Nearest Level Control Based Modular Multi-level Converters For Power Electronics Building Blocks Concept In Electric Ship System

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***Abstract*—Power electronics building blocks (PEBBs) involve the integration of fundamental components into blocks with defined functionality, stacked in series and parallel, to extend converter power ratings to meet naval ship systems' various power conversion needs. The PEBBs concept in literature is based on modular multilevel converters (MMCs). MMCs are promising candidates for medium and high-power system applications owing to their unique features, such as modularity/scalability/simplicity in structure, low switching losses, low quantization on voltage/current, high reliability, and high efficiency. However, a promising switching control method is required in MMCs to balance the capacitor voltage and suppress the circulating current. This paper presents the nearest level control (NLC) method for the PEBBs concept in modern electric ship systems to simultaneously improve capacitor voltage balancing, circulating current, and power quality. The simulation is conducted in MATLAB/Simulink software. A three-phase five-level MMC converter is considered for the simulation to analyze and compare the converter's performance based on the proposed NLC and traditional sinusoidal pulse-width modulation (SPWM) switching methods.**

***Index Terms*—Power Electronics Building Block (PEBB), Modular Multi-level Converter (MMC), Nearest Level Control (NLC), Submodule Capacitor Voltage Balancing, Circulating Current Suppression, Total Harmonic Distortion (THD).**

I. Introduction

Contemporary naval ships are seeing a rise in power demand, leading to the development of all-electric systems. These systems utilize electrical energy for propulsion and supply service loads [1]. With modern ship systems relying on a power electronic interface for all loads, there's a growing interest in multi-functional power converters. These converters facilitate energy conversion and management efficiently. Moreover, modern ships are transitioning from medium-voltage alternative current (MVAC) to medium-voltage direct current (MVDC). This shift reduces cable weight, simplifies generator paralleling, and minimizes voltage dips [2].

New materials like wide bandgap (WBG) materials and silicon carbide (SiC)-based power semiconductor devices, along with concepts like Power Electronic Building Blocks (PEBBs) and integrated power systems, are revolutionizing marine systems, diverging from traditional ones such as steamships and sailing ships [3]. The decreasing costs and improving capabilities of computational devices have spurred the widespread adoption of power electronic devices across various applications [4], [5]. Shipboard electric power systems are benefiting from advancements in power converters, notably PEBB technology, initially proposed by the US Office of Naval Research (ONR) in 1998. PEBB implementation has significantly influenced the innovation, manufacturing, commissioning, and operation of converters in naval electric ship applications [6].

The shipboard electric power system utilizes various power electronic converters, with advancements in voltage stability analysis, power quality, fault detection, thermal management, and protection [7]. Multi-level converters (MLCs) have emerged as promising alternatives to traditional voltage source converters (VSCs), offering benefits such as reduced AC ripple, lower voltage stress on components, and higher effective switching frequencies. Different MLC topologies, including Neutral-Point Clamped type (NPC-MLC), flying capacitor type (FC-MLC), cascaded H-bridge type (CHB-MLC), and MMC, have been proposed, each with unique advantages [8]. While NPC-MLCs excel in high power density with minimal passive component requirements, CHBs and MMCs offer modularity, fault ride-through capability, and high efficiency but require more capacitors and have lower power density [9]. Research into MLCs across various fields, such as renewable energy systems and electric vehicles, has highlighted their advantages in reducing input current distortion and switching losses [10]. However, the complexity and cost associated with multiple components may impact reliability and controller design.

Recent developments, such as PEBB 1000 [11] and PEBB 6000 [12], have been developed based on the MMC configuration to shape the PEBBs concept as a practical solution for developing shipboard electric power systems with improved reliability, modularity, scalability, FRT capability, lower production and maintenance costs, and lower voltage and current quantization. However, in the PEBBs concept, power quality, capacitor voltage balancing, and circulating current

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are pressing issues that must be accounted for simultaneously. Several sinusoidal pulse-width modulation (PWM) methods, such as phase-shifted carrier PWM (PSC-PWM) and level-shifted carrier PWM (LSC-PWM), have been proposed in the literature [13]. Although these methods can somewhat reduce voltage/current harmonics, they require a high switching frequency and a complex Submodule (SM) sorting algorithm. The NLC method was presented to address this, in which no carrier signals were used [14].

