*Journal of Renewable Energy and Smart Systems* *Vol.1, No.2, 2024: 1-12*

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*Renewable Energy and Smart Systems*

*journal homepage: https://sanad.iau.ir/journal/res*

# Proposed an improved method for capacitor voltage grouping measurement and open circuit fault detection for modular multilevel converter

**Abouzar Ahmadi** [1], ***Master Student***, **Mahdiyeh Eslami**[*1], ***Assistant Professor***

[1] *Department of Electrical Engineering, Kerman Branch, Islamic Azad University, Kerman, Iran*

**Article info**

*Keywords:*
Modular Multi-Level Converter; Fault Detection; Capacitor Voltage; Semiconductor Switches; Reduction of Voltage Sensors.

*Article history:*
Received: 3 August 2024
Accepted: 2 September 2024

**Abstract**

Power electronics converters with the integration of renewable energies have become more and more popular. Among them, multi-level converters (MLCs), especially modular multi-level converters (MMCs), are good choices for high and medium power applications because of their ability to replace components, reduce or eliminate output filters, and have desirable power quality at the output. They also have low switching losses. MMCs are a good choice for direct current (DC) energy transmission applications because of their modular structure, lack of need for transformers, and other qualities. These features are in addition to the previously listed ones. Other electrical components, like switches and capacitors, are used more frequently in the converter structure of these devices as the number of sub-modules rises. However, because these components are present, errors are likely to occur in the modules. As a result, MMCs become less reliable. The MMC structure's widespread usage of voltage sensors makes capacitor voltage balancing necessary. This problem raises converter reliability, system costs, and hardware complexity. Our goal is to find faulty modules and promptly identify open circuit faults in order to decrease the number of voltage sensors and boost the converter's serviceability. In this research, an enhanced technique for group measurement of capacitor voltages and a reduction in the number of voltage sensors have been used in an attempt to give a new configuration for open circuit fault detection. The simulation results have been given after the suggested strategy was applied to an MMC with 12 sub-modules using MATLAB Simulink software.

## 1- Introduction

The demand for electronic power converters has increased due to the benefits they offer, including high reliability, efficiency, optimal output performance, and the ability to operate in a range of high powers. Additionally, the rapid development of large-scale renewable energy use and other industrial applications has also contributed to this demand. Multilevel Converters (MC)[1]can be used to convert power for applications where high power is required; for this reason, it has attracted much attention in industry and academia. This technology is proven and complete as

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[1] Multilevel Converters(MC)

it is successfully applied in the industry. These types of converters have been commercialized for different purposes and applications. Including compressors, fans, pumps, reactive power compensators, renewable energy conversion high voltage direct current (HVDC) transmission systems, etc. Some power electronics applications, such as HVDC transmission and large power drives, require higher voltages than today's standard semiconductor switches. One way to answer this need is to use MMC[2] multilevel converters modular multilevel converters (MMC). In addition to the high voltage capability, multilevel converters have the advantage of producing multilevel output voltages, which, compared to Two-level Converters[3] have less distortion in the output. These features make multilevel converters attractive in some applications. As one of the most advanced multilevel converter structures, MMC is extremely popular in high-voltage applications such as HVDC systems. In high-voltage applications, MMC has a large number of capacitors and semiconductor switches . For example, in the MMC project implemented in San Francisco, 1200 capacitors and 2400 IGBT switches were used in its structure. Since the most sensitive parts in multilevel converters are switches and capacitors, and despite the large number of these sensitive parts in multilevel converters, the probability of failure is higher than that of average converters. This affects the reliability of the system. There are usually three types of faults in an MMC-HVDC system. It can happen, first, system level errors, second, converter level errors, and third, submodule level errors . Among them, submodule-level errors have contributed more. Among the sub-module level errors Sub Modules (SM)[4], the possibility of failure of semiconductor switches and capacitors is much higher than that of other errors. Submodule-level errors are divided into two types. The first fault is the open-circuit fault (OC)[5] where the switch is off regardless of the switching signal. The second error is a short circuit error short-circuit fault (SC)[6]In this error, the key is on regardless of the keying signal . Short circuit faults are usually hazardous and cause excessive Current in the system and must be quickly diagnosed and the system corrected. In today's natural systems, the driver of the key gate, which has a high detection speed, is used to detect this type of error. This method converts the short circuit error into an open circuit error using series fuses with keys. On the other hand, the open circuit error of the keys can remain hidden for a long time. The occurrence of an open circuit fault in a modular multilevel converter causes the problem of overvoltage and current and distortion of its output waveform. If it remains in the system for a significant time, it causes a secondary fault in the MMC converter or the entire system.

The three categories of error detection methods Fault Diagnosis Methods[7] (FDM) are as follows. 1- Mechanism-based methods, 2- Signal processing methods, 3- Use of artificial intelligence. Fault diagnosis methods are based on the location of the fault from additional components and sensors. Get benefits. The error in MMC in these methods can be identified by comparing the three internal characteristics (such as circulating current, capacitor voltage, arm current, etc.) and the expected limit. In other words, an error is identified when the observed internal characteristic is different from the expected characteristic. This method is very reliable and straightforward, but the hardware's complexity increases the system's size and cost, so efforts should be made to solve these problems. The ten principles of methods, based on signal processing and artificial intelligence, examine the relationship between the system's actual behavior and its predicted behavior. Methods based on signal processing use the extracted output signals as behavior. However, methods based on artificial intelligence identify the error by analyzing historical data. Although these methods have more complex algorithms, they are relatively economical in terms of hardware complexity and cost.

In reference [1], a method for fault detection in modular multilevel converters is presented, which can identify a faulty submodule in the MMC. The proposed fault detection method is based on a sliding mode observer[8] and switching model in the half-bridge submodule. In this method, it is assumed that an error has occurred in a specific sub-module, and accordingly, the voltage and current of the sub-module are checked. Some of the weaknesses of this method include the long time of fault detection and location (about 200 milliseconds), the inability to identify the faulty key, the inability to identify several open-circuit faults in the converter at the same time, the high volume of calculations in case of using a large number of sub-modules, and the dependence on Keying functions are submodules.

