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Comparative Analysis of Modulation Schemes of Modular Multilevel Converter (MMC)

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***Abstract* — This manuscript presents detailed comparative analysis between three different modulation schemes incorporated in modular multilevel converters (MMC). The three modulation schemes are pulse width modulation (PWM), space vector modulation (SVM) and nearest level modulation (NLM). In this paper, all three modulation schemes are described and analyzed according to their generated harmonic content**

***Index Terms*— HVDC MMC, NLM, PWM and SVM.**

I. INTRODUCTION

Modular Multilevel Converters (MMC) are at the peak of innovation since last 10 years in the field of power electronic converter. MMC based on DC transformer based has various advantages. Some of them includes scalability, low generated harmonic content, fault tolerating capability & high efficiency for power transmission. [1-2]. The MMC differs from the conventional converters as: scalability and modularity, easy integration of less bulky filters, reducing the (dv/dt) op the power semiconductors, reduced switching frequencies and easy renewable energy integration [3]. Among the all discussed features the major one is the output voltage quality which is close to sine waveform, due to this feature the MMC is said to have less design requirements for output filter. [4-5]. So, nowadays, the transmission system i.e., medium voltage transmission and high voltage transmission are incorporated with MMCs, as the limitations in conventional converters are now replaced by MMCs. [6-8].

This manuscript reveals the comprehensive and critical review of the modulation schemes of MMC under steady state conditions. Section 2 of this paper describe the mathematical modeling of MMC whereas Section III describes the modulation schemes of MMC under comparison i.e., PWM, SVM & NLM. Section 4 shows the results.

II. MATHEMATICAL MODELLING

The figure 1 revels modular multilevel converter (MMC). It has upper arms of lower arms. Each arm has submodules in series and tends to 'n' submodules along with inductances to limit the short circuit current.

Applying KVL in upper loop of each arm:

$$V = \frac{1}{2}V_{DC} - V_U - L\,\frac{di_U}{d_t} \qquad (1)$$

Applying KVL in lower loop of each arm:

$$V = \frac{1}{2}V_{DC} + V_L + L\,\frac{di_L}{d_t} \qquad (2)$$

Applying KCL to obtain output current

$$i = i_L - i_U \qquad (3)$$

From equations (1) & (2) the output voltage is:

$$V = \frac{1}{2}(\boldsymbol{V_L} - \boldsymbol{V_U}) + \frac{1}{2}L\frac{di}{dt} \qquad (4)$$

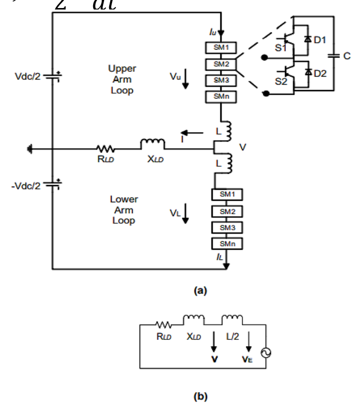

Fig. 1 (a) Modular Multilevel Converter (MMC)
(b) Equivalent circuit of MMC

The AC component voltage (V_E) is:

$$V_E^{Ref} = \frac{mE_{dc}}{2}\cos(\omega t) \qquad (5)$$

Where,

- 'm' refers to modulation index ranges from 0 to 1
- ω is the angular frequency

III. MODULATION SCHEMES

Modulation aims to produce output AC voltage that relates with reference signal given, that is done by insertion indices of all SMs [9].

The modulation schemes of MMC are categorized as in [10] into two major types one is low switching frequency modulation & second one is high switching frequency modulation. These are the two major modulation schemes on which MMC is designed so far.

Low switching frequency modulation is Nearest Level Modulation (NLM) whereas the high frequency modulation refers to the most popular Sinusoidal Pulse Width Modulation (SPWM). SPWM further divides in phase shifted PS-SPWM, which is analyzed in-terms of N+1 & level shifted LS-SPWM.

