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Comparative analysis of principal modulation techniques for modular multilevel converter and a modified reduced switching frequency algorithm for nearest level pulse width modulation

Introduction. *The Modular Multilevel Converter (MMC) is an advanced topology widely used in medium and high-power applications, offering significant advantages over other multilevel converters, including high efficiency and superior output waveform quality.* ***Problem.*** *The modulation techniques and submodule capacitor voltage balancing significantly affect the performance of the MMC, influencing output voltage and current quality, capacitor voltage balancing, and power losses.* ***Goal.*** *This study presents a comparative analysis of 3 modulation techniques for a 3-phase MMC: Level-Shifted Pulse Width Modulation (LS-PWM), Nearest Level Control (NLC), and hybrid Nearest Level Pulse Width Modulation (NL-PWM). In addition, this study proposes a modification to the Reduced Switching Frequency (RSF) capacitor voltage balancing algorithm to adapt it for use with the NL-PWM technique.* ***Methodology.*** *The performance of each modulation technique is evaluated through simulations using MATLAB/Simulink software, in terms of output signal quality, capacitor voltage balancing, converter losses, and behavior under a line-to-ground fault.* ***Results.*** *The results show that both LS-PWM and NL-PWM generate lower harmonic content compared to NLC. However, the NLC technique presents the lowest switching losses, followed by NL-PWM and LS-PWM. The NL-PWM technique shows intermediate performance, making it more appropriate for medium-voltage applications. The results also confirm the proposed modifications to the RSF capacitor voltage balancing algorithm. Additionally, the LS-PWM technique shows greater robustness under fault conditions compared to the other techniques.* ***Originality****. For the first time, a comparative analysis of 3 modulation techniques for the MMC, LS-PWM, NLC, and NL-PWM has been conducted, highlighting their performance under different operating conditions. The study also proposes a modified RSF capacitor voltage balancing algorithm specifically for NL-PWM, which has not been previously explored in the literature.* ***Practical value.*** *The results of this study contribute to the selection of the most suitable modulation technique for MMC for specific applications.* References 34, table 5, figures 17.

Key words: **modular multilevel converter, level-shifted pulse width modulation, nearest level control, nearest level pulse width modulation, capacitor voltage balancing, reduced switching frequency.**

Вступ*. Модульний багаторівневий перетворювач (ММС) – це вдосконалена топологія, що широко використовується в системах середньої та високої потужності, пропонуючи значні переваги над іншими багаторівневими перетворювачами, включаючи високу ефективність та якість вихідної форми сигналу.* ***Проблема****. Методи модуляції та балансування напруги на конденсаторах підмодулів суттєво впливають на продуктивність ММС, впливаючи на якість вихідної напруги та струму, балансування напруги на конденсаторах та втрати потужності.* ***Мета****. Це дослідження представляє порівняльний аналіз трьох методів модуляції для трифазного ММС: імпульсна широтна модуляція зі зсувом рівнів (LS-PWM), керування найближчим рівнем (NLC) та гібридна імпульсна широтна модуляція найближчим рівнем (NL-PWM). Крім того, це дослідження пропонує модифікацію алгоритму балансування напруги на конденсаторах зі зниженою частотою перемикання (RSF) для адаптації його для використання з методом NL-PWM.* ***Методологія****. Продуктивність кожного методу модуляції оцінюється за допомогою моделювання з використанням програмного забезпечення MATLAB/Simulink з точки зору якості вихідного сигналу, балансування напруги на конденсаторах, втрат перетворювача та поведінки при замиканні між лінією та землею.* ***Результати*** *показують, що як LS-PWM, так і NL-PWM генерують нижчий вміст гармонік порівняно з NLC. Однак, метод NLC має найнижчі втрати на перемикання, за ним йдуть NL-PWM та LS-PWM. Метод NL-PWM демонструє проміжні характеристики, що робить його більш придатним для застосувань середньої напруги. Результати також підтверджують запропоновані модифікації алгоритму балансування напруги конденсаторів RSF. Крім того, метод LS-PWM демонструє більшу стійкість в умовах несправності порівняно з іншими методами.* ***Оригінальність****. Вперше було проведено порівняльний аналіз трьох методів модуляції для ММС, LS-PWM, NLC та NL-PWM, що підкреслює їхню ефективність за різних умов експлуатації. У дослідженні також пропонується модифікований алгоритм балансування напруги конденсаторів RSF спеціально для NL-PWM, який раніше не досліджувався в літературі.* ***Практична значимість****. Результати цього дослідження сприяють вибору найбільш підходящого методу модуляції для ММС для конкретних застосувань.* Бібл. 34, табл. 5, рис. 17.

Ключові слова: **модульний багаторівневий перетворювач, широтно-імпульсна модуляція зі зміщенням рівня, керування найближчим рівнем, широтно-імпульсна модуляція найближчим рівнем, балансування напруги конденсатора, знижена частота комутації.**

Introduction. The modular multilevel converter (MMC), initially proposed in the early 2000s by Lesnicar and Marquardt, has become a widely adopted solution for high-power and high-voltage applications, owing to its features, including modularity, scalability, high efficiency, capacitor-less DC link, and transformer-less operation [1, 2]. The MMC is capable of generating high-quality voltages at elevated levels with low-rated power devices and with reduced energy losses [3, 4]. The MMC is currently employed in various projects, including HVDC electric power transmission system [5], wind energy systems [6], photovoltaic energy systems [7], energy storage systems [8], and static compensators (STATCOM) for reactive power [9].

The MMC necessitates a complex control structure to ensure optimal performance across of control dynamics, circulating current, capacitor voltage, harmonic content, and energy losses. In recent years, the MMC has engendered substantial interest among academic researchers, resulting in numerous research publications focusing on various aspects, including control strategies [3], circulating current suppression [10, 11], modulation methods [12–14], and balancing capacitor voltages [1, 15].