Error The open circuit in MMC was identified in reference[2] by comparing the state variables estimated by the Kalan filter and the measured state variables. According to the equations of state, the circulating Current of the MMC converter was

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[2] modular multi-level converter(MMC)

[3] Two-level Converters

[4] Sub Modules (SM)

[5] open-circuit fault(OC)

[6] short-circuit fault(SC)

[7] Fault Diagnosis Methods (FDM)

[8] sliding mode observer

estimated using the Kalman filter method in this research. Also, in this research, additional sensors are not used for fault detection, and the volume of calculations is reduced. However, a relatively long time is spent on error detection and location (about 230 milliseconds). Also, it is not possible to detect a faulty key and detect multiple errors at the same time.

According to reference[3] which complements reference[1]; In this research, the circulating Current of the converter is estimated using the dynamic equations of the modular multilevel converter and the sliding mode observer, and after comparison; If the difference between these two values exceeds the threshold and continues for a certain period; An error is detected . In this method, the detection speed is about 50milliseconds. The disadvantages of this method, despite the reduction of calculations, include the inability to detect a faulty key and the inability to detect multiple errors at the same time; Cited. Also, many submodules and the trial and error method are used to locate the defective submodule. In that case, the volume of calculations increases, which makes using this method difficult in practical applications.

In reference[4], using the MMC equations and Leonberger observer [9]provides the ability to diagnose open circuit faults in each key. In many references, fault diagnosis methods are separate from resilient control methods. They are checked against errors. However, this reference presents a new method for fault tolerance control that merges these two methods. The increase in time between error detection and the location of a large-scale web remap can lead to additional Current in the arms, which is too much for the system. It is encouraging. This method is the first research method to detect errors on the entire web. Among the disadvantages of this method , we can mention the low speed of the fault detection and location method (about 120 milliseconds), the use of a large number of current and voltage sensors, as well as not correctly detecting the fault when several simultaneous faults occur.

The reference method[5] is presented, able to detect faults in voltage sensors and short-circuit and open-circuit faults in semiconductor switches and reconfigure the system to continue the system's regular operation. This authority has proposed a different structure for MMC. However, this article uses a complex algorithm to estimate the voltage. On the other hand, with the addition of at least three sensors to each arm, which increases the cost and reduces the reliability of the system , in this article, the forced activation algorithm is used to speed up the method, which makes this converter unstable. The above detection method relies on the sensor of the arm observer; if this sensor is damaged, it is not possible to detect and locate the fault in the system. Also, in this article, submodules have been used to control resilience, which also deals with the system's active storage.

References [6-8] have used voltage sensors[10] in each sub-module's output terminal. In this method, checking the output voltage of the submodules is used to detect the open circuit error in each of the upper or lower keys of the submodule. The output of the half-bridge submodule can show the value of Vc or zero according to the state of the upper key of the submodule. This method benefits from the high speed of error detection, which is the main advantage of this method. However, the high number of voltage sensors in the converter can be considered the weak point of this name. Also, these three references differ in how they control the MMC converter. In reference[9], a quick method is presented to detect the open circuit fault of the system. In this research, changing the placement of the sub-module voltage sensor, in addition to a voltage estimator based on the sub-module voltage sensor, to check the capacitor capacity and realize the power control of the MMC converter. It is typically configured. This method uses a Boolean relation corresponding to the sub-module's overall function and the voltage sensor output for fault diagnosis. The speed of this method is relatively good in diagnosing open critical circuit errors. Also, monitoring the error capacity of capacitors is done based on a particular method. References [10-13] present a new method to simultaneously detect the open circuit fault in several switches. In this reference, the fault is detected by checking the voltage of the arms . Then, by presenting a new method, defective sub-modules are identified using the RSF capacitor voltage balancing algorithm. One of the main features of this article is the high detection speed and simultaneous detection of several errors in the MMC converter. One of the disadvantages of this research is the error location method; the RSF algorithm is constantly changing. Moreover, it can only be used with NLC modulation. Table 1 reviews articles related to open circuit fault diagnosis methods.

**Table 1:** Reviewing articles related to open circuit fault detection methods

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[9] Leonberger

[10] Voltage Sensors

| Fault Detection | Error detection velocity OC(ms) | voltage sensors ʼnumber | placement method | detection | measured component | Error type | sub-modulesو number | Published year | reference |
|---|---|---|---|---|---|---|---|---|---|
| NO | 200 | 2×4 | Test and error | Arm flow estimation | current and capacitor voltage | OC | 2×4 | 2013 | [1] |
| NO | 235 | 3×2×4 | Voltage monitoring of capacitors | Circulation flow estimation | current and capacitor voltage | OC | 3×2×4 | 2014 | [2] |
| NO | 50 | 3×2×10 | Test and error | Circulation flow estimation | current and capacitor voltage | OC | 3×2×10 | 2016 | [3] |
| NO | 120 | 2×6 | Voltage monitoring of capacitors | Estimation of circulating flow and output flow | current and capacitor voltage and output current | OC | 2×6 | 2015 | [4] |
| NO | 5 | 2×(3+8) | Voltage monitoring of capacitors | Estimation of the output voltage of the sets | The output voltage of the sets | OC-SC | 2×8 | 2017 | [5] |
| YES | 3 repeat | 2×4 | -- | Investigate the output voltage of the submodule | Submodule output voltage | OC | 2×4 | 2017 | [7] |
| YES | 3 repeat | 2×3 | -- | Investigate the output voltage of the submodule | Submodule output voltage | OC | 2×3 | 2017 | [6] |
| YES | 3 repeat | 2×3 | -- | Investigate the output voltage of the submodule | Submodule output voltage | OC | 2×3 | 2018 | [8] |
| YES | 3 repeat | 2×4 | -- | Investigate the output voltage of the submodule | High switch voltage | OC | 2×4 | 2019 | [9] |
| YES | --- | 2×42 | Investigating the voltage sorting process of capacitors | Check the output voltage of the arms | voltage and capacitor voltage | OC | 42×2 | 2021 | [10] |
| YES | --- | 2×42 | Investigating the voltage sorting process of capacitors | Check the output voltage of the arms | voltage and capacitor voltage | OC | 42×2 | 2014 | [11] |
| YES | --- | 2×42 | - |  | voltage and capacitor voltage | OC | 42×2 | 2019 | [12] |
| YES | --- | 2×42 | Voltage monitoring of capacitors |  | voltage and capacitor voltage | OC | 42×2 | 2018 | [13] |

