# Design and Simulation of Asymmetric Multilevel Inverter by Modifying the Switching Method and Reducing the Number of Components to Compensate the Circulating Current

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Abstract

In recent years, application of electronic power devices, especially electronic power converters has increased. One of these converters is symmetric and asymmetric modular multilevel converters that have many applications in the field of FACTS and HVDC and are classified as high power converters. In this study, an asymmetric modular converter is designed and controlled by using a new generalized algorithmic structure. In contrast to symmetric converters, the proposed structure with the same number of modules generates greater output voltage and subsequently it can reduce cost. It should be noted that a new method can control the circulating current. The second harmonic amplitude was reduced by about 50% during the phase circulation, and with circulating current THD in phases A, B and C was 4.02%, 10.61% and 12.39%, respectively.

Keywords: Asymmetric Modular Multilevel Converter, circulating current, Modulation, Proportional Resonance Control.

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## 1- Introduction

In recent years, with regards to advances in science and technology, the methods of energy production and consumption have changed. These modern energy production methods are completely independent from fossil fuels and have the most efficiency in the energy conversion process. Great deal of investment and human resources have been applied to achieve these methods. Likewise, these modern trends in the electricity industry lead to many changes in technology, organization and economics. Some schemes which are related to the electricity industry are include power generation, power transmission, power distribution and trade, respectively [1]. However, technology and science improvement in the electricity industry, as well as privatizations, have led to the separation of the energy order in the electricity industry, so that atmosphere of private company would be competitive. As a result, the performance of networks in terms of technology is more complex than before and those systems would be more sensitive. Effective use of network components is one of the first interests of network operators since economic constraints are far greater than before [1]. Today, many studies have been done about power engineering and Manufacturing System [2-3]. Maximizing power transmission capacity as well as minimizing costs of power grids design lead to more challenges in power engineering. In creating such designs, electronic-power devices is appeared. Therefore, innovative equipment such as power electronics devices is present in the design of modern power grids at all design stages. These innovative devices have led to the emergence of new topologies of electronic power converters and new semiconductor technologies which it can connect to medium voltage networks. In this background, multilevel converters are a good solution for power applications because they can achieve high power by using medium voltage semiconductor technology [4].The main use of multilevel converters is in the drive of high power machines and network applications such as HVDC and FACTS [5-6].Common circuits can be used in order to design a high power converter, so that the switches are design in series or parallel. However, this design has some disadvantage: making keys as series or parallel is practically difficult because the voltage and current distribution among them is a complex challenge. On the other hand, if a high power and high frequency converter is needed, a conventional two-level converter would impose some restrictions on the frequency of the equipment. In contrast, in multilevel converter, the effective switching frequency is much higher than the switching frequency per each switch. Therefore, with relatively low switching frequency, waves with low THD can be produced [1].Multilevel converters have different divisions. These converters are divided into different types depending on the structure of their constituent elements or the type of DC power supply. In terms of structure or topology, multilevel inverters are divided into three main groups: Diode Clamp Multilevel Converter (DC-MC) Flying Capacitor Multilevel Converter (FC-MC), Cascade H-Bridge Multilevel Converter (CHB-MC). There exist other types of multilevel converters that have been made by combining the above categories and they can be considered as a hybrid converters. Today, modular multilevel converters (MMCs) are considered to be the best voltage source converter (VSC) and it can operate in wide range of power and high voltage levels along with excellent efficiency. Topology (MMC) has primary use in high and medium power converters. These applications are related to their good features such as modularity, scalability and lack of high voltage DC link due to the distribution of energy between the capacitors of the cells. MMC should be regarded as a suitable topology for HVDC and FACTS due to mentioned reasons [7].MMC is easily expandable to high power and high voltage levels due to its modularity, by using more modules that are connected in series. In addition, MMC is able to deal with active or reactive power as well as high voltage DC grid, without any need to large and voluminous transformers. Also the switching losses for this converter are lower than NPC and FCC [5]. MMC converters are very attractive due to mentioned features and it shows great potential for future applications. But the number of semiconductor elements in this structure is higher than other topologies, which can be reduced by the promotion of modulation and modification of structure. Multilevel inverters based on DC sources are divided into two groups including symmetric and asymmetric. Symmetric converters contain DC sources with the same voltage value while asymmetric converters have DC sources with unequal voltage value [8].In recent years, similar study has been conducted which is mentioned in the second part, and the proposed method and the way of the proposed structure implementation are discussed in the third section. The results of the simulation of the proposed method and comparing two similar proposed structures are discussed in the fourth section.

## 1- previous study

Several structures have been introduced for multilevel converters, and the most common of them are the neutral point clamp (NPC), the Flying Capacitor Clamp (FCC), the Cascade H- Bridge (CHB). These converters have been widely used in industrial applications. NPC and FCC converters are not easily expandable to high power and voltages due to the complexity of electrical connection, loss distribution and voltage balancing problems [9-12].One of the disadvantages of the clamp diode converter is the unequal distribution of voltage between the capacitors that are connected in series, which this in turn can lead to unbalanced voltage in dc link. These converters require a large number of diodes to generate more voltage levels. Therefore, this kind of converter has lower application in industry [13]. Flying capacitor multilevel converters and their derivatives have better characteristics compare to diode clamp multilevel converter, for instance they need not transformer and self-regulating features of the flying capacitors lead to equal distribution of the switching stress on the semiconductor keys. This kind of converters requires more capacitors in order to generate higher voltage levels [14-16]. Cascade converters also have some disadvantages such as requiring multiple dc voltage sources for each input unit to generate higher voltage levels [17]. New structures such as hybrid multilevel converter and asymmetric cascade converter are introduced to reduce the number of dc voltage sources, thus algorithms is required to determine the dc voltage sources [18-20].Modular multilevel converters have some advantages of conventional multilevel converters and it is also has a modular structure. Moreover, those features make them suitable structure for higher voltage and power applications. Among the various multilevel structures, modular multilevel converters with unique characteristics have attracted the most attention [21].Modular multilevel converter (MMC) was first proposed by Marquardt and Lesnicar [22] and it has been investigated by many researchers. Therefore, various models for modular multilevel converter have been introduced [23-25]. These models varies from the simplest model that considers modules as variable DC sources or as discrete voltage controlled sources, to a more complex and accurate model that predicts dynamic properties such as conversion function and impedance. Lee et al. investigated asymmetric modular multilevel converter composite topology in hybrid bipolar HVDC transmission systems". In this study a hybrid bipolar HVDC system consisted of asymmetric LCC and MMC composites was introduced. The asymmetric composite MMC can adjust DC voltage from zero to graded value in a flexible manner, it can also determine RIDE-

