Open-Switch Fault Diagnosis in Neutral-Point-Clamped (NPC) Inverter Using Data-Mining Technique

Avdhesh Yadav, Santosh Kumar

Department of Electrical & Electronics Engineering, Millennium Institute of Technology & Science, Bhopal (M.P)

***Abstract* –As the inverter is designed around insulated gate bipolar transistor as the power switching devices. The inverter employs software generation of the gate signals for the power switches and gate driver electronics to ensure reliability and insulation between the high power and low power circuitry. The inverter produces a true three level line-to-neutral voltage waveform and a true five level line-to-line voltage waveform. In this paper, different methodologies for open-circuit deficiency discovery and area of the NPC three-level inverter for a moving procedure utilizing a steady voltage-to-recurrence proportion is proposed. So as to analyze open-circuit shortcoming in as short a period as could be expected under the circumstances, information mining calculation is proposed to pick single electrical periods from continuous three-stage flow signals. The measurable qualities of the electrical period signals are extricated, and an arbitrary timberland model is built to understand the state arrangement. Contrasted and the customary fault determination strategy, the proposed calculation discovers issue areas rapidly and precisely. The adequacy and exactness of the proposed calculation are confirmed by tests.**

***Index Terms*—three-level neutral-point clamped (NPC) active rectifier; open-switch fault; fault diagnosis and tolerant control method; space vector modulation (SVM).**

I. INTRODUCTION

Multilevel converter topologies provide advantages in terms of increasing the allowable DC-link voltage and the better harmonics of the input current in comparison with the conventional two-level converters. Hence, three-level neutral-point clamped (NPC) topology systems have been researched in several papers and widely used in various industries. The research topics on the NPC topology systems can be categorized into several groups. Most of the research is related to pulse-width modulation (PWM) techniques for improved performance [1–3] and balancing algorithms of the neutral-point voltages [4–8]. As the results of various research efforts, the performance of NPC topology systems has been greatly improved.

Since the three-level NPC topology has been widely applied to various industries, the system reliability has emerged as an important issue [9]. The converter system consists of a number of components such as a harmonic filter, current and voltage transducers, gate driver circuits and power semiconductors, such as insulated gate bipolar transistors (IGBTs). For this reason, this system is vulnerable to various failures. The faults related to the switching devices, gate drive circuits and IGBTs are among the major issues that need to be dealt with in three-level NPC converter topology. Those faults in the switching devices are further classified into short-circuit faults and open-switch faults.

Generally, short-circuit faults are caused by a malfunction of the gate drive circuit and an intrinsic failure of the IGBT, such as over-voltage and avalanche stress [10]. If the short-circuit fault occurs in the converter system, the circuit breakers or fuses immediately disconnect the power grid from the converter system to avoid the destruction of the system [11,12].

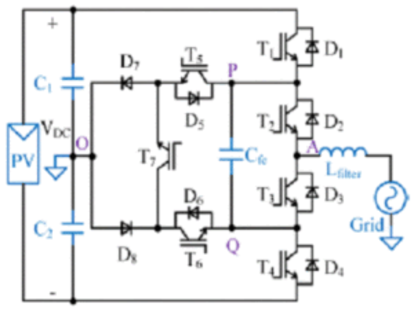


Figure 1: Neutral-point clamped (NPC).

The distorted current causes a fluctuation in the DC-link capacitor voltage and a voltage imbalance between the upper and lower capacitors. If the converter system is continuously operated under the open-switch fault condition, additional failures might occur on other devices and systems connected with the DC-link. In general, the converter system will pause to prevent further failure and repair. However, a sudden shutdown of the converter system causes significant financial losses in a renewable power generation or at some production plants. For this reason, a fault diagnosis and tolerant control method are required to continue operating the converter system.

- **NPC FAULT LEVEL ANALYSIS**

The inverter consists of A, B, and C three-phase bridge arms. Taking A-phase bridge arm as an example, this consists of four power switches (sa1−sa4), four free-wheeling diodes (VD11 − VD14), and two clamping diodes (D1 − D2). Each free-wheeling diode is connected in antiparallel with the power switch to provide a reverse conduction loop for the current. The clamp diode is used to connect the power switches and the midpoint of the DC side capacitor. The output threephase phase voltage signals of the inverter are filtered by LC filter to supply power for the load. The three-phase bridge arms are composed of 12 power switches. The state of each power switch is controlled by the corresponding gate signal. When the gate signal is 1(high level), the power switch is turned on; when the gate signal is 0(low level), the power switch is turned off. The switching mode of the inverter is determined by the modulation strategy. Common modulation strategies include pulse width modulation (PWM), sinusoidal pulse width modulation (SPWM), and space vector pulse width modulation (SVPWM), etc. Among them, SVPWM modulation strategy has the advantages of small harmonic components and high DC utilization, therefore SVPWM modulation strategy is used to control the gate signals of the power switches in this paper.