The modulation techniques significantly influence various aspects of MMC performance, including harmonic content, capacitor voltage balancing, and switching losses [12, 16]. These techniques can be classified into 3 categories according to their switching frequency [17]. Techniques that utilize high switching frequencies include space vector pulse width modulation (PWM) [18], selective harmonic elimination PWM [19], and multicarrier PWM. The multicarrier PWM techniques are commonly employed in low-level MMC for their simplicity, although they result in high switching losses [10, 13]. Furthermore, the number of carrier signals rises proportionally with the increase in the number of submodules (SMs) within the MMC, thereby complicating the implementation of carrier-based PWM methods [20, 21]. The multicarrier PWM techniques can be divided into 2 principal based on the position of the carrier, either level-shifted (LS-PWM) [20] or phase-shifted (PS-PWM) [22]. A comparison between these 2 types of multicarrier PWM modulation was conducted in [23]. The PS-PWM technique allows for a uniform distribution of power and balanced use of switches. Conversely, the LS-PWM technique provides lower harmonic distortion for low-level MMC but results in an uneven power distribution [24]. In contrast, low-frequency modulation methods such as selective harmonic elimination [25] and nearest level control (NLC) [26], operate at the fundamental switching frequency, thereby minimizing switching losses. The NLC method is simpler than the selective harmonic elimination method, which necessitates more complex calculations. However, the NLC method produces lower-quality waveforms in low-level MMC, including low-order harmonics, which consequently leads to a high total harmonic distortion (THD). However, by employing a greater number of SMs, the NLC method can improves the voltage output quality and the reduction of THD, making such an approach more suitable for high-level MMC in HV applications [27]. Furthermore, there are different hybrid modulation methods in the literature. In [28] was presented a hybrid technique, combining both PS-PWM and LS-PWM methods to exploit the advantages of each. In [29] was proposed a hybrid method that combines low and high frequency modulation schemes, applying one technique to half of the SMs in each arm and the other technique to the remaining SMs. Moreover, this method incorporates an additional rotation strategy aimed at ensuring an even distribution of power among all the SMs. In [12] was proposed a hybrid nearest level pulse width modulation (NL-PWM) method, which integrates NLC control with PWM method, to take advantage of the reduced switching frequency (RSF) offered by the NLC technique and the low harmonic distortion achieved by the PWM technique. Therefore, the NL-PWM technique is considered better suited for medium voltage applications.

One of the challenges in controlling the MMC is maintaining the SM capacitor voltages at their nominal values. Imbalance in capacitor voltages results in lower order harmonics in the output voltages, thereby decreasing their quality [1]. Existing methods for balancing capacitor voltages are based on a sorting algorithm, where the capacitor voltages are sorted in each control cycle and the SMs to be inserted are selected based on the capacitor charge state [30]. However, this sorting method results in a higher and variable switching frequency, increasing switching losses and threatening the reliability of semiconductor devices (IGBT/GTO) [15]. To address this problem, several methods have been proposed in the literature, including the RSF voltage balancing algorithm, which eliminates certain unnecessary switching operations to lower the switching frequency and associated losses [15, 31].

The goal of the paper. This research aims to provide a comparative analysis of 3 modulation techniques from different categories for the MMC, namely LS-PWM, NLC, and NL-PWM. The study will evaluate the impact of these techniques on output voltage and current quality, capacitor voltage balancing, switching losses, and their robustness under short-circuit fault conditions. This analysis aims to facilitate the selection of the most suitable modulation technique for specific applications. Furthermore, the capacitor voltage balancing of the SMs in this study was performed using the RSF algorithm. Additionally, to the best of the author’s knowledge, the NL-PWM technique cannot be directly applied with the RSF algorithm. To address this limitation, the paper proposes a modification to the RSF algorithm, enabling its compatibility with the NL-PWM method and opening new perspectives for enhancing MMC performance.

MMC topology and operation principle. The MMC topology utilized in this study is a 3-phase, 9-level configuration (Fig. 1,*a*). It comprises 6 arms, each of which consists of an inductance (L_{arm}) and 8 SMs connected in series. The inductances serve to limit the circulating current in the arms to protect the system in the event of a short circuit [32].

A variety of SM types are available, with the full-bridge SM and the half-bridge SM being the most common [33]. In this study, we have used the half-bridge SM (Fig. 1,*b*).

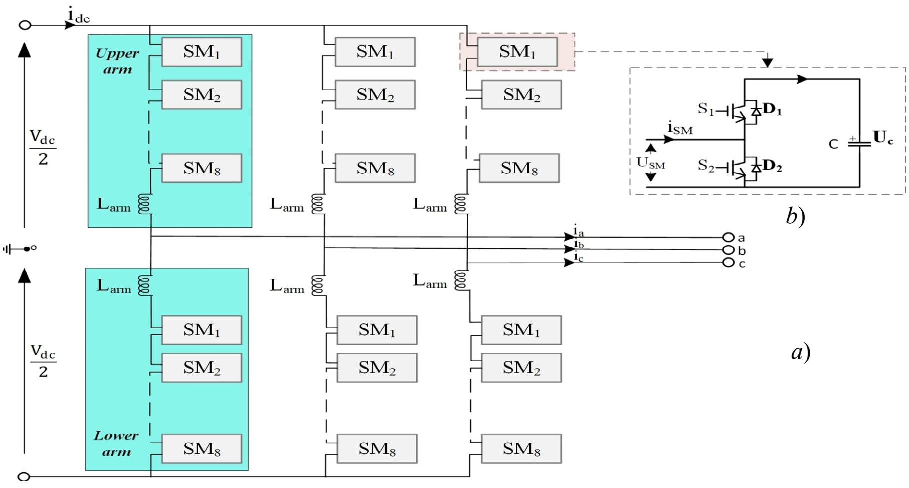

Fig. 1. Topology of the 3-phase 9-level MMC (*a*); half-bridge submodule (*b*)

This SM is composed of a pair of switches and a capacitor (C), with each switch comprising an IGBT or MOSFET and an antiparallel diode. The half-bridge SM is widely utilized in HV applications, particularly in HVDC systems, due to its high efficiency, reduced number of components and low energy losses [20, 32]. The SMs operate according to 2 normal operating states: the active state and the bypass state. In the active state, the lower switch (S_2) is OFF while the upper switch (S_1) is ON. In this mode, the output voltage of the SM (U_{SM}) equals the voltage across the capacitor (U_C), and the capacitor charges or discharges based on the direction of the arm current flow (Fig. 2). Conversely, in the bypass state, switch S_1 is deactivated while S_2 is activated. The voltage across the SM remains at zero, and the arm current does not flow through the capacitor. Table 1 summarizes the operation of the SM based on the switching state and the direction of the current in the arms.