THROUGH DC error capacity. Finally, the full-scale simulation results and empirical results of the DOWN-SCALE show the validation of hybrid bipolar HVDC systems based on asymmetric hybrid MMC- [26]. Allehyani et al. have also investigated an interconnected modular multilevel converter (IMMC) with Suitable sinusoidal Voltage Output for AC drives with high performance. The proposed converter produces a sinusoidal output with adaptive voltage and frequency that are suitable for boosting the power of AC motor drives. The proposed converter is appropriate candidate for AC motor drives with high performance and it has some advantages such as V / F sinusoidal output voltage, lack of noise, lower EMI, any issues related to DV / DT due to long engine running and compact size / weight / volume. This article designs and simulates level 3 and 11 converters. Experimental results of laboratory prototype of converter using GAN 600V devices were also discussed [27]. Dinkel et al investigated the multivariate direct control of modular multilevel converters. While MMC is the current technology in most high voltage / power applications such as HVDC, other important applications will be developed in future (ie multi-terminal DC grids, wind farms, electric ships, etc.). Further advancement in hardware, especially smaller capacitors under the modulus is closely associated with improvement of the control performance. The points would be considered for complete electronic error management and system protection, which will be very important and valuable in the future. A new concept of multivariate control for MMC based on these requirements has been described and simulated [28]. Picas et al have also studied the symmetric modulation for multilevel modular converters in drive motor applications. Non-continuous modulation applied to modular multilevel convectors is an effective way to reduce capacitance voltage failures. In this paper, non-continuous modulation is used in motor drive application. New energy controller was provided for proper convector function, which was suitable for non-sinusoidal reference signals function. Experimental results compared non-continuous modulation with other operating techniques at low engine speeds. The results show the efficiency of non-continuous modulation in capacitance voltage failures reduction and power losses [29]. Goetz et al. studied the issue of controlling a multilevel modular converter [30]. This paper provides a multi-objective based on real-time control strategy for a modular multilevel converter which it can connect to a parallel module called the MMSPC. Their control method optimizes the modules for appropriate voltage balance, minimizing switching and conductivity loss. This work empirically validates the topology and concept of MMSPC. Simulations have reduced the system loss to 5 kW in output power. Tai et al. have proposed a flexible capacitor voltage control strategy for variable speed drive using multilevel modular converters. In this paper, a new flexible capacitance voltage control strategy for MMC as motor drives was proposed, and the capacitance voltage was flexibly controlled by adjusting the DC and AC components, and asymmetric control for Upper arm control and lower arm were used in MMC. With regards to proposed control strategy, the efficiency and accuracy of the output voltage converter can be improved when the engine speed is low, and the DI / DT and D V / DT, motor windings can be reduced. These proposals were implemented in the laboratory prototype and experimental results were investigated. The validity of the control strategy under steady-state and dynamic conditions was confirmed [31].

## 2- The proposed method

Most of the previous articles are very complex and their implementation is very difficult because they require complex algorithms in order to control them. With regards to the difficulties and complexity in the operations, this paper introduces a new topology as an asymmetric modular converter. This topology has some features such as symmetric modular converter, low switching frequency, low harmonic distortion, no need for transformers. There are other benefits such as:

In terms of same modules numbers with the symmetrical modular converter, output voltage levels is increased, which this associate with a lower cost. Conductive losses are decreased compare to symmetric converter, and consequently the system performance is improved. Harmonic voltage distortion (THD) and output current decreased. As a result, output filter inductance is smaller for the asymmetric modular converter compared to symmetric converter, and consequently the system volume, weight and losses are reduced

### 3-1- Modular Multilevel Converter (MMC)

In this section, the symmetric structure was used to achieve the desired asymmetric structure. The basic structure of a three-phase MMC with N modulus is shown in Fig. 1. Each phase in this figure consists of two inductors and two modulus groups. These two modulus groups and two inductors are arranged in a branch that is equal to one phase, this phase is consisted of two symmetric upper and lower branches.