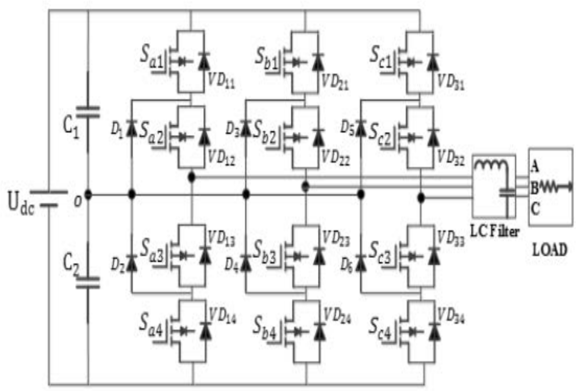


Figure 2: Circuit diagram of the NPC multi-level inverter.

In the actual operation process, In general, short-circuit faults are avoided by the protection circuit. Once short-circuit faults occur in the power switches, the protection circuit is quickly disconnected, eventually converting the short-circuit faults into open-circuit faults [10]. Because short-circuit faults have a short time duration and are rapidly turned into open-circuit faults, this paper focuses on the diagnosis of open-circuit faults in NPC three-level inverter power switches only. NPC three-level inverter power switches are consisted of 12 insulated-gate bipolar transistor (IGBT) devices. Due to the location and number of faulty power switches are random, there can be many types of open-circuit faults. In general, the possibility that three or more power switches all occur open-circuit faults at the same time is very small. This paper focuses on fault diagnosis in the case of open-circuit faults in one power switch or in two power switches.

Open-circuit faults of power switches are divided into four categories:

(1) the power switches all operating normally, which is considered a special fault condition;

(2) only one power switch occurs open-circuit fault;

(3) two power switches simultaneously occur open-circuit faults on a single-phase bridge arm; and

(4) two power switches simultaneously occur opencircuit faults on two crossed arms. There are 73 fault types in these four fault categories, all of which will be discussed in this paper.

II. LITERATUE REVIEW

In this section the comparison of the techniques which are proposed by several authors in order to perform fault detection as well as the classification is performed.

In this paper [5] author uses a novel approach for the control of three-level neutral-point-clamped (NPC) rectifiers in order to tackle the capacitor voltage balance problem. A distinctive feature of the new control approach is that it is based on a model which is written in terms of the duty ratios for each phase at each level. Hence, the system model presents nine duty cycle variables. Despite the fact that this formulation is different from the usual ones, it is shown that the control problem of currents and dc-link voltage can be formulated in a similar way to conventional methods. Furthermore, the control of the capacitor voltage balance can be expressed by means of equations that are decoupled from the currents and dc-link voltage dynamics, which results in a specific controller for the voltage balancing that does not affect the previous dynamics. A key point of the proposed approach is that part of the modulation stage is implicit in the formulation. Two particular controllers are compared in this paper. This problem is overcome in a new proposed controller, which presents similar performance and a satisfactory number of commutations.

In [29], it is shown that this formulation allows to explicitly consider, in the control design stage, the extra degree of freedom associated with the injection of homopolar component. The increase in the number of variables does not make the design significantly more difficult since, with an appropriate change of variables, the dc-link voltage and active and reactive power control problems can be formulated in a similar way to other usual approaches. As a result, the voltage balance controller can be easily designed at the same time that an important part of modulation is not needed. For this, the proposed approach can be considered as a control method with part of the modulation stage included in the control formulation, therefore, in what follows it would be called "Integrated Control and Modulation" (ICM). The main advantage of the proposed control law is its simplicity in implementation compared to modified versions of space vector modulation (SVM) [16] that also tackle the capacitor voltage unbalance but it still presents some advantages with respect to CB-PWM approaches. This is due to the fact that the modulation stage is simplified without losing part of the flexibility of SVM.