A. PS-SPWM

The simplest and most popular modulation scheme for MMC is PS SPWM [10] which is purely based on utilizing $\frac{n}{2}$, θ is given by:

Phase shift = $\frac{360}{n/2}$

In number of research papers, modulation schemes are explained based on the output voltage for MMC. They are N+1 & 2N+1, (n means number of submodules per arm) [11, 12].

The upper arms & lower arms of MMC works independently in 2N+1, so the voltage output depends of the aggregate sum of submodules connected in upper arms and lower arms. This technique reveals with problem of voltage unbalances in SM as it is not possible that all the SM are activated at same time and same rate.

There in inversely commutation of upper & lower arms in N+1 in result, N+1 output levels are generated. Though in comparison with the 2N+1 technique the number of levels is less but the problem of voltage unbalance is reduced almost as the SB switch at the same time.

So, in this regard only N+1 technique is chosen as modulation scheme in comparison. In which there is inverse commutation of upper and lower arms.

B. Space Vector Modulation (SVM)

SVM provides more flexibility to optimize switching waveforms [13]. SVM possess number of attractive features as: usage of control variable by control system directly. Identification of each switching vector and its conversion in complex space as (α, β) and SVM is very easily implemented using digital signal processor [14-15].

The space vector of 3-phase n level converter comprised of 6 main sectors; each consists of (n-1)2 triangles. The space vector diagram for n level converter possess n3 switching states. [14].

figure 2 shows the space vector diagram for 6 level converters.

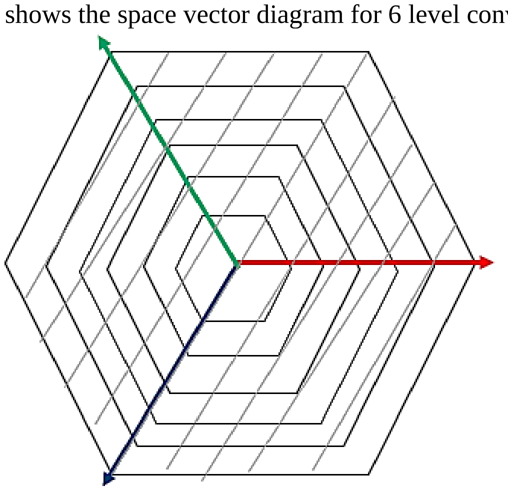

Fig. 2 SVM Algorithm

The SVM algorithm used here is advantageous as: It avoids the use of coordination transforms secondly; it can be extended for any level converter with minimum changes.

In this modulation, four vectors are chosen which are closest to the reference voltages as shown in figure 3.

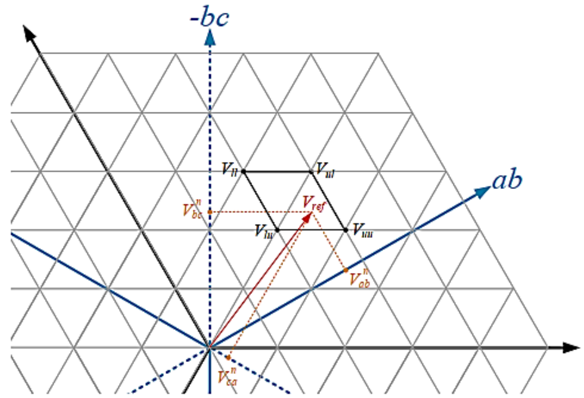

Fig. 3 Vectors against the Reference voltages

In order to avoid the number of problems in machines the zero common mode voltage is recommended and desired. SVM minimizes the common mode voltage.

For converters with an odd number of levels, the algorithm choses only those voltage levels in which common mode voltage in zero in this way its common mode voltage is eliminated [16].

C. Nearest Level Modulation

NLM is also called as the Staircase Modulation, it is widely preferred for applications in MMC as it is flexible & require less efforts in its implementation. [16] [17] [18].

The basic principle of NLM scheme is shown in figure 4 in which there is separate control for each arm.