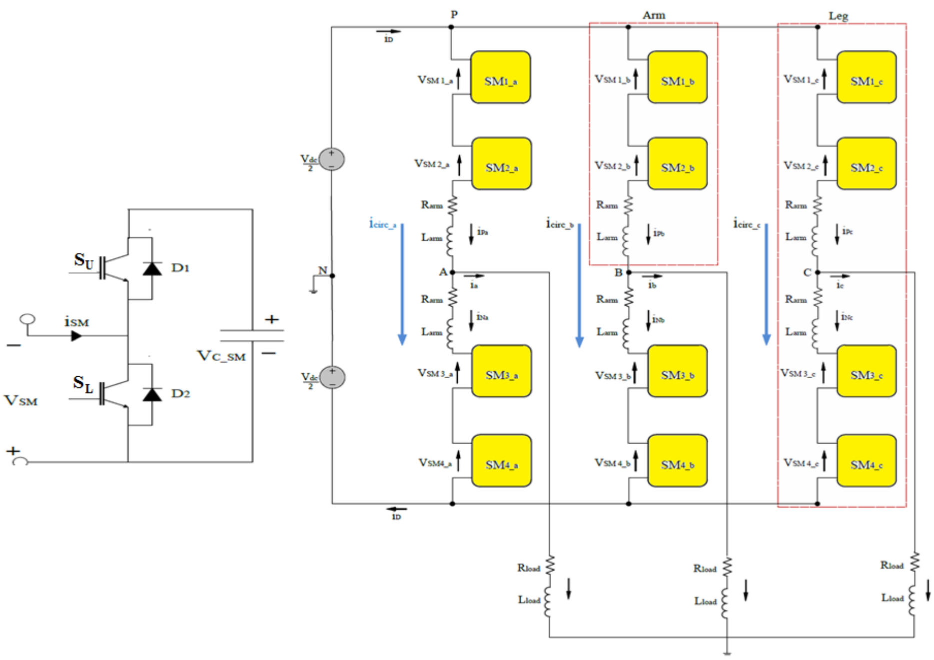

Figure 1. Schematic circuit of a three-phase MMC converter along with half-bridge modulus structure

A classic MMC converter uses half-bridge modules as shown in Figure 1.According to Fig. 1, if the up key or transistor BJT (SU) is turned on, $V_{c\_SM}$ is being located at the module terminal. If the low key (SL) is on, zero voltage will appear in the module terminal. Therefore, with a suitable modulation method, symmetric multilevel voltage converter can be produced in each output phase. The number of voltage levels directly depends on the number of modules per branch $n_{step} = 2N + 1$. This means that n symmetric converter and n-1 module is required.Capacitors as opposed to the symmetric MMC structure are not equal in the H-bridge modules of each branch. In each phase, the capacitor voltage of the SM1 is twice that of SM2 in the upper branch, and capacitor voltage SM3 is twice that of SM4 in the lower branch. At any time, the voltage at the two ends of each branch, consisting of two modules and one inductor, can be adjusted in this voltage range$\left[0, \frac{V_{DC}}{2}\right]$:

$$\frac{V_{DC}}{2} = V_{C\_SM_j} + V_{C\_SM_{j+1}} \tag{1}$$

There is one coupled inductor in each branch. The purpose of these inductors is to control the voltage difference between the upper and lower sections of the converter, and inductors can be used for current control purposes.The inductors will control the current when the error occurs (short connection). According to previous articles [32-33] voltage and current of this structure are mention as follows:

The up branch -voltage and low branch -voltage voltages are mentioned in Equations (2) and (3) which is the combination of the required DC, the output voltage AC voltage (VAN), and the voltage required to control the circulation current

$$V_{up_A} = \sum_{j=1}^{2} V_{SM_{j\_a}} = \frac{V_{DC}}{2} - V_{AN} + V_{diff\_a} \tag{2}$$

$$V_{low_A} = \sum_{j=3}^{4} V_{SM_{j\_a}} = \frac{V_{DC}}{2} + V_{AN} + V_{diff\_a} \tag{3}$$

It should be noted that all of these equations can be used for phases B and C as same as phases A. Branch flow is also obtained as follows:

$$i_{circ\_a} = \frac{I_{dc}}{3} + I_{2f}\sin(2\omega_0 t + \varphi_0) \tag{4}$$

$$i_{circ\_b} = \frac{I_{dc}}{3} + I_{2f}\sin\left(2(\omega_0 t - \frac{2\pi}{3}) + \varphi_0\right) \tag{5}$$

$$i_{circ\_c} = \frac{I_{dc}}{3} + I_{2f} \sin\left(2(\omega_0 t + \frac{2\pi}{3}) + \varphi_0\right) \quad (6)$$

Circulating currents will have adverse effects on the performance of the converter and should be well eliminated or controlled for practical purposes [34]

3-2-Modulation

In this paper, the level shift modulation LS_PWM method has been used to achieve a shorter time response and voltage levels enhancement without increasing in the number of modules between different modulations [34].In this strategy, the high and low modules can have different voltage levels ($V_{low_A}, V_{up_A}$) to create differential voltage in the branch inductors. This can lead to higher voltage levels in output, namely level 5 in symmetric status and level 7 in asymmetric statuses on the condition that two modules in each branch are connected. In other words, the number of switched on modules is not constant. In this method the reference voltage equation (2) and (3) can be applied and thus the current circuit will be controlled. However, there is a considerable ripple in the current circuit due to the differential voltage in the branch inductors. According to Figure 2, different modes of output voltage can be created.

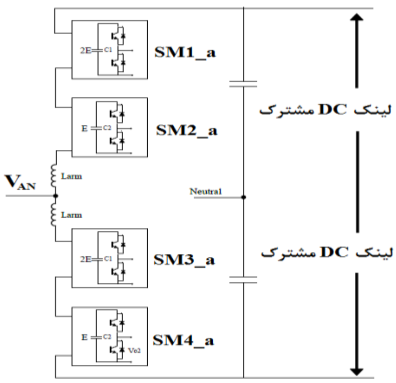


Fig. 2. Single phase modular converter

In this figure, it is possible to obtain different voltage levels by combining voltage for to SM with equal voltage in each branch. In fact, it is easy to understand that how additional levels are obtained by combining different voltages ($V_{low_A}, V_{up_A}$). We can achieve level 7 voltage in the output by having two modules with unequal voltage DC. In a symmetrical modular converter with two modules per branch levels, 5 voltages will be generated. Therefore, we can increase the number of voltage levels. In fact, this concept can be generalized to greater SM.

3-Simulation results

The main purpose of this paper is to design a three-phase asymmetric modular multi-level converter using MATLAB 2018 software. In this study two different design based on MMC was presented and their results were evaluated. The first design is a level 7asymmetric modular converter and the second design is an improved level 9 asymmetric converter. In other words, in this paper, a level 7 asymmetric structure is proposed and then a second-order proportional resonance controller is used to improve the results.