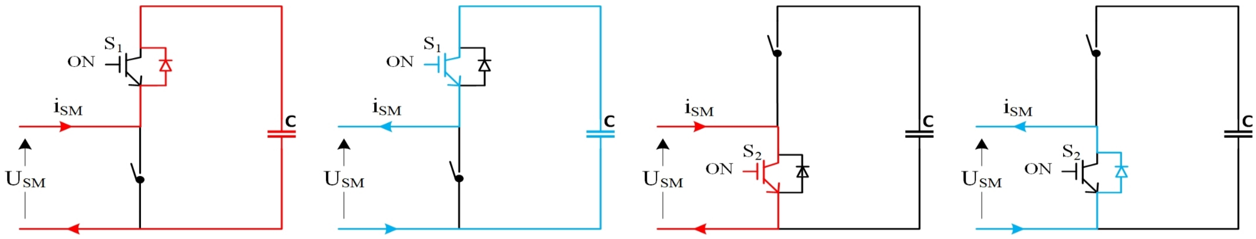

Fig. 2. Operating modes of the half-bridge submodule

Table 1

Switching state of sub-module

Mode	S_1	S_2	i_{SM}	U_{SM}	Capacitor state	S^k
1	1	0	> 0	U_C	Charging	1
2	1	0	< 0	U_C	Discharging	1
3	0	1	> 0	0	Bypass	0
4	0	1	< 0	0	Bypass	0

The output voltage of the SM is expressed as a function of the SM insertion index (S^k) as follows:

$$U_{SMji}^{k} = S_{ji}^{k} \cdot U_{cji}^{k}, \qquad (1)$$

where j is the indices of the upper (u) or lower (l) arms, respectively; $i = a, b, c$ corresponds to the phase indices; k is the index of the k-th SM; U^k_{cji} is the SM capacitor voltage, which can be calculated as:

$$U_c = V_{dc} / N. \qquad (2)$$

The voltage of each arm is the sum of the output voltages of the inserted SMs and is expressed as:

$$U_{ji} = \sum_{k=1}^{N} S_{ji}^{k} \cdot U_{cji}^{k}. \qquad (3)$$

The MMC equivalent circuit models the SM capacitors as a voltage source shown in Fig. 3, where u_{ui}, u_{li} are the upper and lower arm voltages, respectively; i_i is the line current, which is expressed as:

$$i_i = i_{ui} - i_{li}, \qquad (4)$$

where i_{ui}, i_{li} are the circulating currents in the upper and lower arm, respectively.

According to the Kirchhoff's voltage law, the arm voltages are expressed as:

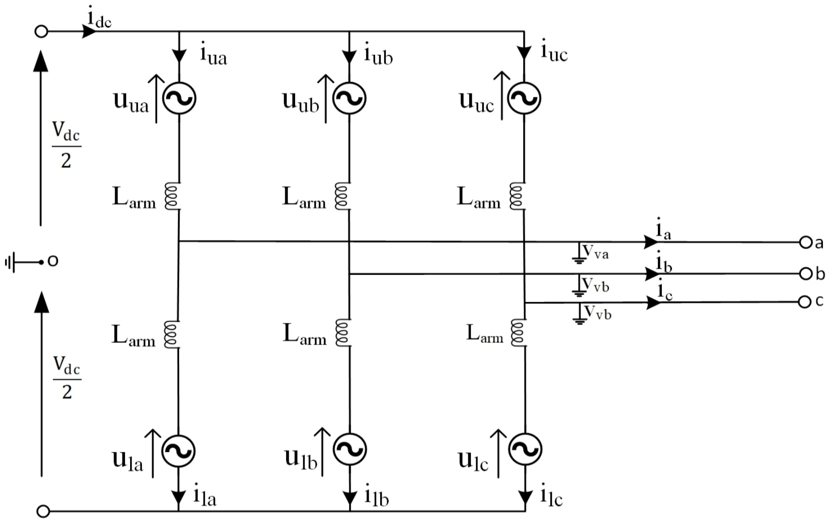

Fig. 3. Equivalent circuit of the MMC

$$u_{ui} = \frac{V_{dc}}{2} - L_{arm}\frac{\mathrm{d}i_{ui}}{\mathrm{d}t} - V_{vi}; \qquad (5)$$

$$u_{li} = \frac{V_{dc}}{2} - L_{arm}\frac{\mathrm{d}i_{li}}{\mathrm{d}t} + V_{vi}, \qquad (6)$$

where V_{vi} is the internal AC voltage of the MMC, which can be defined by the following equation:

$$V_{vi} = \frac{u_{li} - u_{ui}}{2} = \frac{1}{2} V_{dc} M \sin(2\pi f_0 t), \qquad (7)$$

where M is the modulation index of the voltage; f_0 is the fundamental frequency.

Ideally, neglecting the voltage of the inductance and according to (5), (6), the DC bus voltage can be expressed as:

$$V_{dc} = u_{ui} + u_{li}. \qquad (8)$$

MMC modulation methods. The modulation technique influences the behavior and performance of the MMC, particularly in terms of output voltage quality and energy losses. This work presents 3 modulation techniques for MMC: LS-PWM, NLC and NL-PWM. Each technique offers specific advantages and limitations. An analysis of their characteristics will guide the selection of the most appropriate technique for specific projects.

Level-shifted PWM techniques are widely employed in various applications and are categorized into 3 main types: phase disposition (PD), phase opposition disposition, and alternate phase opposition disposition. This study employs the PD-PWM technique, the principles of which are illustrated in Fig. 4. For an (N+1)-level converter, each arm requires N carrier waveforms, where the carriers are amplitude-shifted, have the same amplitude (V_{dc}/N) and frequency [14]. This method can produce a (2N+1)-level waveform by introducing a phase shift of π between the lower and upper arm carriers.

The PD-PWM technique operates by comparing the arm voltage reference with N carrier signals. When the reference signal exceeds a carrier signal, a pulse of 1 is generated; otherwise, the pulse is set to 0. These comparisons are performed in real-time, and the resulting pulses are summed to determine the total number of SMs to activate in the arm (N_{on}), as depicted in Fig. 4,*b*.