MMC converters are usually expensive, and it is usually not economical to completely disrupt the converter's performance when an open circuit fault occurs in one of the submodule switches. The system should continue to work without interruption. Especially in HVDC systems, the converter is only allowed to turn off under any circumstances if it is necessary for periodic and planned maintenance. - Therefore, the critical point is how to quickly detect the error and precisely the submodule to identify the defect and fix the error. This thesis examines the MMC converter's open circuit error and presents a quick error detection method. In this article, we investigated the error at the sub-module level of the MMC converter, and a quick method for detecting and locating the short circuit error is presented. The goal is to achieve better system reliability by reducing electronic elements such as voltage sensors and faster detection and fault location. The research conducted in this field shows that many voltage sensors have been used to detect faults in the MMC converter. This action itself affects the reliability of the system and also increases the cost of the converter. This research aims to provide a fast method for fault detection along with the reduction of voltage sensors in the MMC converter. In addition, we can mention the achievement of other goals, such as increasing the system's reliability, saving money, combining detection and location methods, and ease of fault detection. This method has been investigated using MATLAB Simulink software simulation, and its results in the future sections will confirm the correctness of this issue.

## 2- proposed method for group measurement of capacitor voltage and open circuit fault detection for modular multilevel converter.

In this section, the effect of the open circuit error of each of the switches on the flow path of the submodules has been discussed first. Then, the proposed voltage sensor configuration is presented to reduce a significant challenge of using MMC, i.e., many voltage sensors. Also, a simple scheme for accurate voltage estimation of capacitors is provided. Finally, a quick fault detection method is presented based on the configuration method of voltage sensors. In the next step, the open circuit fault in the electronic keys is quickly identified by using a group sensor setting and providing a method based on reducing the number of voltage sensors. Finally, using the simulation results in MATLAB / Simulink software, the correctness of the proposed method is checked and confirmed.

### 2.1 The effect of open circuit error of switches in MMC

In MMC-HVDC systems, reliability is of great importance due to the high cost of the system. One of the main reasons for reduced reliability is the large number of half-switches in the converter structure, which are subject to open-circuit and short-circuit faults. Figure (1) and Table (2), the main flow paths of the arm ($I_{arm}$), show the submodules in normal mode. As it is known, if the submodule is on (S1=1) be; The current passes through the switch or diode above . In this condition, the output voltage of the submodule is equal to the capacitor voltage. Also, if the submodule is inactive (S1=0), the current passes through the switch with the lower diode and does not affect the capacitor voltage. However, an open circuit fault in any switch may alter the flow path compared to normal operating conditions. Fault in the upper switch (S1), in the condition that the current sign of the arm current is negative, will cause current to flow through D2 instead of S1. As a result, the capacitor will not get a chance to discharge, and its load will increase beyond the permissible limit. Also, in case of an error in the lower switch (S2), in the condition that the arm current sign is positive, the Current will flow through D1 instead of S2. In this situation, the opportunity to charge the capacitor is more excellent than the discharge, and the voltage of the capacitor increases . As a result, the occurrence of an error in the upper or lower switch will increase the voltage of the capacitor from the permissible range, and if it is not detected in time, it will cause serious risks. Therefore, it is necessary to provide a suitable solution for quickly detecting open circuit faults.

Table 2: Glossary

| | |
|---|---|
| arm resistance | $R$ |
| Arm inductance | $L$ |
| DC link voltage | $V_{dc}$ |
| High arm voltage | $V_u$ |
| Lower arm voltage | $V_l$ |
| Phase output current | $I_o$ |
| circulating current | $I_c$ |
| Upper arm flow | $I_u$ |
| Lower arm flow | $I_l$ |
| Phase angle | $\phi$ |
| Angular frequency | $\omega_o$ |
| Sampling time | $T_s$ |
| Upper arm submodule keying mode | $S_{ui}$ |
| Lower arm submodule keying mode | $S_{li}$ |
| Upper arm submodule output terminal voltage | $V_{SM,u(i)}$ |
| Lower arm submodule output terminal voltage | $V_{SM,l(i)}$ |
| Output voltage of set i | $V_{SET(i)}$ |

**Table 3:** Half-bridge submodule switching status in normal conditions

| Keying status | $I_{arm}$ | Sub-module output voltage in normal mode |
|---|---|---|
| $S_1$=1 | $I_{arm}>0$ | Vc |
| | $I_{arm}<0$ | Vc |
| $S_1$=0 | $I_{arm}>0$ | 0 |
| | $I_{arm}<0$ | 0 |

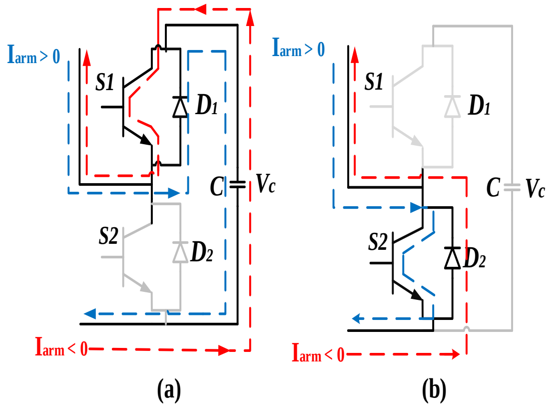

**Figure 1:** Arm flow path in normal state, a) S1 = 1, b) S1 = 0

### 2.2 Proposed plan to reduce voltage sensors:

The presence of floating capacitors in the configuration of MMC sub-modules has made it necessary to use voltage sensors in capacitor voltage balance control algorithms. This increases the converter's manufacturing costs and hardware complexity and causes the processors to face many limitations. Therefore, reducing the number of voltage sensors in the MMC converter reduces the above problems . However, this should be done in a way that keeps the reliability of the converter high. This thesis presents a plan to reduce voltage sensors based on the grouping of sub-modules. Figure 2 shows the proposed plan to reduce voltage sensors. In the proposed design, the number of $\frac{N}{2}+1$ voltage sensors in each arm of the transducer is used. For both sub-modules, a group monitor voltage sensor is used. Also, an arm monitoring sensor is used for each arm. The group monitoring sensor has been used to estimate the capacitors' voltage and detect the faulty key's location. The arm monitoring sensor has been used to monitor the arm's position. The following sections give a complete explanation of the functions of the sensors.