In this paper [1] author proposes a fault diagnosis and tolerant control methods for an open-switch fault caused in a three-phase three-level neutral-point-clamped (NPC) pulse-width modulation (PWM) active rectifier. The open-switch deficiency in the three-level NPC dynamic rectifier causes a mutilation in the information stage current and a wave in the DC-interface capacitor voltage. Subsequently, appropriate fault determination and lenient control strategies are required to forestall extra disappointments and execution corruption in the rectifier framework. This paper led a definite investigation of the impact of the single open-switch fault on the NPC PWM dynamic rectifier and proposed a deficiency conclusion strategy using the DC interface voltage and the stage point of the information lattice voltage. Moreover, this paper proposes a deficiency lenient control technique to decrease the impact of the open-switch issue by remunerating a misshaped reference voltage. The viability of the proposed deficiency analysis and lenient control techniques are confirmed through trial results.

In this paper [2] author proposed an approach is based on the already available phase current time series measurements for different operating conditions (motor speed, load, and environment noise). Both fault detection and classification are studied and the efficiency performances of the proposed selected features are shown. For the fault detection, we focus on the first four statistical moments and the extracted features and then the Cumulative Sum (CUSUM) algorithm as the feature analysis technique to improve the performances. For the classification study, we propose to couple the knowledge on the faulty system brought by the statistical moments and the Kullback-Leibler divergence particularly suitable for the detection of incipient changes. The Principal Component Analysis (PCA) is then used to perform the classification. A 2D framework is obtained, which allows the faults to be classified efficiently within the considered operating conditions for all the selected fault durations.

III. PROBLEM DEFINITION

1. The proposed algorithm provides simple and dv/dt and total harmonic distortion in its ac output voltages are smaller in comparison to those in conventional two-level inverters. Owing to these advantages, the NPC inverters have been widely used in grid-connected systems and in high-power industrial applications such as voltage source converter based high-voltage dc transmission, static VAR compensators, and high-power adjustable-speed motor drives.
2. Since, the number of switches in the NPC inverter is much higher than in a two-level inverter. Therefore, the possibility of a switch fault in the NPC inverter is higher.
3. On the other hand, the open-circuit fault does not require the system to be shut down. However, it can induce noise and vibrations in the system. Therefore, if an open-switch fault is not handled immediately, it can cause secondary problems in other parts. Thus, it is important to monitor switching device faults and for this reason an approach involving the fault-detection and location of an open-switch fault in a single switch for a grid-connected NPC inverter has been proposed in the present work.

IV. PROPOSED METHODOLOGY

In this section the proposed methodology is described with the 5-level NPC inverter.

Simulation of Grid connected DC system with 5-level NPC inverter

Multilevel converters are widely considered to be the most suitable configurations for renewable energy sources. Their high-power quality, efficiency and performance make them interesting for PV applications. In low-power applications such as rooftop grid-connected PV systems, power converters with high efficiency and reliability are required. For this reason, 5 level NPC inverter based configurations have been proposed and commercialized in the industry.

Development of fault detector and locator

When there is a break in the conductor, it is called open-circuit fault. The open-circuit fault can check by a megger. For this purpose, the three conductors of the 3 core cable at far end are shorted and earthed. Then resistance between each conductors and earth is measured by a megger. The megger will indicate zero resistance in the circuit of the conductor that is not broken. However if a conductor is broken the megger will indicate an infinite resistance.

Wavelet transform based feature extraction

The wavelet change gives a proper premise to picture taking care of in light of its gainful highlights. The benefits of the wavelet change are:

1. The variable goal decay with practically uncorrelated coefficients.

2. The capacity of a dynamic transmission, which encourages the gathering of a picture at various characteristics.

SVM based fault detector and locator

SVM algorithm combined with kernel function has the nonlinear attribute and can better handle the case where samples and attributes are massive. In addition, with forehand optimizing the parameters using the cross-validation technique, SVM can produce high accuracy in fault detection. Therefore, there is no need to deal with original data or refer to other algorithms, making the classification problem simple to handle. By comparing the indices of detection performance, the SVM technique shows superior fault detection ability to the PLS algorithm.