The application of the MMC topology has also shown great potential in various transportation sectors [15]. The salient features offered by the MMC topology are as follows [9]: modularity in structure, simplicity in structure, scalability in structure (no DC-link limitation), good fault ride-through capability, low quantization on voltage/current (low harmonics), no bulk filter requirement (low requirement, if needed), low switching frequency, bypassing a failed SM without tripping the converter, high reliability, and high efficiency.

However, there are some disadvantages to the MMC topology. Data acquisition and the interface between SMs are complicated. The number of capacitors and SMs is quite high. So they can be inexpensive depending on the application. Control circuits are required to balance the current and voltage of SMs. Also, more sensors are required as the number of SMs increases.

A. State Of Contributions

This study aims to improve the performance of the MMC-based PEBBs concept used in electric navy ship systems. Along outstanding features of the MMC topology, namely modularity/simplicity/scalability in structure, low quantization on voltage/current (low harmonics), no bulk filter requirement (low requirement, if needed), low switching frequency, bypassing a failed SM without tripping the converter, a cost-effective switching control method plays a vital role in helping to improve the voltage and power quality of the PEBBs concept. In this paper, the NLC switching method is proposed to reduce the THD outputs, thereby enhancing the power quality of the PEBBs concept. This feature is particularly pivotal in all-electric navy ship systems, where the poor performance of the PEBBs stacks results in high maintenance costs for the entire system. Moreover, the proposed NLC helps balance SM capacitor voltages and suppress circulating currents, the two main concerns that must be accounted for simultaneously.

The remainder of this paper is organized as follows. Section II presents the MMC topology's principal and mathematical model. Section III starts with the traditional PSC-PWM switching method and then details the proposed NLC method and how it produces switching signals to serve the purposes of this work. Section IV provides the simulation results of the MMC topology in the PEBBs concept based on the traditional PSC-PWM and the proposed NLC switching methods to compare their performances. Finally, this paper is concluded in Section V.

II. Modular Multi-level Converter (MMC)

A. Principal

Figure 1 shows the three-phase MMC configuration. There are three legs for the three phases, each comprising two arms (upper and lower). Each arm has N identical half-bridge SM connected in series. These SMs can be full-bridge, half-bridge, or a combination of both. This paper uses the half-bridge SM, which includes two complementary IGBTs with anti-parallel diodes and a capacitor connected in parallel. In addition, each leg has an inductor (L_{arm}) used to limit the short-circuit current of the converter. A series resistor with this inductor may be considered to help reduce the power losses of the converter.

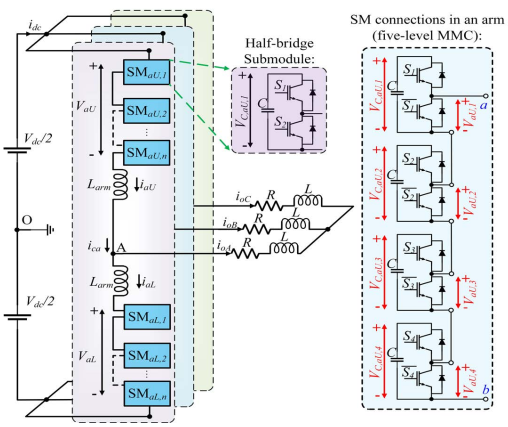

Fig. 1. Three-phase N-level MMC configuration

For simplicity, four half-bridge SMs ($n = 4$) in each arm are considered in this study. Note that, owing to the high number of outputs for all four SMs, only ph-a figures are presented in this paper. Figure 1 also shows SM connection in a five-level (5L) MMC configuration, in which the output terminals of the SMs are connected in series to form an arm voltage (in this case, V_{aU}). Here, $V_{aU,1}$, $V_{aU,2}$, $V_{aU,3}$, and $V_{aU,4}$ are the output voltages of the SMs, $V_{ab} = V_{aU}$ denotes the arm voltage, the subscripts a, b, and c indicate the three-phase, subscripts U and L denote the upper and lower arms, $n = 1, 2, 3, ..., n$ denotes the number of SMs, L_{arm} is the arm inductance which is identical for all arms, V_{aU}, V_{bU}, and V_{cU} are the upper arm voltages, V_{aL}, V_{bL}, and V_{cL} are the lower arm voltages, i_{aU}, i_{bU}, and i_{cU} are the upper arm currents, i_{aL}, i_{bL}, and i_{cL} are the lower arm currents, i_{oA}, i_{oB}, and i_{oC} are the output currents, i_{c_a}, i_{c_b}, and i_{c_c} are the circulating currents, R and L are the load resistance and inductance, V_{dc} is the DC-link voltage, and $V_{C,aU,1}$ to $V_{C,cL,n}$ are the capacitor voltages.