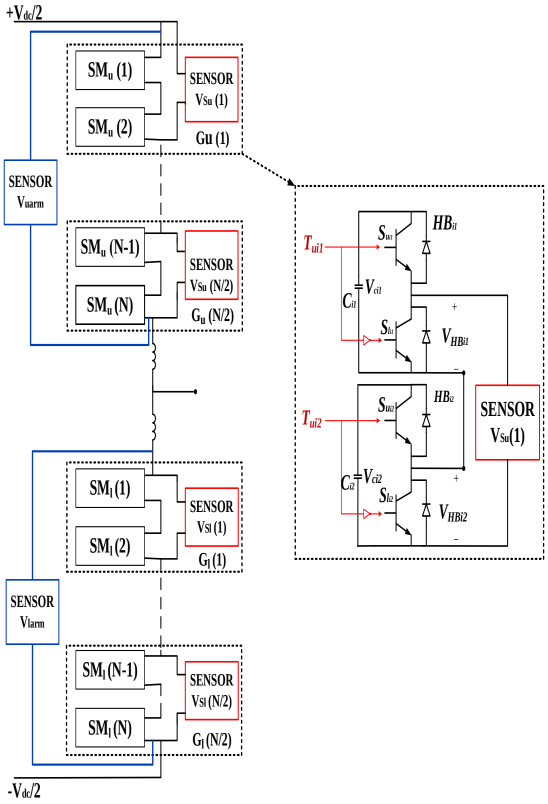

**Figure 2:** Proposed plan to reduce voltage sensors

### 2. 3 Voltage estimation plan of capacitors :

Eliminating individual capacitor sensors makes it necessary to use a capacitor voltage estimation method to obtain real-time voltage information. This thesis uses a simple method with the least volume of calculations to estimate the capacitors' voltage accurately. The proposed method uses the voltage difference of the capacitors at the current and previous moment in each group. In the following, the theoretical foundations of the proposed method are given.

The voltage that the monitoring sensor of the group measures at any moment is equal to the sum of the output voltages of the submodules of the group, so we have (due to the similar operation of the MMC arms, the equations are written only for the upper arm:

$$V_{sui}(t)=\sum_{j=1}^{2}V_{HBij}(t) \qquad (1)$$

In the above relationship, $V_{su}(t)$ is the voltage measured by the monitoring sensor of the i -the group, and $V_{HBij}(t)$ is the output voltage of the submodule. On the other hand, according to Table 3, the output voltage of each submodule can be estimated according to the switching state of the submodule. Therefore, the output voltage of each group can be estimated in the following time-discrete form:

$$\hat{V}_{sui}(t) = \sum_{j=1}^{2} T_{uij}(t-1)\hat{V}_{Cij}(t) \qquad (2)$$

In the above relation, Vsuit is the estimated voltage of the group; $T_{uij}$ (t-1) is the switching state of the submodule; and $V_{Cij}$(t) is the estimated voltage of the capacitor of the corresponding submodule. The proposed capacitor voltage estimation method requires the group voltage difference at each sampling time. The voltage difference of the group at the moment t is using the estimated voltages of the capacitor at the moment t-1, which is stored in the memory of the algorithm, and the value measured by the voltage sensor of the group can be calculated as follows.

$$\widehat{\Delta V}_{sui}(t) = V_{sui}(t) - \hat{V}_{sui}(t-1) \qquad (3)$$

ΔVsuitThe voltage changes of the capacitors during a sampling time are Vsuit, which is the measured voltage of the group at the current moment by the voltage sensor, and Vsuit-1, which is the estimated voltage at a previous sampling time. The voltage of the capacitors used in making the group voltage has changed when the current passes through them,, and the new voltage of each capacitor in a group is obtained by VCij(t))dividing the voltage changes . Therefore, the voltage of the capacitor in step t is estimated as follows :

$$\hat{V}_{Cij}(t) = \hat{V}_{Cij}(t-1) + [\frac{T_{uij}(t-1)}{\sum_{i=1}^{2} T_{uij}(t-1)}]\,\widehat{\Delta V}_{sui}(t) \qquad (4)$$

In this way, by using the voltage difference of the capacitors of the group in two consecutive sampling times, the voltage of the capacitors of the group can be estimated quickly and by avoiding the use of complex algorithms. Nevertheless, in all estimation methods, there is an error between the measured and estimated values, which is used in the proposed two-step method to compensate for the estimation error, which is described below:

**a. When only one submodule is active in the group:**

When the modulator sends the command to generate a voltage level in each group, only one capacitor contributes to the voltage generation. In this process, the group voltage sensor directly measures the active submodule's capacitor voltage, and the capacitor voltage's estimated and measured values will be equal. As a result, the estimation error converges to zero in each cycle, and the cumulative error is eliminated.

### b. Capacitor voltage balancing process:

When the estimated capacitor voltages deviate from the standard range, the sorting process tries to bring them back within the acceptable sorting range and minimize the deviation between the estimated and measured voltages. In the case of incremental estimation error, when the estimated voltage of the capacitor is higher than the measured value, the capacitor participates in the switching process only with the opposing arm current. In this case, the voltage of the capacitor decreases and approaches the measured value. In the reduction estimation error, when the estimated voltage of a capacitor is lower than the measured value, the capacitor participates in the switching process only with the positive arm current, and its voltage increases. Therefore, the capacitor voltage will be balanced and never exceed the standard range using the sorting process. As a result, the estimation process is done by dividing the voltage difference equally between the capacitors participating in the switching operation. In addition, with the two features mentioned above, the estimation error converges to zero at each sampling time, and capacitor voltage balancing is performed with fewer voltage sensors.