Algorithm flowchart-

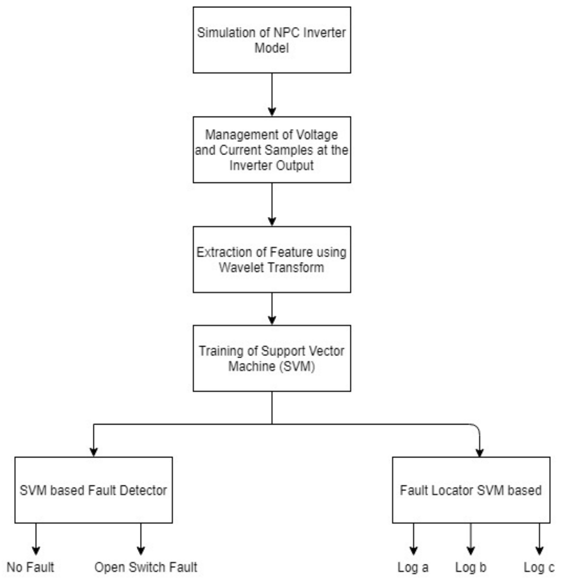


Figure 3: Flowchart of proposed algorithm.

In the above figure 3 the flowchart of the proposed algorithm has been proposed. Below is the descriptionof the following steps involved in the flowchart-

Step 1: The work of the proposed algorithm starts from the simualation of the NPC inverter model which is the first step.

Step2: In the second step the function call goes at the management of the current and voltage samples at the inverter outputs.

Step 3: In the third step the control will switch to the extraction of the features with the help of wavelet transform.

Step 4: In the next step training of support vector machine will work thoroughly. The loop will follow the following conditions- if the fault detects then the function control will go to the SVM based fault detector and generate output as –no fault and open switch fault. Otherwise, in second category it will generate outptus as-fault locator SVM based as log a, log b and log c.

V. SIMULATION SETUP

For the Experimental simulation, the simulation has been done using MATLAB simulation. The MATLAB code was developed using the MATLAB m-file editor toolbox. The test results and performance of the fault algorithm are shown in the following below sections.

Parameters Used

The model is able to analyze the variation of PV parameters such as the ideality factor , Series resistance, thermal voltage and Band gap energy of the PV module with temperature as well as time. Finally a novel intelligent method based on Probabilistic Neural Network for fault detection and classification for PV farm with string inverter technology is proposed.

Result Analysis

In this section the outputs obtained at different stages is given-

PV Array-

It contains seven module strings with 3350 parallel strings. The convertor is shapely employing a 5-level Neutral purpose clamped (NPC) electrical converter. The electrical converter choke RL and alittle harmonics filter C square measure wont to filter the harmonics generated by the IGBT bridge. A 250-kVA 250V/25kV two-phase electrical device is employed to attach the electrical converter to the utility distribution system.

Inverter management

The system contains 5 major Simulink based mostly subsystems:

• MPPT Controller: the utmost electric receptacle chase (MPPT) controller is predicated on the 'Perturb and Observe' technique. This MPPT system mechanically varies the VDC reference signal of the electrical converter VDC regulator so as to get a DC voltage which is able to extract most power from the PV array.

• VDC Regulator: confirm the desired Id (active current) reference for this regulator.

• Current Regulator: supported this references Id and I.Q. (reactive current), the regulator determines the desired reference voltages for the electrical converter. In our example, the I.Q. reference is ready to zero.

• PLL & Measurements: needed for synchronization and voltage/current measurements.

• PWM Generator: Generate firing signals to the IGBTs supported the desired reference voltages. In our example, the carrier frequency is ready to 1980 Hertz (33*60).

 ISSN: 2395-2946

Utility Grid.The grid is shapely as a typical distribution grid. It enclosed 2 thirty four.5 potential unit feeders, loads, grounding electrical device and constant 120-kV transmission.

Simulation
Run the simulation and observe the ensuing signals on the assorted scopes.

The initial input irradiance to the PV array model is a thousand W/m2 and also the operative temperature is forty five deg. C.