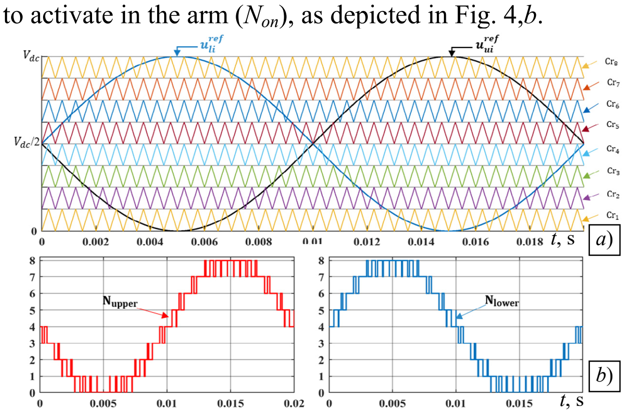

Fig. 4. Principle of PD-PWM:
references and carriers waves (*a*); number of inserted SMs (*b*)

Nearest level control. The NLC technique offers several advantages, including reduced switching losses, excellent harmonic characteristics in high-level MMC, and simplified implementation. The principle of this method is illustrated in Fig. 5, where the reference signal is divided by the capacitor voltage and then rounded to the nearest value to determine the number of SMs to be inserted in the arm. The output signal generated by the NLC method is discrete and can approximate a sinusoidal shape when a large number of SMs are used.

The arm reference voltages are:

$$u_{ui}^{*} = N_{ui} \cdot U_c ; \tag{9}$$

$$u_{li}^{*} = N_{li} \cdot U_c , \tag{10}$$

where N_{ui}, N_{li} are the number of SMs activated in the upper and lower arms, respectively.

The arm voltages generated by the NLC technique are expressed as:

$$u_{ui} = \text{round}\left(\frac{u_{ui}^{*}}{U_c}\right) \cdot U_c ; \tag{11}$$

$$u_{li} = \text{round}\left(\frac{u_{li}^{*}}{U_c}\right) \cdot U_c ; \tag{12}$$

where «round» is the function that rounds a number to the nearest integer. If the decimal part is 0.5 or higher, the number is rounded up; if it is less than 0.5, it is rounded down.

According to (2) and (9)–(12), the number of SMs to be inserted into the upper and lower arms can be calculated as:

$$N_{ui} = N \cdot \text{round}\left(\frac{u_{ui}^{*}}{V_{dc}}\right) ; \tag{13}$$

$$N_{li} = N \cdot \text{round}\left(\frac{u_{li}^{*}}{V_{dc}}\right) . \tag{14}$$

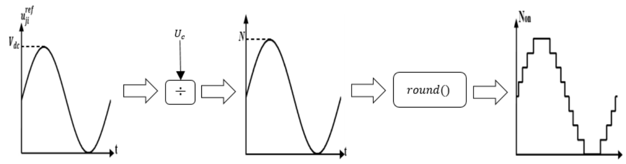

Fig. 5. Principle of the NLC technique

Nearest level PWM. The NL-PWM modulation technique combines the 2 previous modulation approaches, offering an effective solution to 2 major challenges encountered in power converters: high-frequency switching in PWM techniques and the low-order harmonic issue found in the NLC in low-level MMC [12].

The strategy of this technique is illustrated in Fig. 6. In this technique, each arm of the MMC has an SM operating in PWM mode to reduce harmonic distortion, with the capacitor voltage balancing algorithm determining which SM operates in PWM mode. The reference signal is quantified by the «floor» function to determine the number of SMs operating in the active state (Fig. 7,*a*). The remainder of the signal is then used to generate the reference signal for the SM operating in PWM mode (Fig. 7,*b*). Additionally, the converter can generate (2*N*+1)-level by using opposing carriers in both arms [12].

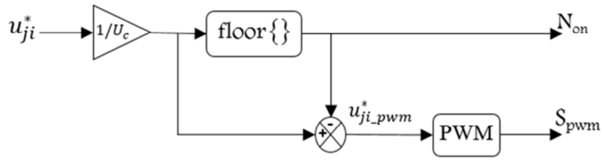

Fig. 6. Strategy of the NL-PWM technique

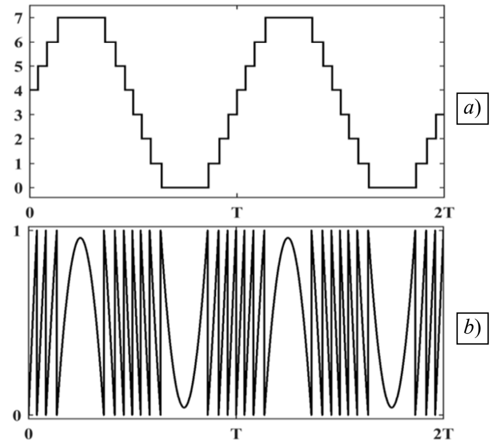

Fig. 7. NL-PWM technique: number of SMs to be inserted (*a*); reference wave of the PWM module (*b*)

The number of SMs in active mode is calculated as:

$$N_{ui} = \text{floor}\left(\frac{u_{ui}^{*}}{U_c}\right) ; \tag{15}$$

$$N_{li} = \text{floor}\left(\frac{u_{li}^{*}}{U_c}\right) , \tag{16}$$

where «floor» represents the mathematical function that rounds a number down to the nearest integer.

The reference voltages for the SMs in PWM mode are expressed as:

$$u_{ui\_pwm}^{*} = \frac{u_{ui}^{*}}{U_c} - \text{floor}\left(\frac{u_{ui}^{*}}{U_c}\right) ; \tag{17}$$

$$u_{li\_pwm}^{*} = \frac{u_{li}^{*}}{U_c} - \text{floor}\left(\frac{u_{li}^{*}}{U_c}\right) . \tag{18}$$

Capacitor voltage balancing algorithm. Balancing the capacitor voltages of the SMs is essential for ensuring the stability of the MMC converter. In this study, the RSF voltage balancing algorithm is employed, and a modified version is proposed to adapt it to the NL-PWM technique.

RSF capacitor voltage balancing algorithm. The RSF algorithm is based on the classical principle of capacitor voltage balancing, which aims to discharge overcharged capacitors and charge undercharged capacitors. Accordingly, when the arm current is positive, the SMs with the lowest voltage are inserted. Conversely, when the arm current is negative, the SMs with the highest voltage are inserted [14]. In addition, the RSF algorithm includes specific operations to avoid sorting when the number of SMs inserted or bypassed in an arm remains constant, thereby reducing both switching losses and energy losses in the MMC [15].