The number of SMs used in the arm determines the converter output level. Considering n SMs in each arm, the output line-to-neutral and line-to-line voltages will have $n+1$ and $2n+1$ levels, respectively. This is based on the state of each SM, which can be connected or bypassed. Note that the IGBTs in each SM are complementary to one another. When one IGBT is ON, the other is OFF, and vice versa. Therefore, an SM is connected when the upper IGBT is ON and bypassed when the upper IGBT is OFF. Table I presents SM switching states.

TABLE I
SWITCHING STATES OF AN SM (E.G., $SM_{aU,1}$)

S_1	S_2	D_1	D_2	i_{arm}	Capacitor State	$V_{aU,1}$
0	1	0	0	Positive	Unchanged	0
0	0	0	1	Negative	Unchanged	0
0	0	1	0	Positive	Charging	V_c
1	0	0	0	Negative	Discharging	V_c

B. Mathematical Model

Applying Kirchhoff's current law (KCL) to the ph-a of the MMC topology, the output current is written as follows:

$$i_{oA} = i_{aU} - i_{aL} \tag{1}$$

The mean value of the upper and lower arm currents provides the circulating current:

$$i_{c_a} = (i_{aU} + i_{aL})/2 \tag{2}$$

Now, using Kirchhoff's voltage law (KVL), the voltage equations for the upper and lower legs are expressed as follows:

$$-\frac{V_{dc}}{2} + V_{aU} + L_{arm}\frac{di_{aU}(t)}{dt} + Ri_{oA} + L\frac{di_{oA}(t)}{dt} = 0 \tag{3}$$

$$-\frac{V_{dc}}{2} + V_{aL} + L_{arm}\frac{di_{aL}(t)}{dt} - Ri_{oA} - L\frac{di_{oA}(t)}{dt} = 0 \tag{4}$$

Employing i_{oA} calculated in (1) to the sum of (3) and (4), the output voltage (V_{oA}) can be expressed as follows:

$$V_{oA} = Ri_{oA} + L\frac{di_{oA}(t)}{dt} = \frac{V_{aL} - V_{aU}}{2} - \frac{L_{arm}}{2}\frac{di_{oA}(t)}{dt} \tag{5}$$

Another way to express the arm voltages is as follows:

$$V_{aU} = N_{SM,U}\overline{V_{C,aU}} \tag{6}$$

$$V_{aL} = N_{SM,L}\overline{V_{C,aL}} \tag{7}$$

Where $N_{SM,U}$ and $N_{SM,L}$ are the number of connected SMs in the upper and lower arms, respectively. $\overline{V_{C,aU}}$ and $\overline{V_{C,aU}}$ are the mean values of the capacitor voltages in the upper and lower arms, respectively. Provided that the SM capacitor voltages remain constant at the nominal levels ($V_C^* = V_{dc}/(N-1)$) and that the decrease in voltage across the arm inductors is insignificant, the output voltage can be written as follows:

$$V_{oA} = V_C^*[(N_{SM,U} + N_{SM,L})/2] \tag{8}$$

Note that the above equations are for ph-a, and a similar procedure can be followed for the other two phases, b and c. This study considers a 5L MMC ($n = 4$) for the PEBBs concept for navy ship systems. Figure 2 shows phase unit stages and voltages of the single-phase 5L MMC configuration. The switching states, SMs' output voltages, and arm voltages are presented in Table II. For instance, the arm voltage of ph-a can be expressed as:

$$V_{aU} = \Sigma_{i=1}^{n} V_{aU,i} = \Sigma_{i=1}^{n} S_i V_C \tag{9}$$

TABLE II
SWITCHING STATES AND VOLTAGE LEVELS OF A 5L MMC

S_1	S_2	S_3	S_4	$V_{aU,1}$	$V_{aU,2}$	$V_{aU,3}$	$V_{aU,4}$	V_{aU}	Level
0	0	0	0	0	0	0	0	0	0
1	0	0	0	V_C	0	0	0	V_C	1
0	1	0	0	0	V_C	0	0	V_C	
0	0	1	0	0	0	V_C	0	V_C	
0	0	0	1	0	0	0	V_C	V_C	
1	1	0	0	V_C	V_C	0	0	$2V_C$	2
1	0	1	0	V_C	0	V_C	0	$2V_C$	
1	0	0	1	V_C	0	0	V_C	$2V_C$	
0	1	1	0	0	V_C	V_C	0	$2V_C$	
0	1	0	1	0	V_C	0	V_C	$2V_C$	
0	0	1	1	0	0	V_C	V_C	$2V_C$	
1	1	1	0	V_C	V_C	V_C	0	$3V_C$	3
1	1	0	1	V_C	V_C	0	V_C	$3V_C$	
1	0	1	1	V_C	0	V_C	V_C	$3V_C$	
0	1	1	1	0	V_C	V_C	V_C	$3V_C$	
1	1	1	1	V_C	V_C	V_C	V_C	$4V_C$	4

The arm voltage will have five levels in a 5L MMC ($n = 4$), from 0 to $4V_C$. As shown in this table, $4V_C$ and 0 are the highest level (by turning ON all switches) and the lowest level (by turning OFF all switches), respectively. The middle levels are produced by employing several switching combinations (known as redundancy switching states) that can help balance the capacitor voltages of the SMs. This paper sorts the selection of the SMs in a increasing order, as shown in Figure 2.

III. METHODOLOGY

A. Sinusoidal Pulse Width Modulation (SPWM)

Depending on the carrier, several multi-carrier SPWM switching control methods, such as PSC-PWM and LSC-PWM, have been proposed in the literature review. This study employs the PSC-PWM method, [13], as the traditional SPWM method to which the proposed NLC method is compared. The PSC-PWM has one sinusoidal waveform as the reference signal and n triangular carriers with the same amplitude and frequency for each SM. Thus, four carrier waveforms exist for the 5L MMC topology, as shown in Figure 3. The carriers are always compared with the reference signal to create switching pulses.

B. Nearest Level Control (NLC)

Switching control methods for MMC can be categorized based on the switching frequency range. For high-level applications of the MMC topology (i.e., all-electric ship systems), low-frequency switching control methods, such as nearest level control (NLC) methods are a great candidate because the output voltage can be created effortlessly in staircase forms, thus lowering the quantization of the output voltage and current,

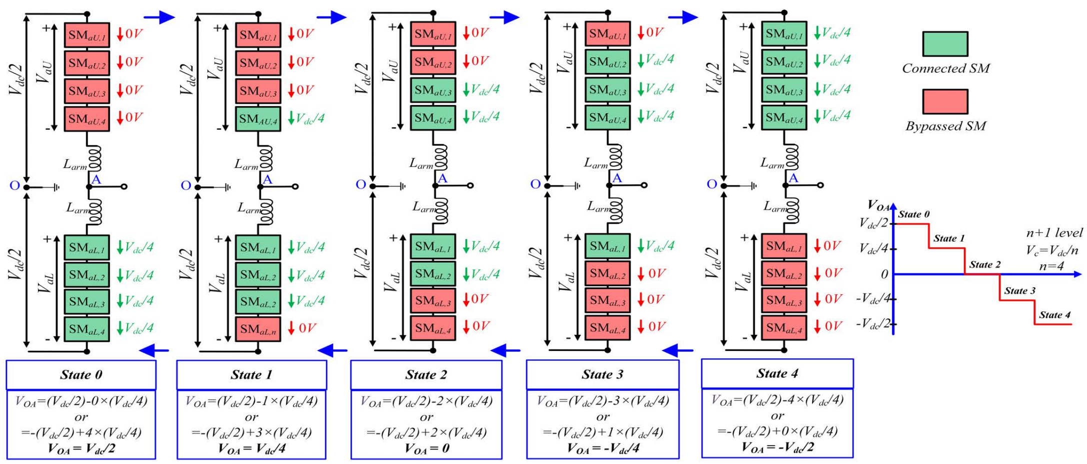

Fig. 2. Phase unit stages and voltages of a single-phase 5L MMC (ph-a)