We compared the promoted level 9 THD with proposed level 9 and level 7 structures.  To avoid overloading, the asymmetric level 7converter structure was ignored

4-1-Design and simulation of promoted level 9 asymmetric modular converters. As mentioned above, it is obvious that asymmetric modular converters with the same number of modules compare to the symmetric converters can produce higher output voltage. In this section, we present a new and more comprehensive algorithm for selecting DC voltage modules, so that this algorithm is also a generalization of the first proposed scheme. We can obtain higher levels and output voltage than the symmetric converter with the same number of modules by using this algorithm. This algorithm is an innovative method that can be applied to all MMC converters. The proposed method would be discussed in more detail. The basic structure of the asymmetric multilevel modular converter (MMC) can be observed in Figure 3. Each phase is consisted of two branches and two subunits of the SM module).Therefore, in each phase contained 2N modulus, there are N modulus in the upper branch and N modulus in the lower branch. Each branch also has a non-coupling inductor ($L_{arm}$).  The modules have a half-bridge structure according to the first design, with regards to the S1 and S2 key commands, each module can have zero voltage levels or VC_SM,  at any time,. Assuming that in the DC voltage symmetrical converter all capacitors are equal to E, then in the proposed asymmetric converter in each branch, at least capacitance voltage of one of the modules is equal to 2E.In order to have an asymmetric converter it is enough to have a different voltage in N modulus. It is important to note that the number of modules that their capacitor voltage is 2E can be the same in the upper and lower branches in all phases

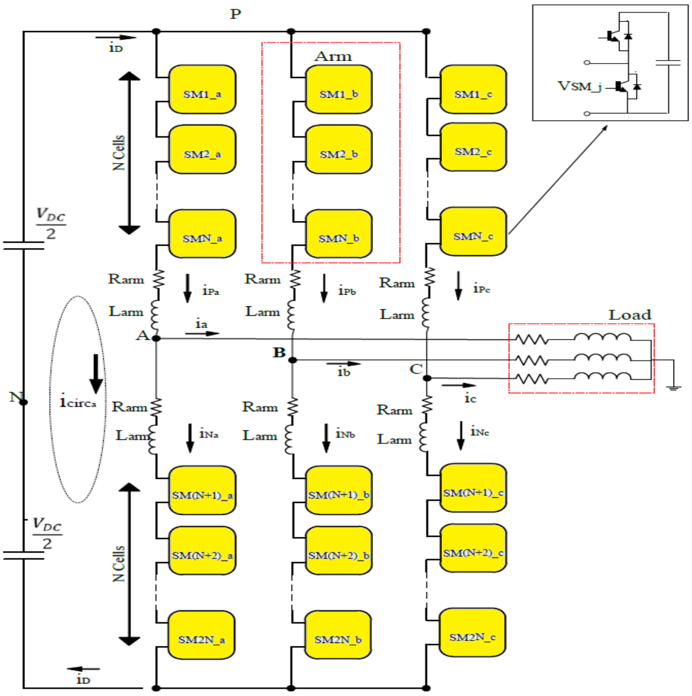


Figure 3. The main structure of the asymmetric modular converter

The capacitors as opposed to the symmetric MMC structure are not equal in the half-bridge branch. According to the proposed DC voltage selection algorithm, in the asymmetric converter based on the number of modules in each branch (N) and the number of modules with different DC voltage (m):

$$V_{C,SMj} = 2E \qquad j = 1,2,\ldots,m \tag{7}$$

$$V_{C,SMj} = E \qquad j = (m+1),(m+2),\ldots,N \tag{8}$$

The number of output voltage levels ($n_{step}$) will be as follows:

$$n_{step} = 2(N+m)+1 \tag{9}$$

The maximum output line voltage can also be obtained from the following equation:

$$V_{O,\max} = (N+m+1)E \tag{10}$$

According to the selection model of DC voltage proposed in this thesis, the number of voltage levels has increased. In an asymmetric converter, the capacitors of DC are not the same and capacitors with higher voltage have lower capacitance. The capacitance is obtained by Eq. 11 and with regards to the modulation index, allowed ripple value and the base frequency can be determined:

$$C_{dc} = \frac{I_{sk}[1-\sin(\arccos(\frac{\pi M}{4}))]}{\sqrt{2}\pi f_{grid}\Delta V_{dc}} \quad (11)$$

Where modulation index (M), grid frequency ($f_{grid}$), nominal current ($I_{sk}$) can be seen in Equation. According to IEEE standard, $\Delta V_{dc}$ is allowed ripple , it accounted for 15% of voltage on capacitor. With regards to this relationship, capacitor with higher voltage will have lower capacity (k = a, b, c). The overview of the asymmetric modular converter control is illustrated in Figure 4