### 2.7 Suggested method of detecting open circuit fault in switches

Based on the configuration plan of the proposed voltage sensors, a two-step method for detecting the open circuit fault in the faulty switches of the submodules has been presented and described below.

**a. first stage**

In the first step of the proposed method,, the faulty arm is detected by the voltage sensor monitoring the arm . For this purpose, the voltage measured by the arm monitoring sensor is compared with the reference value using the following relationship (relationships are given for the upper arm).

$$-\%20\, V_{Cnam} < V_{uarm} - V_{uref} < +\%20\, V_{Cnam} \qquad (5)$$

In the above relation V uref, The arm reference voltage can be calculated as follows:

$$V_{uref} = (\sum_{i=1}^{N} T_{uij}(t-1))V_{Cnam} \qquad (6)$$

In the above relation, V cam is the rated voltage of the capacitors. If the result of relation (5-3) was in the desired range, it indicates the system's regular operation and that no error occurred in the arm. The above range represents the error threshold values obtained experimentally, and because it depends on many factors such as system noise, measuring sensors, and voltage drop of semiconductor switches, a - theoretical method cannot be expressed for it. Also, if the result of relation (5-3) applies in one of the following conditions, it indicates an error in one of the arm switches.

If an error occurs in the upper switch, the voltage measured by the arm monitor sensor will be lower than the reference value. Therefore, the result of the above expression will be less than -20% $V_{cnam}$, and the error detection method quickly detects the error of the upper switch in the arm.

If an error occurs in the lower switch, the voltage measured by the arm monitor sensor will exceed the reference value. Therefore, the result of the above expression is more than 20% Vcnam and the error detection method quickly detects the error of the lower switch in the arm.

In this way, in the first step, the proposed method of determining the faulty arm and the type of error (error in the upper and lower switches) is determined, and an error warning is sent to locate the faulty switch. By sending an error warning,, the second step of the proposed method starts .

### b. second stage

After detecting the fault in the faulty arm, the location of the faulty switch in the arm should be determined based on the type of detected fault. For this purpose, the proposed location method compares the voltage measured by the group sensor and the expected voltage of the group output in different switching conditions. Table 4 shows the measured and expected output voltage in different conditions in the I -th group.

**Table 4:** In different switching conditions *i* output voltage of the group

| Keying signal | | | | $I_{arm}$ | Group output voltage | | | | | form |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | normal | Error palcement | | | | |
| $T_{ui1}$ | $T'_{ui1}$ | $T_{ui2}$ | $T'_{ui2}$ | | | $S_{ui1}$ | $S_{li1}$ | $S_{ui2}$ | $S_{li2}$ | |
| 1 | 0 | 1 | 0 | $>0$ | $V_{ci1}+V_{ci2}$ | $V_{ci1}+V_{ci2}$ | $V_{ci1}+V_{ci2}$ | $V_{ci1}+V_{ci2}$ | $V_{ci1}+V_{ci2}$ | ***1*** |
| | | | | $<0$ | $V_{ci1}+V_{ci2}$ | $V_{ci2}$ | $V_{ci1}+V_{ci2}$ | $V_{ci1}$ | $V_{ci1}+V_{ci2}$ | ***2*** |
| 1 | 0 | 0 | 1 | $>0$ | $V_{ci1}$ | $V_{ci1}$ | $V_{ci1}$ | $V_{ci1}$ | $V_{ci1}+V_{ci2}$ | ***3*** |
| | | | | $<0$ | $V_{ci1}$ | 0 | $V_{ci1}$ | $V_{ci1}$ | $V_{cu1}$ | ***4*** |
| 0 | 1 | 1 | 0 | $>0$ | $V_{ci2}$ | $V_{ci2}$ | $V_{ci1}+V_{ci2}$ | $V_{ci2}$ | $V_{ci2}$ | ***5*** |
| | | | | $<0$ | $V_{ci2}$ | $V_{ci2}$ | $V_{ci2}$ | 0 | $V_{ci2}$ | ***6*** |
| 0 | 0 | 0 | 0 | $>0$ | 0 | 0 | $V_{ci1}$ | 0 | $V_{ci2}$ | ***7*** |
| | | | | $<0$ | 0 | 0 | 0 | 0 | 0 | ***8*** |

As can be seen, modes 3 ‹4 ‹5 and 6 are unique modes that, based on the keying of each group, determine the ability to detect the error of all types of keys in a group. According to Table 4, there are four types of open circuit errors. There are keys in a set. As you can see, there are eight flow paths in one set. If the switch S1 has an open circuit fault. In this case, the fault is detected only when submodule number 1 is on, submodule number 2 is off, and the arm current is negative. Under regular operation, the assembly output should show a voltage of V cu1 . while the observer sensor will see the zero value set under these conditions. In such a situation, the flow path will be path eight instead of path 4 In the event of an open circuit error in the S2 key, when sub-module 2is on, and sub-module 1 is off. In this case, due to the open circuit of the switch S2, the flow path will be forced to move through path one instead of path 5. In this case, in the normal operation mode of the set, the observer sensor should have measured the value of V cu2, but due to the open circuit of the S2 key, the Current passed through the reverse parallel diode of the S 1 key.

The observer sensor of the set measured the voltage V cu1 + observes V cu2. In case of an S3 open circuit error, the reverse of the S1 critical open circuit error occurs; that is, in route number 6, while submodule 2 is on and submodule 1 is off, the monitoring measures measures zero instead of V cu2 voltage and The flow path changes to path eight . In the case of the S 4 critical error, the opposite of the S2 error also . Where submodule 2 is off and submodule 1 is on. In this case,, the voltage monitoring sensor Vcu1 + Vcu2 observes ; While he should have V V cu1. In this case, the flow path has changed to path one instead of path 3. In short, in the event of an error in the upper switch of submodule number 1 (S ui1 ) of the group, in the condition that the current sign is negative and state four from Table 4 occurs, the observer of the group measures zero volts at the output of the sensor group. This is while the expected voltage is equal to Vci1 Is. In other words, the error in each group is detected only when only one submodule is active, reducing the amount of calculations. In this way, by using the proposed method with the least volume of calculations and the number of reduced sensors, in addition to reducing the costs of the converter, the reliability of the converter is also maintained, which is an essential advantage for this proposed method.