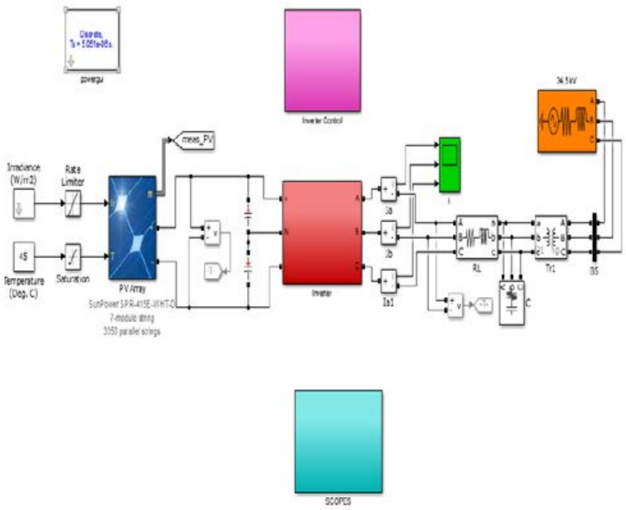


Figure 4: Grid connected PV system Simulink model.

The figure 4 above is of grid connected PV system without MPPT. The maximum power point is not achieved in this technique and the power from the PV array lost in many folds. The PWM technique is used in this to provide gate pulse to the inverter switches.

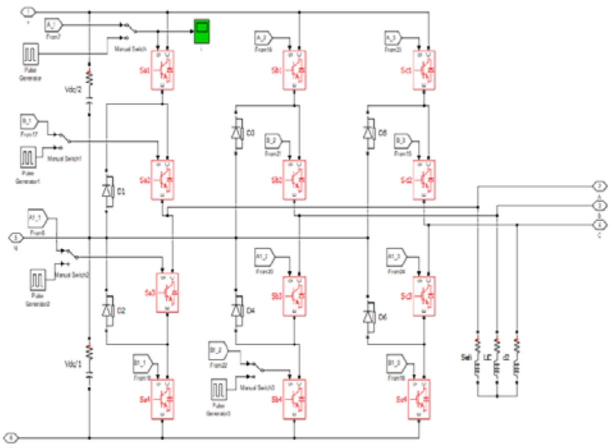


Figure 5: A simulink model of 5-level Neutral point clamped (NPC) inverter configuration.

In the above figure 5 the NPC multi-level inverter is prone to faults under high-frequency switching of power switches and complex environmental conditions. Most of the faults in the inverter are related to faults in the power switches, which include power switches open-circuit faults and short-circuit faults.

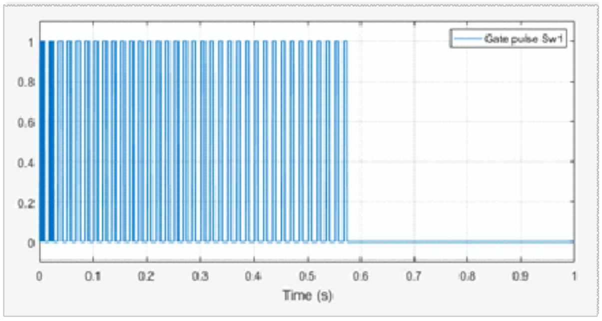
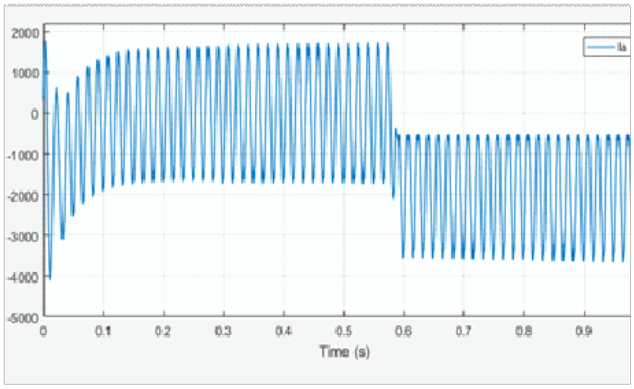
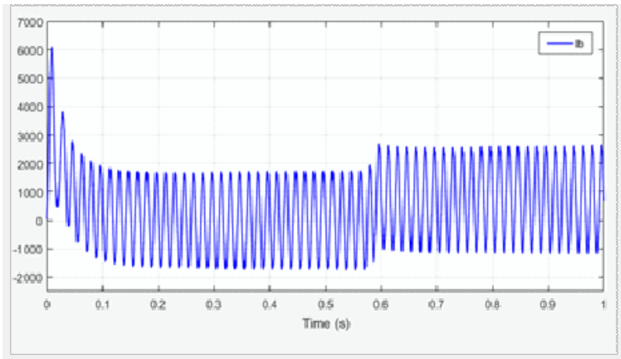


