

Investigative uses of overmodulation techniques in modular multilevel cascaded converter

Mohan P. Thakre¹, Jayesh A. Gangurde¹, Rakesh Shriwastava², Deepak P. Kadam³, Sunil Somnath Kadlag⁴, Haridarshan S. Sonawane⁵

¹Department of Electrical Engineering, K. K. Wagh Institute of Engineering Education and Research, Nashik, India

²Department of Electrical Engineering, Matoshri College of Engineering and Research Center, Nashik, India

³Department of Electrical Engineering, MET Institute of Engineering, Nashik, India

⁴Department of Electrical Engineering, Amrutvahini College of Engineering, Savitribai Phule Pune University, Pune, India

⁵Department of Energy, Government of Maharashtra, Nashik, India

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ABSTRACT

Sinusoidal pulse width modulation (SPWM) is a method to generate the switching gate pulse of the converter. Overmodulation is a method where the modulation index exceeds the unity value and the system goes into the nonlinear region. To maintain the system in a linear region when operating in the overmodulation region, some techniques are developed. These techniques helped to operate the system in the linear range. Medium and high-power energy conversion systems mostly use a modular multilevel cascaded converter (MMCC), which has been an issue improving significantly in recent years. In this article, MMCC-based overmodulation techniques are compared with conventional PWM and analyzed on DC bus utilization (DBU), and total harmonic distortion (THD). MATLAB/Simulink digital platform used demonstrate overmodulation technique.

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Corresponding Author:

Mohan P. Thakre

Department of Electrical Engineering, K. K. Wagh Institute of Engineering Education and Research

Mumbai Agra Road Amrutdham, Panchavati, Nashik, Maharashtra 422003, India

Email: mohanthakre@gmail.com

1. INTRODUCTION

A modern transmission and distribution system faces an increasing demand for large power with superior quality and excessive reliability at minimum cost. As we move towards renewable energy sources, more attention is on the efficient use of traditional and non-traditional energy sources. Energy efficiency is the implementation of using the least energy to provide the same amount of useful output in service [1]. The most effective controlling and modulation techniques introduced for this type of inverter are multilevel Sinusoidal pulse width modulation (SPWM), multiple particular harmonic eliminations, and space vector pulse width modulation (SVPWM) for the Modular multilevel cascaded converter (MMCC) scale-up controlling technique, in which more no. of sub-modules can be proposed by a small progressive group of sub-modules [2]. The MMCC has achieved substantial awareness and growth owing to its optimistic benefits such as superior output performance, higher modulation parameters, easy expandability, and low level of current and voltage rating demand for the power converter switches [3], [4]. The analysis for reliability is executed to differentiate the performance indices of the MMCC-based conventional modulation methods and scale-up controlling techniques [5].

For medium or high-power energy conversion systems, the MMCC has become more important. Significant research has been conducted in recent years to overcome the technical issues involved with the MMCC's functioning and control [6]-[8]. The MMCC outperforms typical two-level and multilevel

converters in several areas [9]. The MMCC can be used in a variety of medium and high-voltage power conversion systems, including high-voltage direct current (HVDC) transmission systems, medium-voltage motor drives, renewable energy systems, battery energy storage systems (BESS), static synchronous compensators (STATCOM), (hybrid) electrical vehicle chargers and drivers, and power interfacing applications [10]-[12].

A linear relation between the reference voltage and output voltages within a bounded span is provided by carrier-based PWM techniques. The modulation characteristics. Helped with the determination of the linear voltage range of a voltage-source inverter (PWM-VSI) drive [13]-[15]. Overmodulation extended the linear range of control output but various problems are generated, like generation of lower order harmonics, 5th and 7th probably [16]. Method of linearization was proposed for the voltage gain value in every span up to the six-step prototype presented. Differentiating the proposed technique with a pulse-width control technique on the quality of output voltage is taken out. Four types of optimized PWM algorithms are compared for the overmodulation region. The optimum value calculation is performed to reduce the value of the loss factor, which demonstrates the harmonic loss values of the AC machines. Evaluation of the loss factors is done for various pulse ratios. Modulation indexes are correlating with pulse ratio [17], [18].