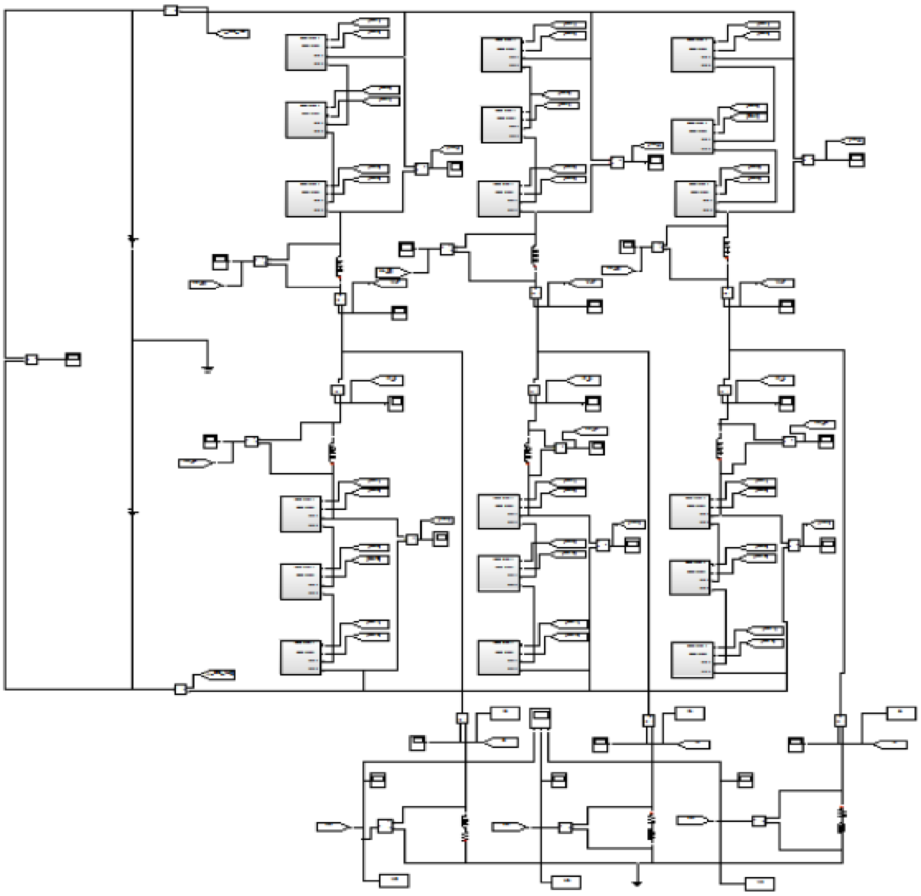

Figure 4. Schematic of level 9 Asymmetric Modular Converter

In this converter, there are three modules in each branch and one of the modules has a DC link voltage which it is two times higher than other two modules. The values of the converter parameters are also reported in Table (1).

Table 1.Parameters of level 9 asymmetric modular converter

| the amount of | Idiom | parameters |
|---|---|---|
| 3 KW | $P_{AC,out}$ | rated power |
| 600 (V) | $V_{DC}$ | DC bus voltage |

| | | |
|---|---|---|
| 2 | N | The number of modules in each branch |
| $C_{1,2}$=600(uF), $V_{C1,2}$=200(V) | $V_{C\_SM}$,C | The capacity and voltage of the capacitor modules in each branch |
| $C_3$=1200(uF), $V_{C3}$=100(V) | | |
| 5 (KHz) | $f_{SW}$ | Keying frequency |
| 5 (mH) | $L_{arm}$ | Indolence of the predecessor of the branch |
| 10 (Ω) | $R_{load}$ | load resistance |
| 5 (mH) | $L_{load}$ | Load inductance |

Figure 5 illustrates the wave of the three-phase voltages of asymmetric converter. As it is clear from the figure, voltage level is not visible.

The peak voltage is 200 volts. This voltage is obtained by the modulation method described in the previous section. Harmonic analysis of the output voltage in phase A is also shown in this figure. These results show the amount of THD (14.16%) which it is acceptable value for this type of converter

These results are also valid for other phases.

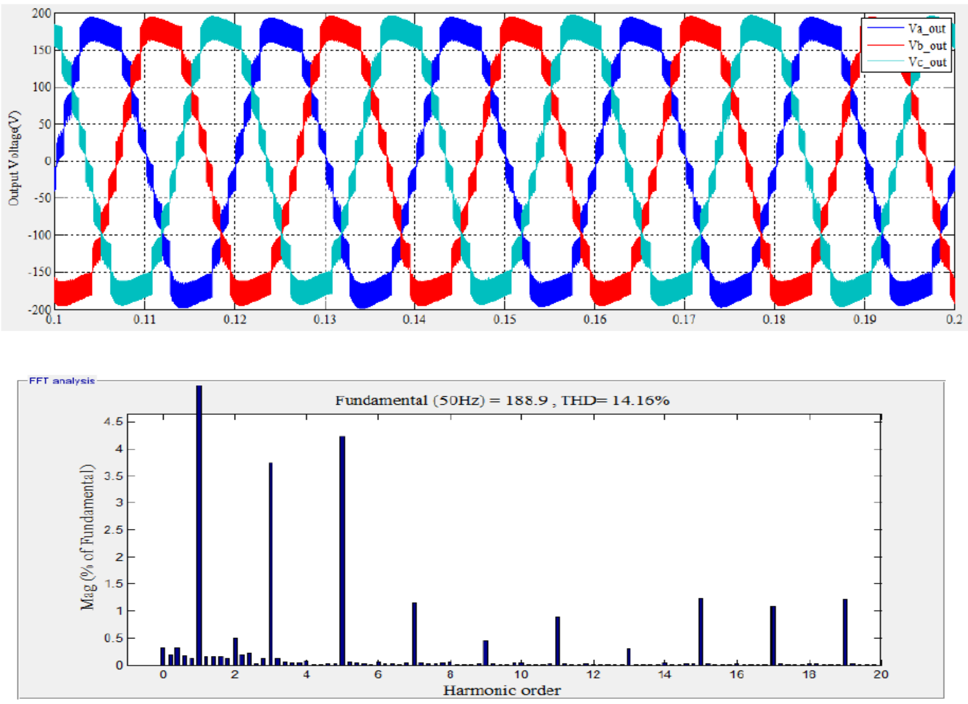


Figure 5. Waveform of three phase output voltage converter

The output voltage of phase A and current of this phase are compared with the main component (Fig. 6). As it is shown, the multilevel waveform follows the sinusoidal signal.