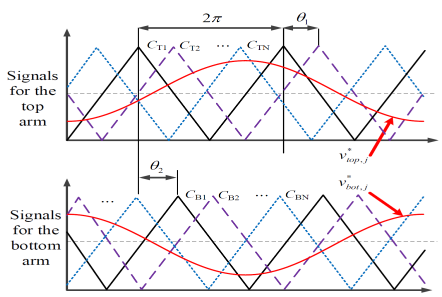

Fig. 3. Carrier and reference signals of the PSC-PWM method: the upper arm (top) and the lower arm (bottom) [13]

which leads to lower filter requirements (no filter most of the time) and lower power loss. It bears noting that the NLC method is prone to reducing the voltage quality when it comes to low SMs. Thus, this method is more suitable for high-level applications of the MMC topology, where many SMs are used.

The NLC method, also called the round method, operates by selecting the nearest voltage level obtained through the conversion process to match the desired output voltage reference. This method allows for the independent control of the three phases through separate comparisons. Figure 4 shows that the reference value is compared with the current voltage level to convert it into a staircase pattern. The NLC output voltage is specified by comparing the reference voltage with the current output voltage. The round function is used to specify the number of SMs that must be connected to reach the next voltage level in the output. This function rounds the input signal to the nearest value.

First, the reference value is normalized per the number of levels (n). Next, the normalized value goes through a round function to determine the integer closest to the real value. Therefore, the number of SMs that must be switched ON in an arm is calculated as follows [16]:

$$V_{ref}^{n} = \left(\frac{N-1}{2}\right)\left(\frac{V_{ref}}{V_{dc}}\right) \tag{10}$$

$$V_{ref}^{MMC} = round(V_{ref}^{n}) \tag{11}$$

$$n_{SM,U} = V_{ref}^{MMC} + \left(\frac{N-1}{2}\right) \tag{12}$$

$$n_{SM,L} = (N-1) - n_{SM,U} = n - n_{SM,U} \tag{13}$$

The staircase waveforms of the NLC method with 6 and n SMs in the MMC topology are shown in Figure 5. Plus, the NLC improves SM capacitor voltage balancing and circulating current suppression.

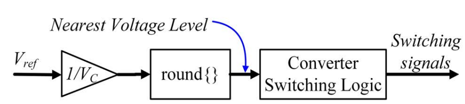

Fig. 4. Working principle of the NLC method

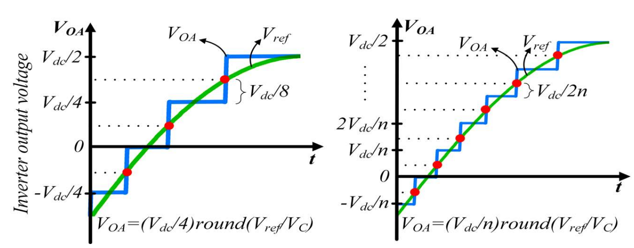

Fig. 5. Staircase waveform of the NLC method: a 5L with 6 SMs (left) and an N-level with n SMs (right)

IV. Simulation Results

To validate the effectiveness of the NLC method in the MMC topology for the PEBBs concept in all-electric ship systems, the simulation of a three-phase 5L MMC configuration ($n = 4$) is carried out using MATLAB/Simulink software. A simulation is done based on the PSC-PWM and proposed NLC methods, and the results are compared to monitor the effect of each method on the performance of the MMC topology. The parameters used in the simulation are listed in Table III.