## 3. Simulation results

The performance of the proposed voltage balance control of capacitors and fault detection using MMC converter simulation is done in MATLAB Simulink environment. For this purpose, an MMC converter is simulated with 12 submodules per arm. Also, the PSC-PWM modulation and VBC methods have been used to control the voltage balance of capacitors. For this simulation, the DC link input voltage is considered to be 36Kv, which makes each sub-module withstand 3Kv. Other technical specifications of the simulated converter are given in Table 5.

**Table 5:** technical specifications of the converter MMC

| | |
|---|---|
| 36KV | Link voltage DC |
| 50HZ | Base frequency |
| 12 | The number of submodules per opening |
| 6200µF | Capacitance |
| 1e-5s | Sampling time |
| 5MH | Arm inductance |
| 0.3Ω | arm resistance |
| 2Ω | Output resistance |
| 16mH | output inductor |
| 3KV | The initial voltage of the capacitors |
| 1KHZ | Switching frequency |

### 3.1 Simulation results in steady state

In this part, the method of controlling the voltage balance of the capacitors in the stable state is investigated when the converter is working in completely normal conditions. The purpose of investigating these conditions is the effect of reducing the number of sensors on the average performance of the converter. Figure (3) shows the operation of the converter in normal conditions. As can be seen from Figure 3 A, the output voltage levels have been produced at 13 levels and with the most minor distortion. Figure 3 b shows the waveform of the output current, which is generated sinusoidally and with a phase difference with the output voltage without additional harmonics. Figure 3 also shows the voltage of the MMC converter's upper and lower arm capacitors. As can be seen, the voltage of the capacitors is balanced around the reference voltage of 3Kv with a standard ripple of less than 3%.

Figure 4 shows steady-state simulation results for C u11 (capacitor number one upper arm). In Figure 4 A, the measured and estimated waveforms are displayed, and the estimated values follow the measured values well. Also, Figure 4 b shows the estimation error value (measurement value minus estimation value). As it is clear from the results, the estimation error is less than 1 volt, which is a minimal value. Figure 5 shows a composite distribution chart of estimation error values with a random sampling of 19200 samples for C u11. According to the results, it can be seen that the estimation error range is 0.6 ±V. In addition, many samples are in the range of zero volts. In this way, the error of the proposed method is small, which indicates the correct performance of the proposed method. In this regard, by examining the results of the proposed method in stable conditions, it is clear that the proposed method does not have any adverse effect on the converter. Despite the reduction in the number of MMC sensors, it shows good performance .

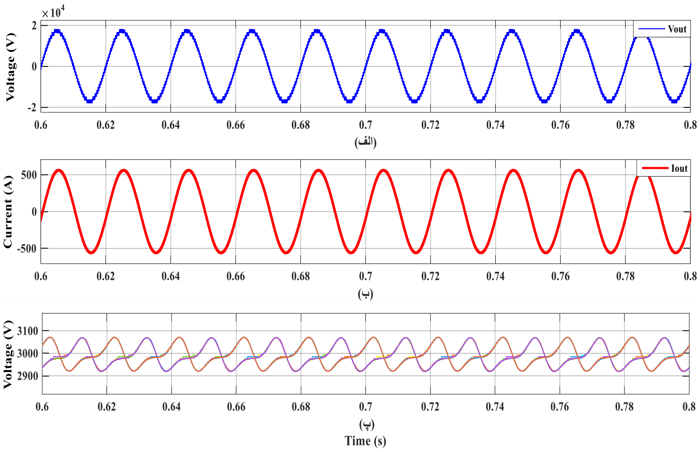

**Figure 3:** Stable MMC state simulation results, a) output voltage, b) output current, c) voltage of capacitors

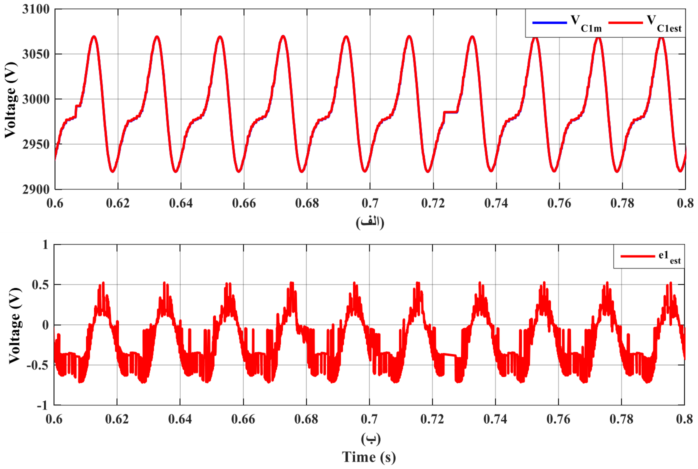

**Figure 4:** MMC steady state simulation results, a) measured and estimated Cu11 voltage values, b) estimated error values for Cu11

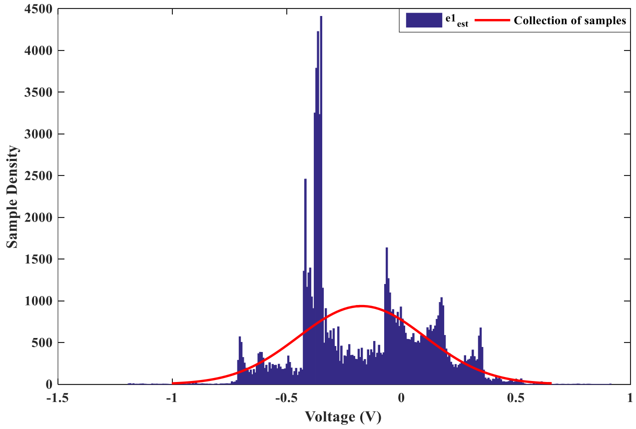

**Figure 5:** Combined distribution of the error value of the capacitor voltage estimation method

### 3.2 Simulation results in a transient state

Due to the reduction in the number of sensors, it is necessary to check the converter's performance in transient conditions. For this purpose, the performance of MMC has been investigated in two scenarios: reducing the modulation index and switching frequency. Figure 6 shows MMC's performance with the modulation index's reduction from 0.95 to 0.6. As can be seen, with the reduction of the modulation index at time t=0.6s, the output voltage and current levels have suddenly decreased. In this situation, if the proposed estimation method's performance is suitable, the capacitors' voltage balance is expected to be recovered. However, it can be seen that the capacitors are completely balanced in the reference value. Therefore, the proposed method performs well if the modulation index is reduced.