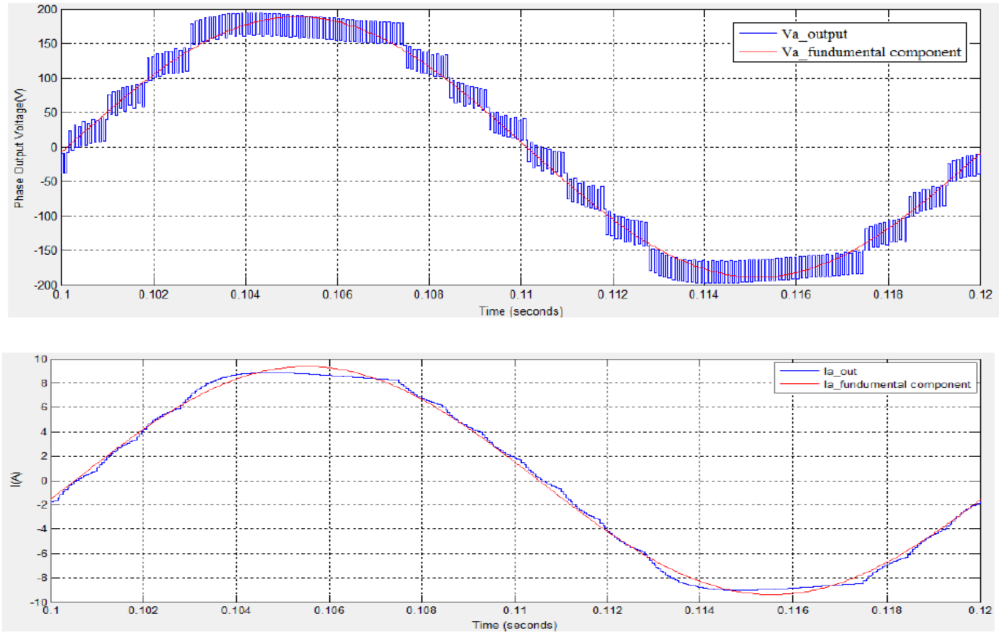


Figure 6. Comparison of the voltage waveform and the output current with the main component in a power cycle

Output currents of the level 9 asymmetric modular three-phase converter are shown in Fig. 7. With regards to this figure and also the harmonic analysis of the output phase current, the current has minor harmonic disturbances, so that THD output current is 5.26%

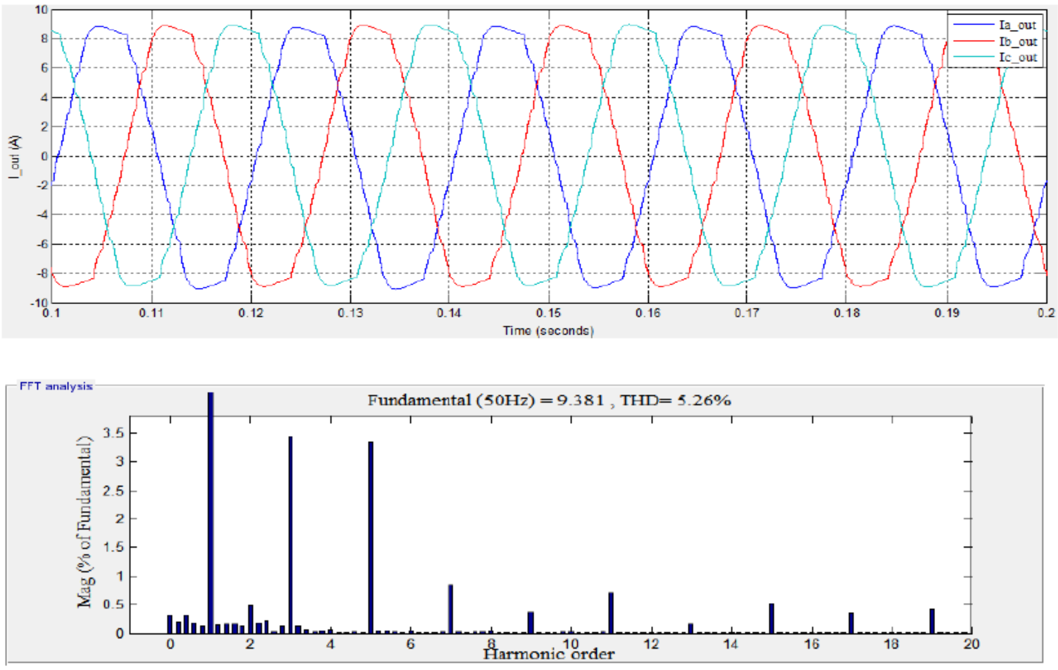


Figure 7. Waveform of three-phase output voltage converter

The results of the voltage balancing algorithm of capacitors in the upper and lower modules of phase A are shown in Fig. 8 and Fig. 9.

These results are obtained by applying the balancing algorithm presented in the previous sections and implementing simultaneously the total energy of the capacitors.

The capacitors voltage was well fixed at the predicted value (100 volts) for two modules with a larger capacitance and 200 volts for a module with a smaller capacitance. The capacitor ripple voltage is very low (less than 5%).