TABLE III
MMC Parameters

Parameters	**Value**	**Unit**
Rated power	20	kW
DC-link voltage (V_{dc})	4000	V
No. of arm SMs (n)	4	–
SM capacitor voltage (V_{Csm})	1000	V
SM capacitance (C_{sm})	10	mF
Arm inductance (L_{arm})	1	mH
Arm resistance (R_{arm})	1	Ω
Load inductance (L_{load})	10	mH
Load resistance (R_{load})	10	Ω
Carrier frequency (f_C)	150	Hz
Switching frequency (f_{sw})	100	kHz

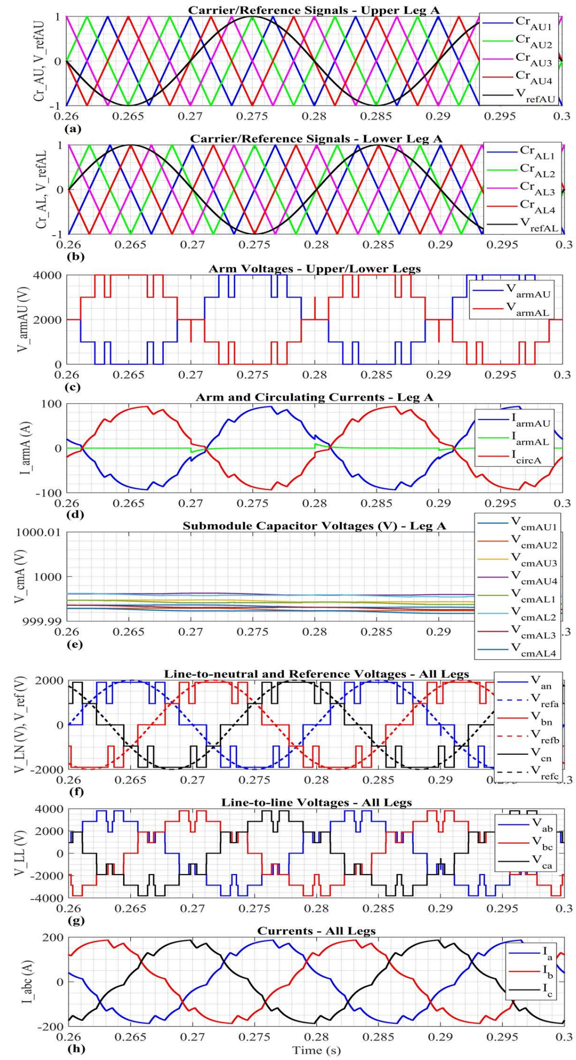

Fig. 6. Simulation results of a 5L MMC with the PSC-PWM method (ph-a): (a) carrier and reference signals of the upper arm, (b) carrier and reference signals of the lower arm, (c) upper and lower arm voltages, (d) upper/lower arm, and circulating currents, (e) upper arm capacitor voltages, (f) line-to-neutral and reference voltages, (g) line-to-line voltages, and (h) currents

Figure 6 shows the 5L MMC topology simulation results (ph-a) obtained using the PSC-PWM method. Figures 6(a) and (b) show the carrier and reference signals of the PSC-PWM method, upper arm and lower arm, respectively. As shown in Figure 6(c), the PSC-PWM method causes harmonics in the arm voltages. The circulating current is shown in Figure 6(d), which experiences spikes while the arm currents contain some harmonics. The capacitor voltages are successfully balanced, as shown in Figure 6(e). However, the circulating current is not well suppressed. The line-to-neutral voltages, line-to-line voltages, and three-phase line currents are shown in Figures 6(f), 6(g), and 6(h), respectively. The voltage and current contain low-frequency harmonics, and the circulating current is poorly controlled. This leads to poor voltage and power quality and lower reliability of the MMC topology.

The simulation results of the 5L MMC topology (ph-a) when the proposed NLC method is applied are depicted in Figure 7. Figures 7(a) and (b) show the number of connected submodules in the upper and lower arms. As shown, the sum of connected submodules in a leg is always four. Figure 7(c) shows that the harmonics observed in the arm voltages are reduced using the NLC method. The circulating current is now controlled and well suppressed. The circulating current is shown in Figure 7(d). In addition, the upper and lower arm currents contain low harmonics. The capacitor voltages are better balanced with the NLC method, as illustrated in Figure 7(c), as opposed to the capacitor voltages obtained by the PSC-PWM method (Figure 6(c)). The line-to-neutral voltages, line-to-line voltages, and three-phase line currents are shown in Figures 7(f), 7(g), and 7(h), respectively. As observed, the voltage and current do not have low-frequency harmonics experienced by the PSC-PWM method. The circulating current is also considerably suppressed. Therefore, the voltage and power quality are enhanced, leading to higher reliability of the MMC topology. These advantages will help improve the performance of the PEBBs concept in which many power converters (e.g., SMs in the MMC topology) connected in series and parallel form the stacks to enhance the converter power ratings by meeting various power conversion needs of naval ship systems.