The PWM technology on which VSI relies should take into account the utilization of DC bus (UDB), especially if the drive system is operating in the over-modulated region [19]. Overmodulation, flat-topped overmodulation, min-max overmodulation, and third harmonic injection techniques are compared and analyzed collectively [20]. Article [21], [22] emphasized the harmonic reduction of a 3-phase cascaded H-bridge-multi-level inverter (CHB-MLI) with field-oriented control (FOC) with the help of the. To achieve phase cluster voltage balance, a non-sinusoidal voltage having a fundamental component and its 3rd-harmonic component is added. This method decreases the higher value of DC-link capacitor voltage for converters having star configuration [23], [24]. Several recent studies are conducted on MMCC, in [25] addition of a common-mode voltage at the phase to neutral voltages of the star-connected MMCC was applied. This method permits natural point injection of a voltage nonsinusoidal wave to the neutral node of the inverter, hence attaining interphase cluster voltage balance [26].

2. METHOD

Figure 1 indicates the imprecise representation of a 3-phase MMCC containing a DC voltage source or capacitor, an AC terminal, and a converter having 3-phase legs. Every leg or phase has two symmetrical arms named the upper arm followed by the lower arm. Both upper and lower arms comprise a set of similar sub-modules attached in series conjunction with a chock inductor to extinguish higher-order frequency elements in the arm current. Bidirectional power conversion is achieved with MMCC. The MMCC control program allows its high performance related to terms like safe, secure, reliable, and efficient. The control is having lots of challenges and sophistication implying substantial sub-modules and multiple control targets associated with the output current and voltage control, submodule voltage, and circulating current control.

Development of different PWM methods generated for improving the performance of MMCC and to produce the desired output voltage. One of the typical PWM methods is the carrier-based PWM method, where multilevel converters produce controlling signals by comparing the modulation criteria for each phase with multiple carrier waveforms. For comparison, triangular or saw-tooth waves are essentially used as carrier signals. These methods are based on multiple carrier placement and are again classified into phase shift carrier-based (PSCPWM) and level shift carrier-based (LSCPWM) technologies. In this article, overmodulation methods are compared and analyzed.

In (1) shows that amplitude modulation index m_a is defined as the ratio of the amplitude of modulating signal to the amplitude of the carrier signal. Figure 2 and Figure 3 show the linear and over modulation waveform with pulse generations, and linear and nonlinear range plots respectively Table 1 shows various operating regions in PWM, when $m_a > 1$ it gives the peak value greater than $V_{dc}/2$ thus output value of voltage is increased, several obstacles arise when PWM modules operated in overmodulation.

$$\text{Amplitude modulation index } (m_a) = \frac{A_m}{A_c} \quad (1)$$

where, A_m - amplitude of modulating signal and A_c - the amplitude of carrier signal.

Table 1. Linear and overmodulation operating region

Modulation index	Range of Voltage
$m_a=0$	$V_{an}(\text{peak})=0$
$m_a=1$	$V_{an}(\text{peak})=V_{dc}/2$
$m_a>1$	$V_{an}(\text{peak})>V_{dc}/2$