One of the most critical performance parameters of MMC is the ability of the converter to operate at low switching frequencies. Due to the large number of switches used in the MMC configuration, the losses will increase significantly if the switching frequency is high. Figure 7 shows the performance of MMC by reducing the switching frequency from 1000 Hz to 250 Hz at t=0.5s. As can be seen, the distortion in the voltage of the capacitors has increased with the reduction of the switching frequency. However, the voltage balance of the capacitors is maintained. As a result, the proposed estimation method is highly accurate in estimating the voltage value of capacitors.

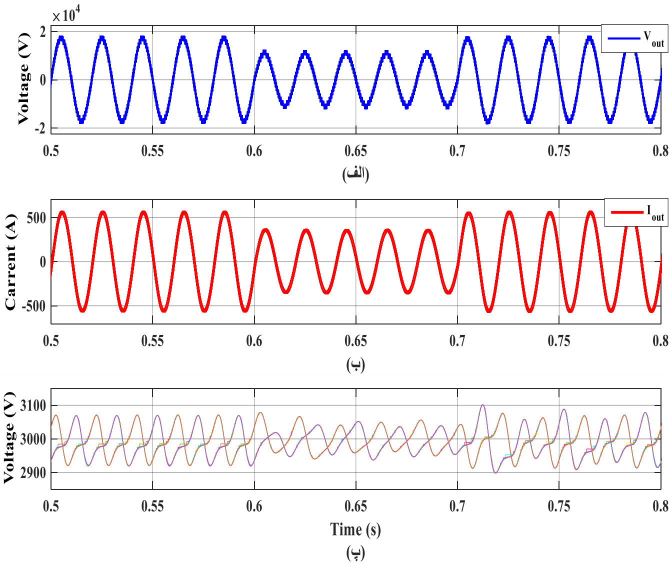

**Figure 6:** MMC transient mode simulation results with modulation index reduction, a) output voltage, b) output current, c) voltage of capacitors

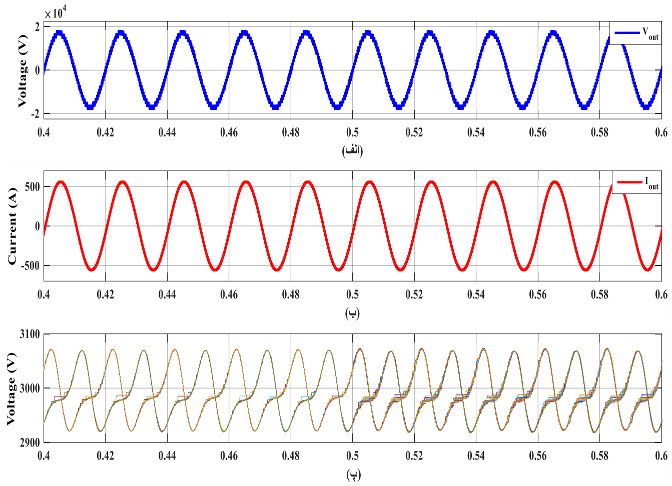

**Figure 7:** MMC transient state simulation results with a reduction in switching frequency, a) output voltage, b) output current, c) voltage of capacitors

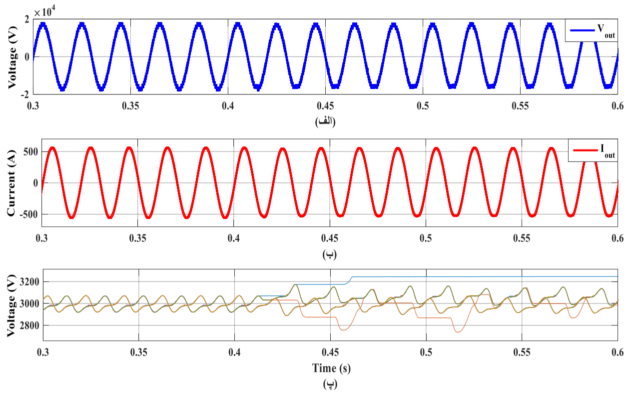

**Figure 8:** simulation results with open circuit error in S11 switch, a) output voltage, b) output current, c) voltage of capacitors

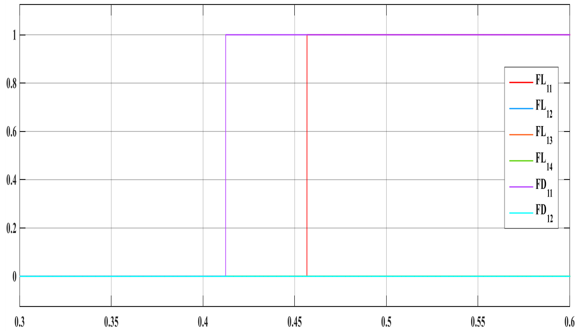

**Figure 9:** Fault detection and location signals

### 3.3 Simulation results with errors in the keys

In this section, the performance of the proposed error detection method has been investigated, and due to the similarity of the behavior of all groups, only the results of group 1 have been raised. Figures 8 and 9 show the performance results of the proposed error detection method by creating an error in the S11 key. For this purpose, at t=0.4s, a game circuit error has been created by interrupting the keying command signal for the specified key. As it is clear from Figure 8, the output voltage waveform has had problems creating low levels after the fault, and the output current range has decreased. Also, Figure 8 shows that immediately after the error in the balance switch, the voltage of the capacitors is completely lost, and the voltage of the faulty submodule has increased. Figure 9 shows the diagnosis and fault location signals. As can be seen, after the fault occurs, the proposed method has a faulty phase at t=0.4123s has identified After identifying the faulty phase, the fault detection signal is sent to the fault location part, and the faulty switch has been located at t=0.457s. In this way, it is possible to evaluate the performance of the error detection system in the face of the errors of the upper keys.

