

The benefits listed below highlight why predictive control is such a viable option.

1) The ideas are straightforward and simple to grasp.

2) It has broad systemic applicability.

3) The scenario with several variables may be readily taken into account.

4) it's possible to make up for downtime.

5) Nonlinearities may be added to the model with little effort.

6) Constraints are handled simply

7) The developed controller can be easily implemented.

8) Variations and additions to the technique are welcome as needed for particular uses.

### *D. Advantages of Three-Level NPC Inverters*

The exceptional success that the three-level NPC VSC (3L-NPC-VSC) has had on the market may be attributed to the fact that it has a number of appealing characteristics. A modular design that has great reliability and availability is made possible by power electronic building blocks (PEBBs) that are based on IGCTs and IGBTs. Moreover, the low component count of power parts makes this design possible. Applications that need high power and several drives may make use of the standard DC bus designs. The converter is able to function in a grid-friendly manner if an extra sine filter or higher pulse transformers (12p and higher) are used for the AFE solution, or if 12p, 18p, or 24p diode rectifiers are used.

Very high flexibility may be achieved by only including certain choices, such as braking choppers or dv/dt, on either the machine or the transformer side of the equation. Rolling mills are one example of an application that has extremely high dynamic requirements and may benefit from the use of sophisticated control strategies such as vector control or direct torque control to achieve a good dynamic behaviour.

## IV. CONCLUSION

For the NPC inverter with grid connection, techniques for open-circuit fault detection and fault-tolerant control have been presented. This research begins by considering the operation of the network-connected NPC inverter during an open-circuit failure. Network-connected NPC inverter architecture now includes open-circuit problem diagnosis and problem-tolerant control methods. Existing approaches, which were developed based on the bends in outputs for the conventional two-level inverter structure, have difficulty distinguishing the fault switch under the lattice-associated situation. If the output current of the faulty stage drops by half during this period, you know you have a problem with the switches or squeezing diodes. Injecting an underexcited receptive current for a short time is a hallmark of a faulty switch between the top and bottom switches. On account of the open-circuit deficiency in the clipping diode, the faulttolerant control technique can be applied. The NPC inverter may be used with respectable output execution and without de-rating of the output power, despite an increase in the THD of the output flows.

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