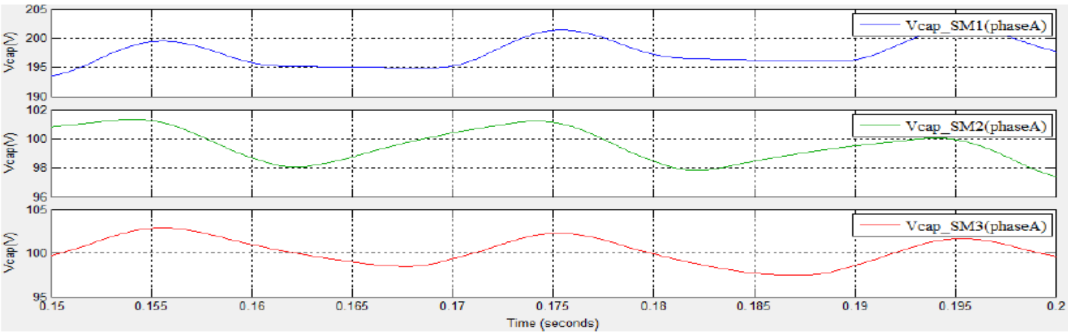


Figure 8. Capacitor voltage of upper-branch modules in phase A

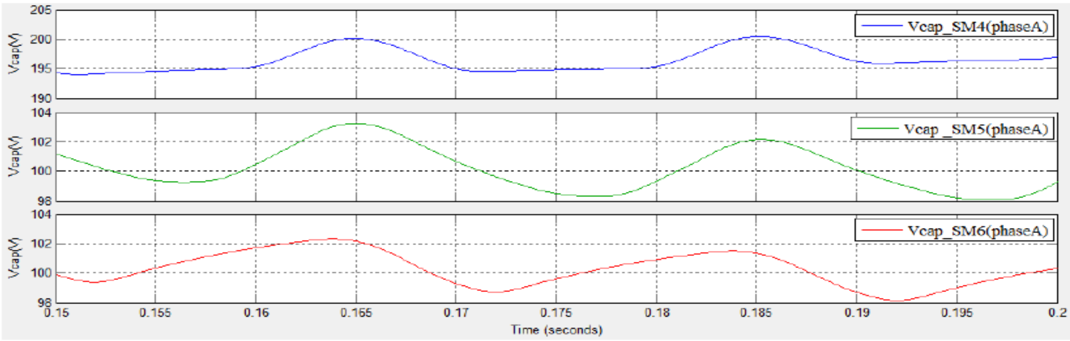


Figure 9. Capacitor voltage of lower branch modules in phase A

The upper and lower branches in phase A can be seen in Fig. 10. Assuming an equal current output AC between the upper and lower branches, DC and harmonics circulating current can be observed.

In other words, the circulation current between upper and lower branches does not affect the converter output

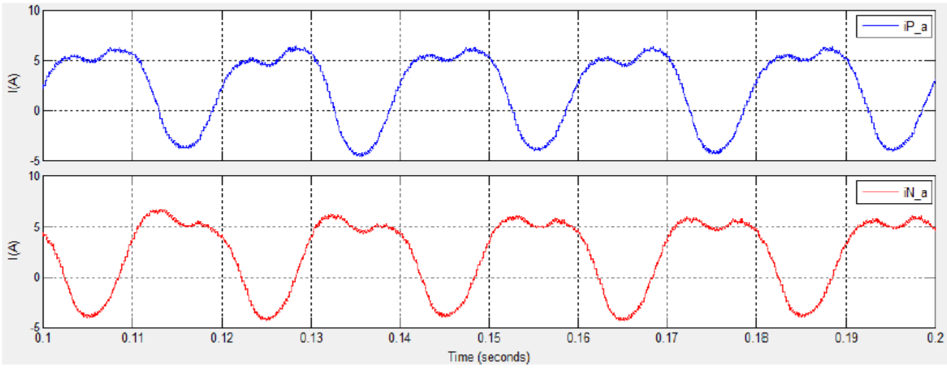


Figure 10. Upper and lower branch converter

The pattern of circulating current for all three phases A, B and C is shown in Fig. 11. These currents is equal to one third of the DC current (2.3 amps) with different harmonic components. Among these harmonics, second harmonic component was the dominant ones.

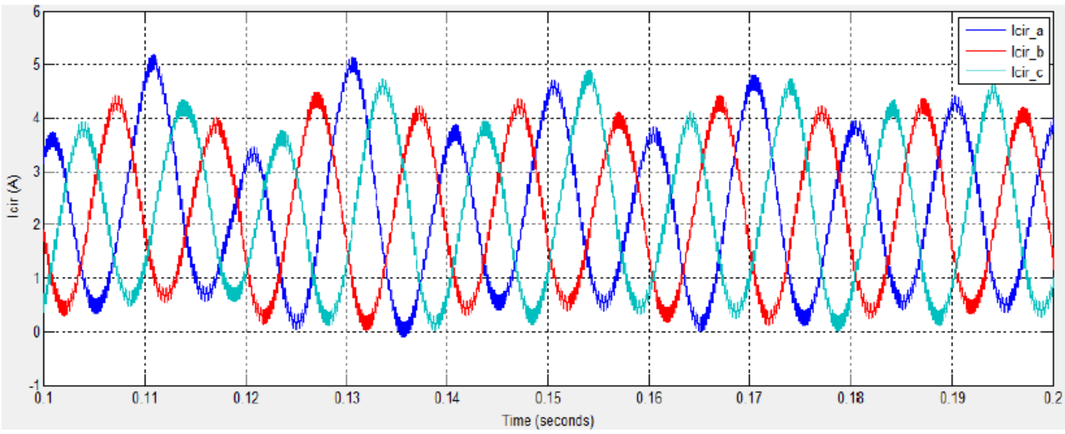


Figure 11. Circulating current shape in phases A, B and C

Figure 12 shows the DC converter current. This current can supply the energy needed for charging the capacitors. One of the consequences of the circulating current is the induction of current harmonics to DC current. As shown in the figure, these harmonics can be seen on the DC current. Controlling and compensating the DC current will filter the DC flow. As the DC current is filtered and oscillations caused by the circulating current, the ripple voltage of the capacitors and the MMC response time will be decreased. On the other hand, system stability is also guaranteed