Figure 6: Gate pulse with switch Sa1 short-circuited at t=0.57s

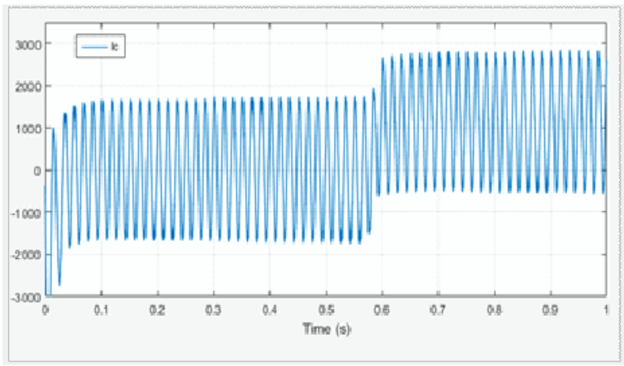
In the above figure 6 the graphical representation of the Gate pulse with switch Sa1 short-circuited at t=0.57s, the x-axis shows the time hich is denote in sec. the y-axis shows the gate pulse with the switch Sa1 t=0.57s.



(a)



(b)



(c)

Figure 7: Current waveform in the three phases due to short-circuit operation of the switch Sa1 at t=0.57s (a) Current in A phase, Ia (b) Current in B phase, Ib and (c) Current in C phase, Ic

In the above figure 7 the graphical representation of the Current waveform in the three phases due to short-circuit operation of Sa1 at t=0.57s, the x-axis shows the time which is denote in sec. the y-axis shows the gate pulse with the switch Sa1 at t=0.57s.

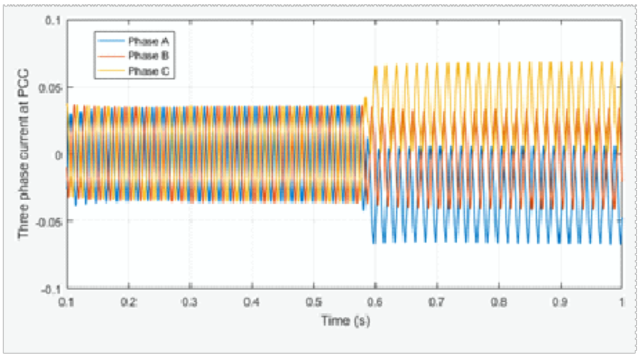


Figure 8: Three-phase current signal at PCC bus B1 due to the short circuited operation of Sa1.

In the above figure 8 the graphical representation of the Three-phase current signal at PCC bus B1 due to the short circuited operation of Sa2, the x-axis shows the time which is denote in sec. the y-axis shows the gate pulse with the switch Sa2.

Table 1: Performance of SVM based switch fault detection scheme.

S.No	Faulty Leg	Faulty operation of Switch	Detection accuracy of SVM (%)
1	Leg a	Sa1	99.5%
2		Sa2	98.9%
3		Sa3	99.3%
4		Sa4	98.0%
5	Leg b	Sb1	99.1%
6		Sb2	99.6%
7		Sb3	98.3%
8		Sb4	98.9%
9	Leg c	Sc1	99.0%
10		Sc2	99.3%
11		Sc3	99.1%
12		Sc4	98.7%
Overall accuracy			**98.97**

In the above table 1 the tabular representation of the obtained values are shown that determines the problem of fault detection system for a class of discrete-time switched systems subject to Gaussian noise. The faulty leg are described as leg a, leg b, leg c on which the faulty operation are performed from Sa1 to Sa4 onto several accuracy is also detected, second for Sb1 to Sb4 with an accuracy rate as well. Thus, an overall accuracy rate of 98.97 is achieved.

VI. CONCLUSION & FUTURE WORK

A simple and direct, but very interesting and valuable, model of neutral-point potential in three-level NPC converters is proposed. From this model, simulation and experiment, some conclusions can be drawn from this model, as follows: The basic reason for the neutral-point potential drift is the uneven shunt loss caused by parametric perturbation, and the capacitance error has no influence on it.

- Zero-sequence voltage can be used to control the potential drift with the combination of the active current of the converter.
- The total shunt loss, which is related to the output voltages and currents of the converter, is inversely proportional to the stable drift potential value.
- The total DC capacitance has no influence on the stable drift potential value, but it affects the dynamic performance and amplitude of the third component.

Future work will focus on NPC converters with a higher number of levels based on the proposed analysis method.

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