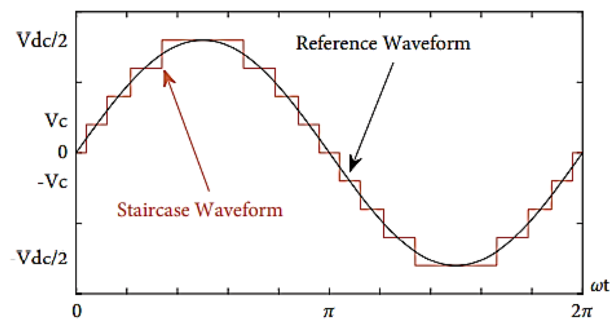

Fig. 4 Basic principle of NLM

The block diagram of NLM control figure 5.

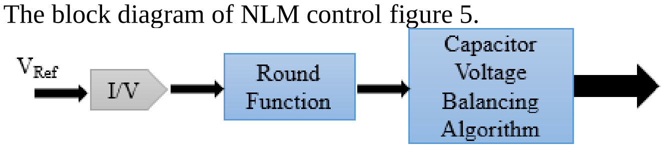

Fig. 5 Control Structure of NLM

NLM can also be implemented as modified version as discussed in [19] [20] in which third harmonic component is injected to reference waveform.

NLM scheme is more preferred for many numbers of sub modules even if they of unable to count. Otherwise in case of smaller number of SBs, the alternating current (AC) side of MMC has no voltage. So, it has easy implementation [21] whereas, its also its limitation for low voltage system which are designed to run on PWM instead of NLM [22].

IV. RESULTS

A. Pulse width Modulation (PWM)

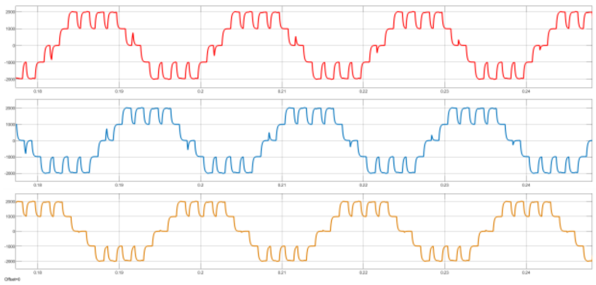

Fig. 6 Pulse Width Modulation (PWM)

The above diagram shows the voltage output of 5 levels modular multilevel converter (MMC) connected with three phase system. The generated harmonic content for this converter is 30.26% as shown in figure 7.

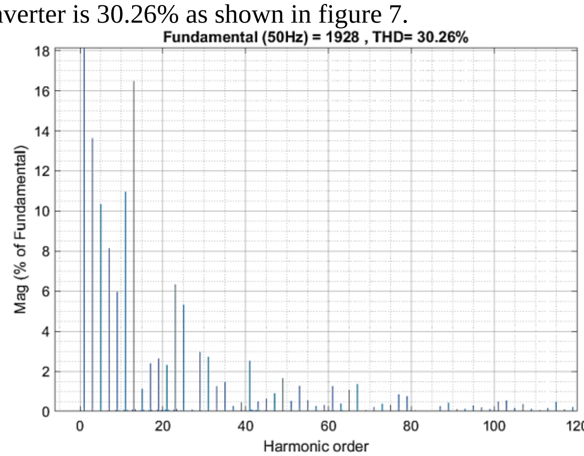

Fig. 7 Harmonic Content in PWM Modulation

B. Space Vector Modulation

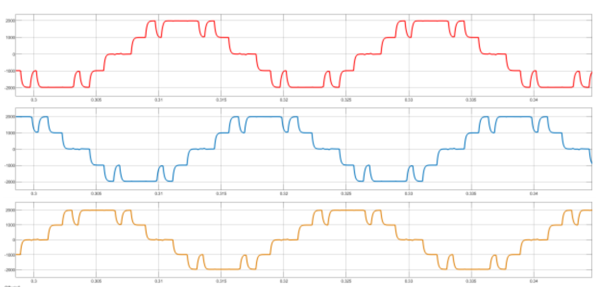

Fig. 8 Space Vector Modulation (SVM)

The figure 8 shows for the SVM modulation for three phase MMC the generated harmonic content as shown in figure is 22.38 %. The SVM caters low harmonic content in comparison with PWM modulation.