Table IV draws a comparison of voltage and current THD values provided by the PSC-PWM and the proposed NLC method. As the reduction percentage shown in this table, the proposed NLC reduces the voltage and current harmonics to a great extent.

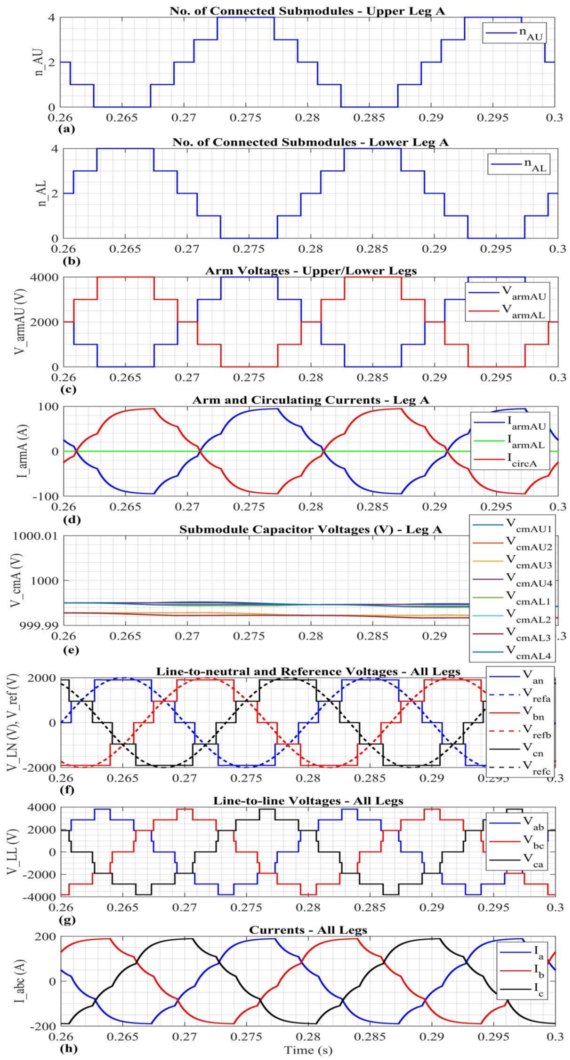

Fig. 7. Simulation results of a 5L MMC with the proposed NLC method (ph-a): (a) number of connected submodules in the upper arm, (b) number of connected submodules in the lower arm, (c) upper and lower arm voltages, (d) upper/lower arm, and circulating currents, (e) upper arm capacitor voltages, (f) line-to-neutral and reference voltages, (g) line-to-line voltages, and (h) currents

TABLE IV
THD COMPARISON OF CONTROL METHODS

Control Method	THD - V_{LN} (%)			THD - V_{LL} (%)			THD - I_{abc} (%)		
	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}	i_a	i_b	i_c
PSC-PWM	19.85	21.32	21.30	19.66	22.37	19.65	8.19	7.91	7.84
Proposed NLC	14.00	13.99	13.99	13.52	13.50	13.52	4.25	4.20	4.31
Reduction (%)	**29.47**	**34.38**	**34.31**	**31.23**	**39.65**	**31.19**	**48.10**	**46.90**	**45.02**

V. CONCLUSION

This paper introduces the NLC switching method to enhance the performance of MMC-based PEBBs in electric navy-ship systems. The proposed method aims to reduce THD outputs, thus improving power quality, which is crucial for all-electric navy ship systems. Poor PEBB stack performance often leads to high maintenance costs for the entire system. Simulation results show that the NLC method improves power quality, balances SM capacitor voltages, and suppresses circulating currents, offering a better solution for PEBB's performance.

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