the simulation results show an error in crucial S12 (lower key of submodule number 1 of group 1). As it is clear from the Figure, the output voltage and current have been disrupted due to an error at t=0.4s. Also, the voltage balance of the capacitors is lost, and the voltage of the defective submodule has significantly increased, which will cause adverse effects on the system if it is not detected in time. Figure 11 shows the fault detection and location signals, which shows that the proposed method successfully located the faulty switch in t=0.4026s. As a result, the proposed method performs very well in detecting errors in the lower keys. Also, the results of the error detection signal for the second group (FD12 **Fault Detection)** It was also checked and found not to show false performance. Thus, the proposed method's performance can be described as detecting various types of errors.

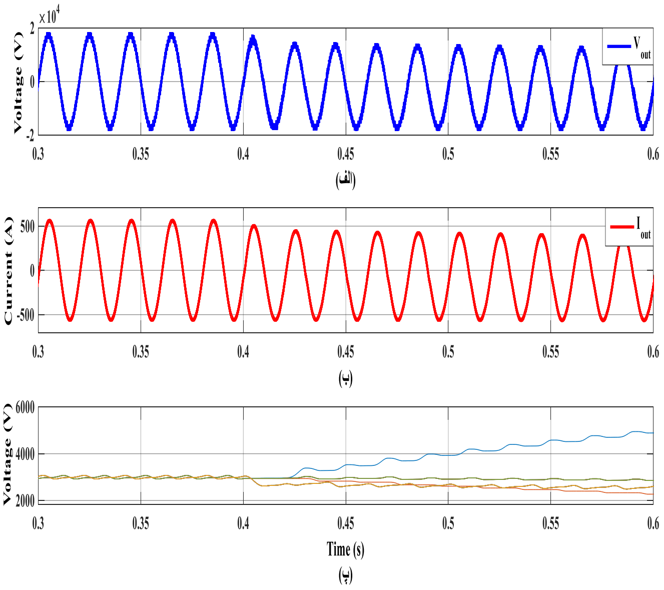

**Figure 10:** Simulation results with open circuit error in S12 switch, a) output voltage, b) output current, c) voltage of capacitors

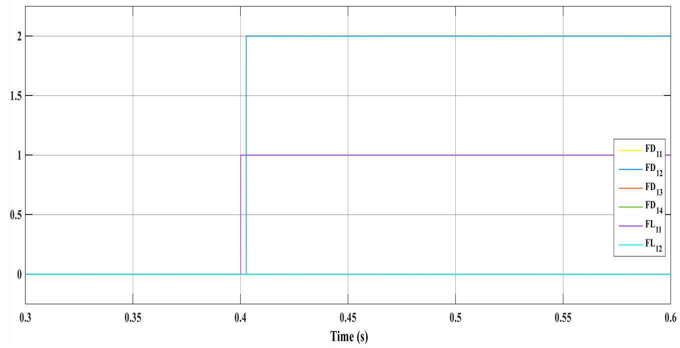

**Figure 11:** Fault detection and location signals

As seen, the open circuit fault characteristic on the sub-modules in the MMC converter was investigated. A method of reducing the number of voltage sensors to identify the open circuit fault is presented. The proposed method is used to determine the internal behavior of the converter at the time of the open circuit fault. Comparing the three normal operation modes and the mode after the fault occurrence identifies the fault in each section. Finally, validation of the prediction method using modeling in Simulink MATLAB software under Modulation (PSC-PWM) phase-carrier-shift has been done. This method can provide a suitable diagnosis of the system error in unfavorable conditions.

## 4. Conclusion

The MMC converter is used extensively in the business, hence it is imperative to find and address any flaws in this converter. The incompatibility of the system resulting from the extensive use of capacitors is one of the main problems with MMC. By using fewer sensors for a modular multilevel converter, this thesis seeks to propose a superior approach for sensing capacitor voltage group and open circuit fault detection. This field has seen a great deal of research to date, which is covered in the second chapter. Every technique has drawbacks, including the need for several voltage sensors, intricate algorithms, slow speed, and the incapacity to detect several faults at once. This letter concludes with a way for locating the open circuit fault. As. numerous studies have been conducted on lowering the number of sensors by estimating capacitor voltage using various techniques. Nonetheless, the open circuit defect in the keys can typically be found using these techniques. In this final letter, the system has learned to detect open circuit faults by lowering the number of sensors and the voltage of capacitors. This was achieved by dividing the remajoules of each arm into two groups using the voltage of the capacitors for each group and comparing the three modes of operation of the groups in the normal state and after the error. Based on the information provided in the earlier chapters, the MMC converter Open circuit fault detection techniques are necessary for optimal operation. Additionally, in order to save money, this converter's high number of capacitors must be reduced. Errors in the system are therefore less likely as a result. To address the aforementioned need, this study provides an ideal technique to enhance the system's open circuit failure detection. The primary benefits of this approach are its simplicity, speed in identifying open circuit failures, and avoidance of the need for intricate algorithms. The paper's overall outcomes can be summed up as follows: Enhancing the speed at which open circuit faults are detected (as seen in figures 8 and 9; at time t=0.4s, the error signal was transmitted, and the system was able to locate the fault at t=0.457s and identify it at time t=0.4123s). Based on the recorded times, it is evident that the system locates the error approximately 40 milliseconds after detecting it in 12 milliseconds. Other benefits of the system include lower costs due to fewer voltage sensors, higher system reliability because there are fewer Haskar in the MMC structure, and a single method that combines fault detection and location.

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