The principle of the RSF balancing algorithm (Fig. 8) involves inserting or bypassing specific SMs based on the variation in the number of SMs activated during each control cycle (Δ*N*). |Δ*N*| indicates the additional number of SMs to insert or bypass during the current control cycle. N_{on} is the number of SMs to activate, while N_{on_prev} is the number of SMs activated in the previous cycle. The RSF voltage balancing algorithm operates as follows:

- When ΔN is positive, $|\Delta N|$ SMs must be inserted. These SMs are selected from those in a bypass state, with no switching applied to those already in an active state.
- If ΔN is negative, certain active SMs must be switched to a bypass state, with no SMs currently in a bypass state being activated.
- If ΔN is zero, no changes are made.

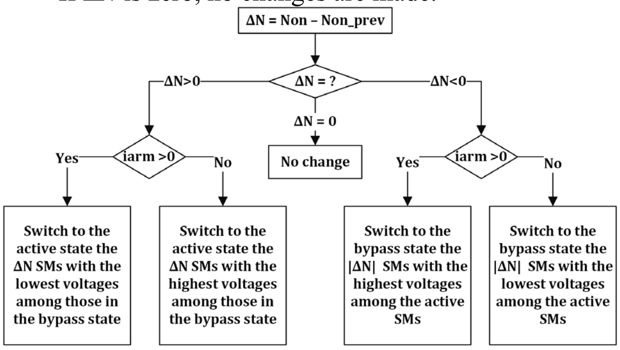

Fig. 8. Flowchart of the RSF voltage balancing algorithm

Modified RSF voltage balancing algorithm. The NL-PWM technique cannot be used with the RSF balancing algorithm, as the latter requires adjustments for selecting the SM that should be activated in PWM mode. The SM operates in PWM mode alternates between the active and bypass states, resulting in a reduction in the discharging or charging currents of its capacitor compared to other SMs operating in the active state. This work proposes modifications to the RSF algorithm to adapt it for compatibility with the NL-PWM technique (Fig. 9).

The principles of the modified RSF algorithm are explained below:

- When ΔN is positive, the last SM selected in PWM mode is switched to the bypass state. Then, among the SMs in the bypass state, ΔN SMs are switched to the active state, and one SM is activated in PWM mode. These SMs are selected based on the direction of current flow.
- When ΔN is negative, the last SM activated in PWM mode is switched to the active state, while $|\Delta N|$ others SMs are switched to the bypass state, and one SM among those in the active state is selected in PWM mode.

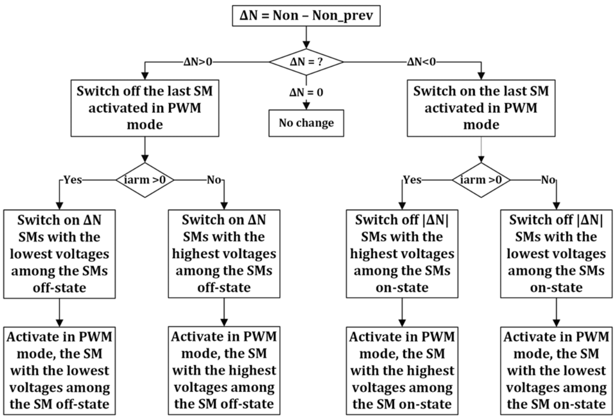

Fig. 9. Modified RSF voltage balancing algorithm

Simulation results. The LS-PWM, NLC and NL-PWM modulation techniques, along with the modified voltage balancing algorithm presented in this paper, were evaluated by simulation using MATLAB/Simulink software. The simulated system consists of a 3-phase MMC with an R-L load. Table 2 presents the system parameters.

Table 2

Parameters of the MMC system

Parameter	Values
DC-side voltage V_{dc}, kV	11
Number of SMs per arm N	8
SM capacitor C, mF	25
Load resistance R, Ω	10
Load inductance L, mH	15
Arm inductance L_{arm}, mH	0.1
Rated frequency f_s, Hz	50
Carrier frequency of LS-PWM, kHz	3
Carrier frequency of NL-PWM, kHz	1
Voltage modulation index	0.95

Output and capacitor voltage analysis. The 3 modulation techniques studied were evaluated in terms of line current quality, phase voltage, and capacitor voltage balancing. The results are presented in Fig. 10–13. Figure 10 shows the line current, while Fig. 11 presents its THD. Similarly, Fig. 12, 13 illustrate the output voltages and their corresponding THD, respectively.

Figure 11 shows that the THD of the line current is less than 5% for the 3 techniques studied, with the NLC technique providing the lowest quality. For the output voltage (Fig. 12, 13), the MMC generates the lowest THD (6.86%) using the LS-PWM technique due to the absence of lower-order harmonics. The THD obtained with the NL-PWM technique (7.05%) is close to that of LS-PWM. In contrast, the NLC technique has the highest THD (9.33%).

These results are summarized in Table 3.

Table 3

Analysis of line current and phase voltage

	Current		Voltage	
	Fundamental, A	THD, %	Fundamental, V	THD, %
LS-PWM	494.6	0.28	5475	6.86
NLC	500.5	1.28	5548	9.33
NL-PWM	492.4	0.56	5412	7.05

However, the NL-PWM and LS-PWM techniques are well-suited for low-level converters due to their low THD. In contrast, the THD decreases with an increasing number of SMs when using the NLC technique, making it more suitable for high-level converters.

Figure 14 shows the capacitor voltages in the upper arm of phase A. When the RSF balancing method is used with the LS-PWM technique, the capacitor voltages converge to the nominal value. The NLC method shows more pronounced oscillations due to a lower switching frequency, indicating a greater need for higher capacitance capacitors in low-frequency modulation techniques.

In contrast, the NL-PWM technique shows less oscillations compared to the NLC technique, with capacitor voltages varying around the nominal value of 1375 V. These results confirm that the RSF algorithm is suitable for use with the NL-PWM technique, validating the proposed adjustments to the RSF algorithm.