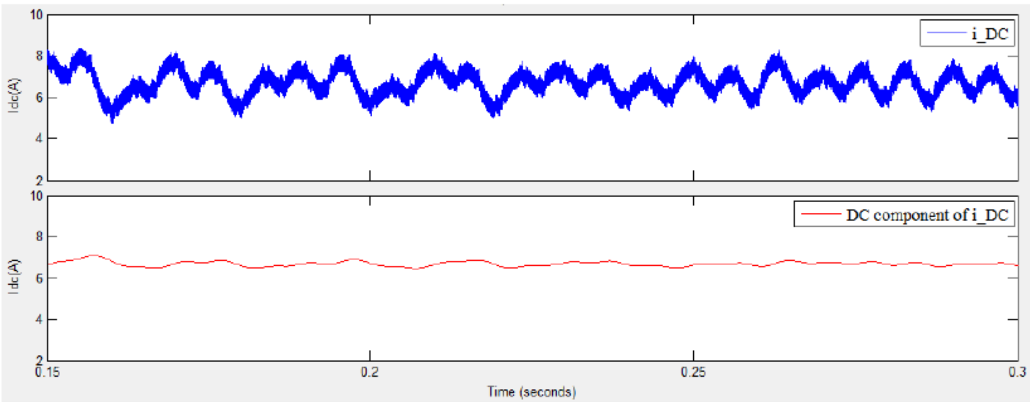


Figure 12. DC current

In order to reduce and compensate the circulation current in each phase of this converter, a second-order proportional resonance controller was applied. In fact, a proportional resonance controller was used in each phase. This controller can operate independently in each phase due to its unique features and does not require dq conversion. Figure 13 shows the circulation currents for phases A, B and C. The controller is activated at t = 0.3 s.

As shown in Fig. 13, the controller has been able to reduce circulation current.

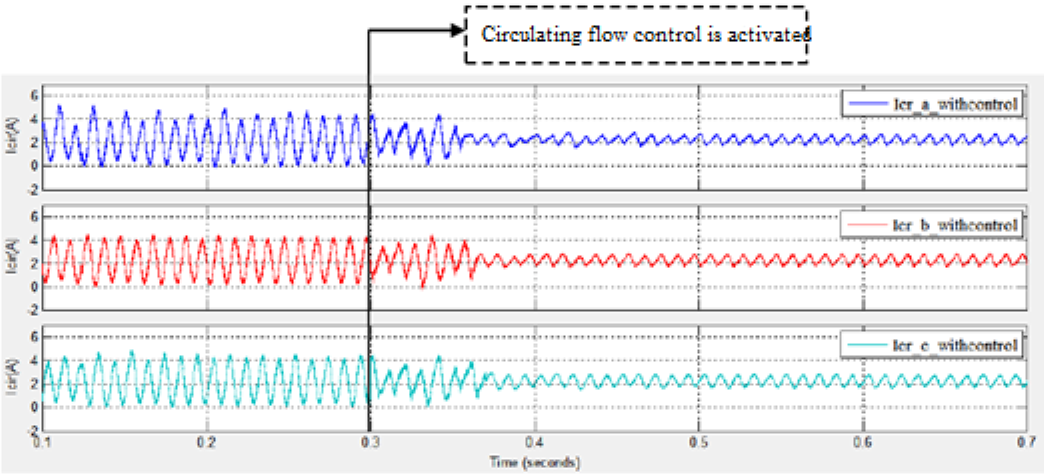


Figure 13.Three-phase circulating current with proportional resonance controller

Table 2. Results of different proposed structures

| circulating current THD | Current THD of each phase | THD voltage of each phase | Using second order proportional | Converter type | ردیف |
|---|---|---|---|---|---|

| | | | | resonance controller | | |
|---|---|---|---|---|---|---|
| 53/6% | فازA | 12/4% | 95/10% | no | 7 asymmetrical surface | 1 |
| 16/25% | فازB | | | | | |
| 52/23% | فاز C | | | | | |
| 02/4% | فازA | 57/3% | 31/6% | Yes | 7 asymmetrical surface | 2 |
| 01/11% | فازB | | | | | |
| 27/12% | فاز C | | | | | |
| 76/70% | فازA | 7% | 25/18% | no | 9 asymmetrical surface | 3 |
| 6/75% | فازB | | | | | |
| 83% | فاز C | | | | | |
| 21/15% | فازA | 26/5% | 16/14% | Yes | 9 asymmetrical surface | 4 |
| 82/17% | فازB | | | | | |
| 03/21% | فاز C | | | | | |

## 3. conclusion

In this study, a new orbital topology as an asymmetric modular converter is designed to improve the performance of modular converters. The proposed converter structure was mathematically analyzed and modeled. The level shift modulation method was introduced as a suitable method for modulation and extraction of switching signals. THD for multilevel three phase output voltage was about 11% and THD for three phase output was 4.12%, which it was acceptable. The presence or absence of circulation current in asymmetric multilevel converters was also investigated. The result showed that this current was also the in asymmetric modular multilevel converters. As a result, a suitable control algorithm based on proportional resonance controller was used to compensate the circulation current. The proportional resonance controller was adjusted to the frequency of the AC oscillations of the circulation current, that it twice the original frequency and they were compensated by using the undesirable oscillations and components of the circulation current. The second harmonic amplitude was reduced by about 50% during the current circulation, and THD in the phases A, B and C was 4.02%,10.61% and 12.49%, respectively. The good response of this controller in circulating current control was confirmed by the obtained results. Finally, in order to improve the performance of the asymmetric converter and to extend the proposed structure, a new algorithm was proposed to selecting the voltage of DC link capacitors. This algorithm showed how to increase the output voltage levels without increasing the number of modules and only by selecting the appropriate voltage of DC link modules. For further investigation a level 9 asymmetric modular converter was simulated. Implementation of balancing algorithm of voltage in capacitance applied an acceptable voltage ripple, about 5% for capacitors. On the other hand, controlling and compensating the circulating current by proportional resonance controller for this converter also reduced the second harmonic amplitude, as the dominant harmonic of the circulating current, and consequently it also reduced some side effects.

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