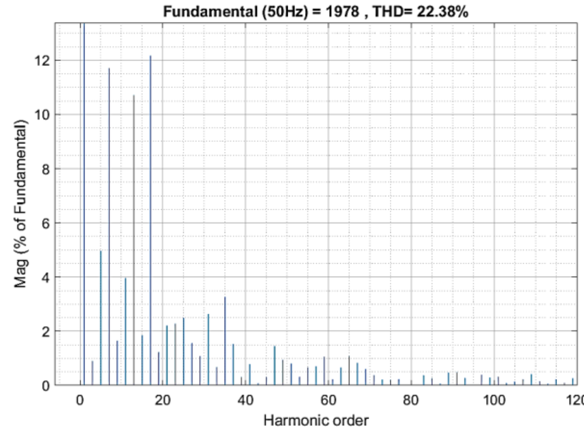

Fig. 9 Generated Harmonic content in SVM

C. Nearest Level Modulation

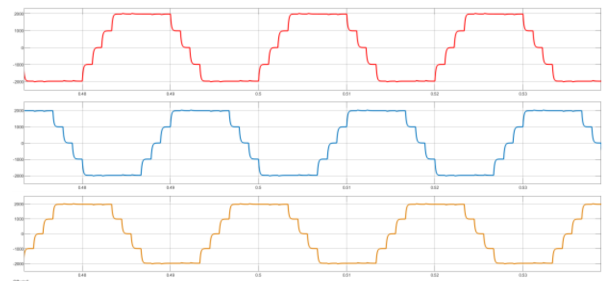

Fig. 10 Nearest Level Modulation

Figure 10 shows the voltage output waveforms for nearest level modulation connected with three phase system.

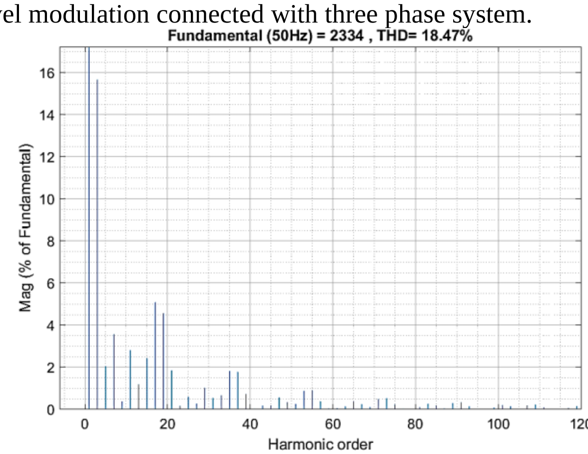

Fig. 11 Harmonic Content in NLM Modulation

All the three modulations schemes are compared & the conclusions are drawn as follows: Nearest level modulation has the lowest generated harmonic content as comparison with pulse width modulation & space vector modulation as shown in figure 12.

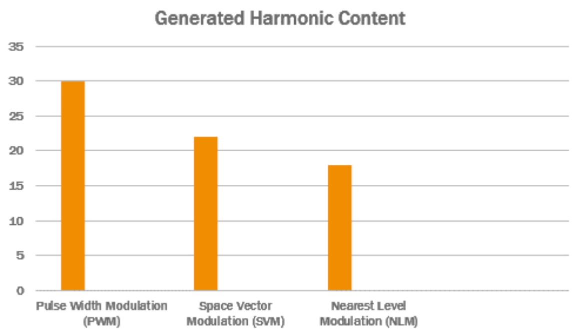

Fig. 12 Overall Comparison of Generated Harmonic Content

V. CONCLUSION

Hence, the modulation schemes were compared in three phase system where the generated harmonic content was compared which revealed that Nearest level modulation scheme is the best modulation scheme which generates low harmonic content in comparison with the PWM and SVM. Secondly, NLM can be implemented for high voltage dc transmission system (HVDC) as it performs best with large number of sub modules.

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