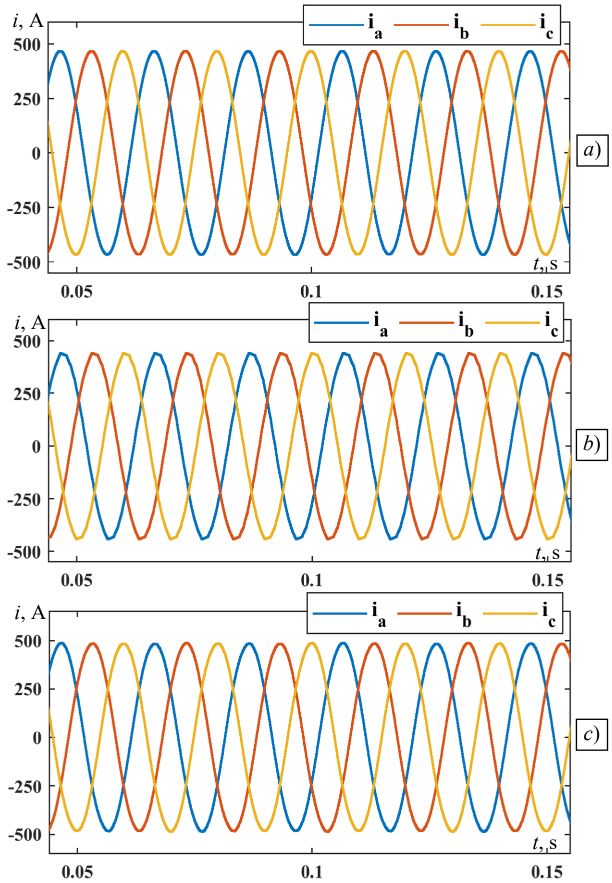

Fig. 10. Line currents: LS-PWM (*a*); NLC (*b*); NL-PWM (*c*)

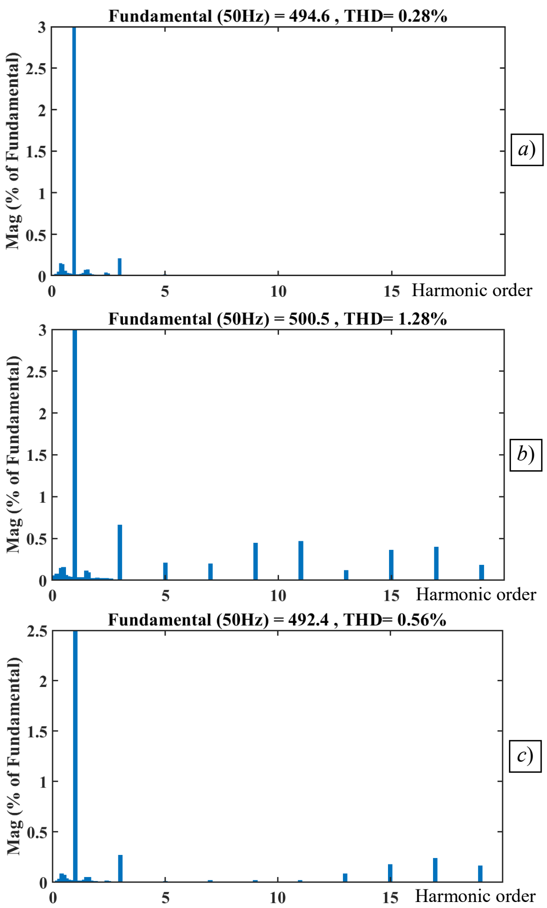

Fig. 11. THD analysis of output currents: LS-PWM (*a*); NLC (*b*); NL-PWM (*c*)

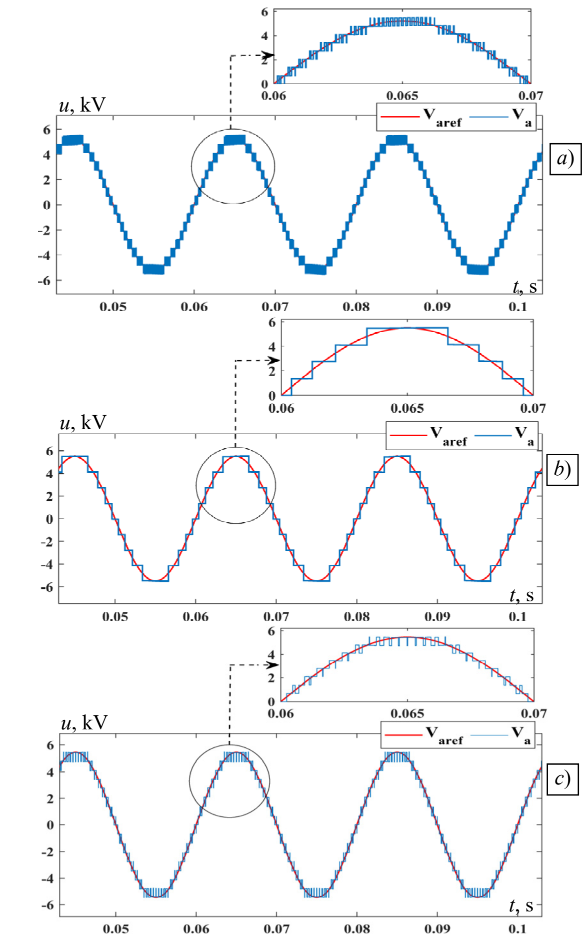

Fig. 12. Output voltages: LS-PWM (*a*); NLC (*b*); NL-PWM (*c*)

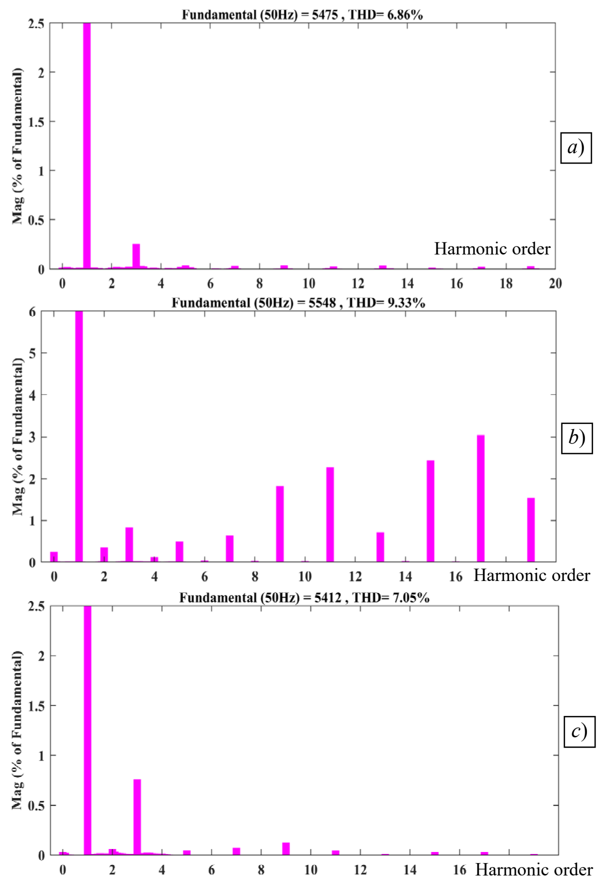

Fig. 13. THD analysis of output voltages: LS-PWM (*a*); NLC (*b*); NL-PWM (*c*)

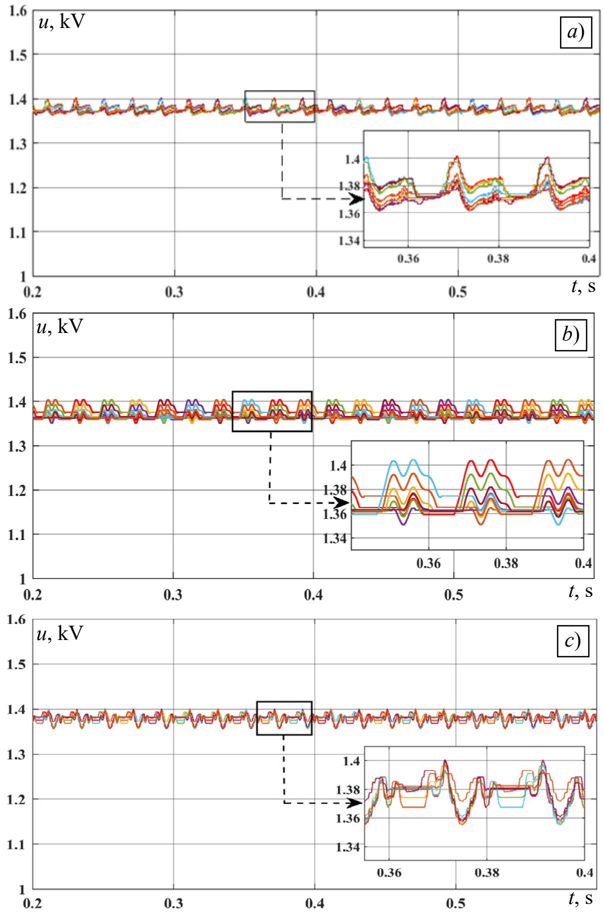

Fig. 14. Capacitor voltages in the upper arm of phase A: LS-PWM (*a*); NLC (*b*); NL-PWM (*c*)

Power loss analysis. Power losses in the MMC include those associated with both diodes and IGBTs. The total losses for the IGBTs can be expressed as:

$$P_{loss\_IGBT} = P_{c\_IGBT} + P_{sw\_IGBT}, \qquad (19)$$

where $P_{c\text{-}IGBT}$ is the conduction losses; $P_{sw\text{-}IGBT}$ is the switching losses. Switching losses occur during transitions between the on and off states, resulting from the energy dissipated during the switching period.

For diodes the total losses are given by:

$$P_{loss\_diode} = P_{c\_diode} + P_{rec\_diode}, \qquad (20)$$

where $P_{c\text{-}diode}$ is the conduction losses; $P_{rec\text{-}diode}$ is the reverse recovery losses, generated during the transition from the conducting to the blocking state.

In this study, the FZ3600R17HP4 IGBT/diode module was used, and its characteristics are presented in Table 4. The power losses were calculated according to the methods described in [34].

Table 4

Parameters of IGBT module FZ3600R17HP4

IGBT	V_{CES}, V	1700
	$I_{C\text{-}nom}$, A	3600
	V_{CE}, V	2.25
	E_{on}, mJ	800
	E_{off}, mJ	1500
Diode	V_{RRM}, V	1700
	I_F, A	3600
	V_F, V	1.9
	E_{rec}, mJ	1100

Figure 15 illustrates the switching pulses for the 4 SMs in the upper arm of phase A. Table 5 shows the total power losses and efficiency associated with each modulation technique. The results show that conduction losses are relatively similar among the 3 techniques, which is explained by their independence from the modulation method. In contrast, the switching losses vary considerably. The NLC technique has the lowest switching losses, characterized by a single switch per period, while the LS-PWM technique results in the highest losses.

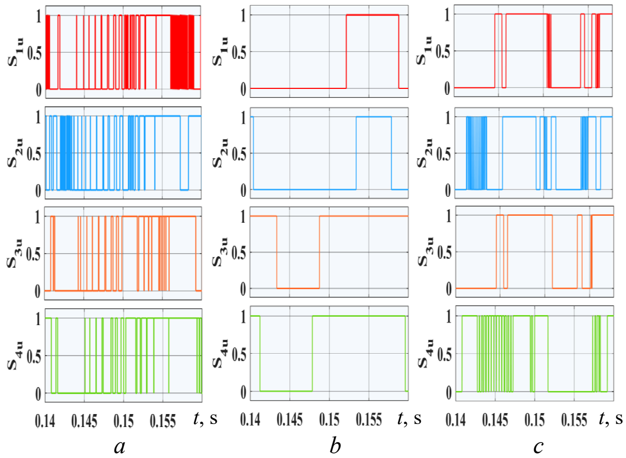

Fig. 15. Gate signals of 4 SMs in the upper arms of phase A: LS-PWM(*a*); NLC (*b*); NL-PWM (*c*)

Table 5

Power losses and efficiency of the MMC

Power losses	LS-PWM	NLC	NL-PWM
IGBT conduction losses, kW	18.575	18.846	18.729
IGBT switching losses, kW	54.084	24.472	31.634
Diode conduction losses, kW	1.992	1.973	1.912
Diode reverse recovery losses, kW	0.569	1.829	1.073
Total power loss, kW	75.22	47.12	53.35
Efficiency, %	97.98	98.75	98.39

Analysis under fault condition. To evaluate the robustness of the modulation techniques under fault conditions, a line-to-ground (L-G) short circuit was simulated. This type of fault is one of the most common in power transmission systems. The fault was applied between phase *A* and the ground at t = 1.4 s, with a duration of 50 ms. The impact of this fault on the RMS value of the voltage and on the capacitor voltages is illustrated in Fig. 16, 17, respectively. The performance of the each modulation techniques was compared in terms of their ability to maintain stability and balance the capacitor voltages after the fault is eliminated.

At the time of the L-G fault (t = 1.4 s), as depicted in Fig. 16, an immediate drop in the RMS voltage is observed for all the techniques studied. The NLC technique exhibits the most significant disturbance, followed by NL-PWM, while the LS-PWM technique shows the least voltage decrease. During the fault period, the LS-PWM technique maintains the most stable RMS voltage, with minimal oscillations. After the fault, LS-PWM is characterized by a rapid and stable return to the nominal value, in contrast to the NLC and NL-PWM, which show significant overshoot before stabilizing.

Moreover, as shown in Fig. 17, the fault significantly affects the balancing of the capacitor voltages.

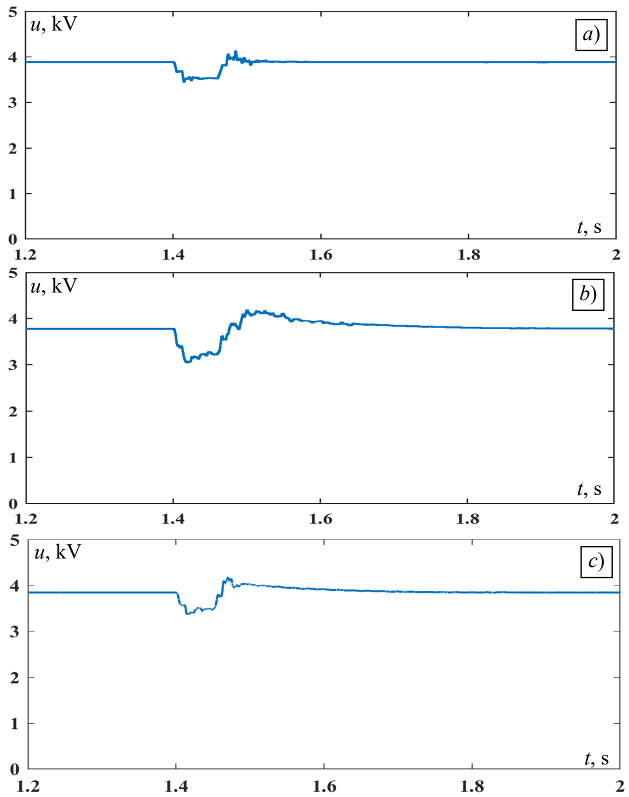

Fig. 16. RMS voltage of phase *A* under L-G fault: LS-PWM (*a*); NLC (*b*); NL-PWM (*c*)

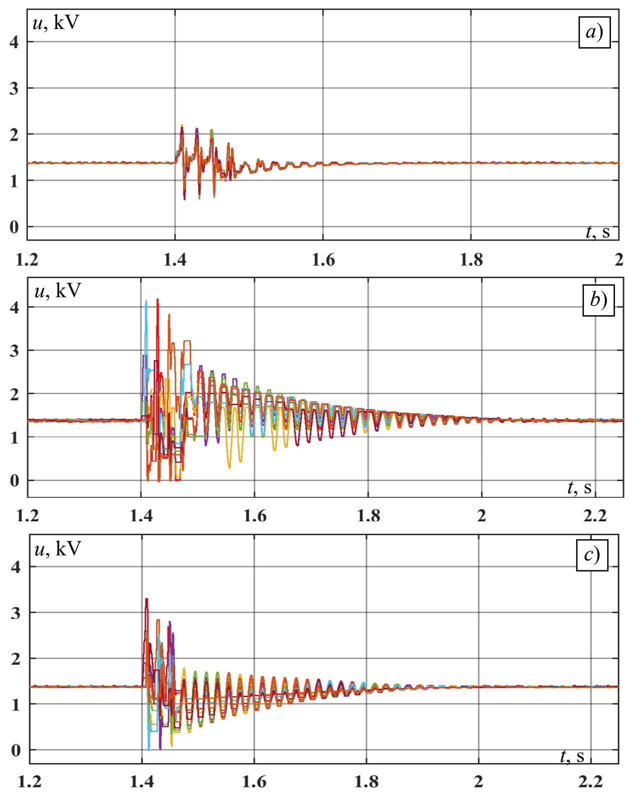

Fig. 17. Capacitor voltage in the upper arm of phase A under L-G fault: LS-PWM (*a*); NLC (*b*); NL-PWM (*c*)

The LS-PWM technique exhibits the most subdued oscillations and the fastest return to equilibrium. In contrast, with the NLC technique, the capacitor voltage increases up to 3 times its nominal value at the start of the fault, causing significant oscillations and a longer stabilization time. The NL-PWM technique shows intermediate performance, offering more effective balancing than the NLC technique, but less effective than the LS-PWM.

Conclusions. This article presents a comparative analysis of the performance of 3 modulation techniques for the MMC: LS-PWM, NLC and NL-PWM. The analysis focused on key criteria, including the harmonic content of the output signals, power losses, behavior under short-circuit conditions, and the impact on capacitor voltage balancing. The study was conducted on a 9-level 3-phase MMC connected to an R-L load. LS-PWM and NLC modulation techniques were used with the RSF capacitor voltage balancing algorithm, while the NL-PWM technique was used with the modified RSF algorithm proposed in this study.

Simulation results show that the LS-PWM and NL-PWM techniques generate output signals with similar total harmonic distortion, which is lower than that obtained with the NLC technique. Furthermore, capacitor voltage balancing was effectively achieved with the NL-PWM technique, validating the modification of the RSF algorithm proposed. In addition, the NLC technique exhibited more pronounced oscillations in the capacitor voltages compared to the other techniques, indicating that low-frequency modulation techniques require capacitors with higher capacity.

In terms of power losses, the NLC technique is characterized by lower switching losses than the others, with an efficiency of 98.75 %. Furthermore, regarding fault robustness, the LS-PWM technique shows the best performance, with a rapid and stable return to equilibrium after a short circuit.

The results of the study demonstrate that the LS-PWM and NL-PWM techniques are particularly suited for low-level MMC used in low or medium-voltage applications, while the NLC technique is more suitable for high-level MMC, intended for high-voltage applications such as HVDC systems.

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Conflict of interest. The authors declare that they have no conflicts of interest.

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