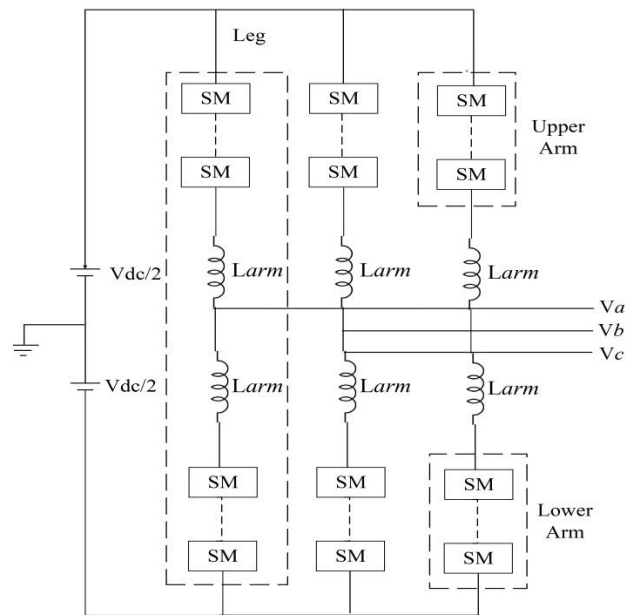


Figure 1. Modular multilevel cascaded converter

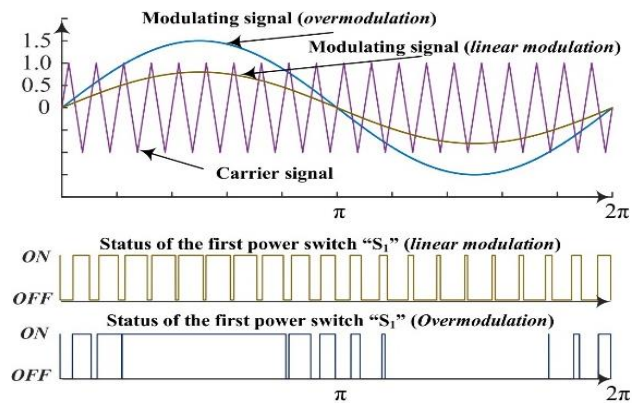


Figure 2. Linear modulation and over modulation pulse generation

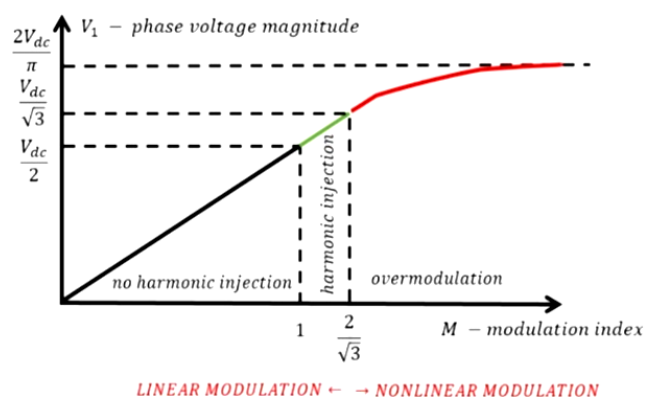


Figure 3. Linear modulation and over modulation

Such as a reduction in the output voltage waveform quality and the UDB [18]. Due to over modulation unwanted lower order harmonics are generated (5th and 7th order harmonics). If the further

increase in the value of m_a generates the square wave output waveforms just like a three-phase inverter. Several studies and research projects have been undertaken to improve and enhance the performance of continuous PWM in the overmodulation region. If anyhow decrement in the peak of modulated waveform within the limit will solve the problem of harmonics and DC bus utilization. Flat-topped overmodulation, and min-max overmodulation, these are some overmodulation techniques. Third harmonic injection (THI) is the most effective method of all, THI block diagram Figure 4 shows the methodology applied in this paper.

2.1. Third harmonic injection

One-sixth value of the third harmonic is added with Modulating or reference waveform to increase voltage gain of the VSI [18]. The result has been shown the reduce the waveform output by a factor of 0.866, without changing the base fundamental amplitude of the voltage. The output voltage range of VSI can be utilized by an increase in the amplitude of modulating waveform by factor k [19].

$$V = K(\sin \omega t + \frac{1}{6} \sin 3 \omega t) \quad (2)$$

$$1 = K \times 0.866 \rightarrow K = 1.155 \quad (3)$$

In (2) and (3) indicated that the amplitude of the fundamental phase voltage waveform grew by a certain percentage which is 15.5. Comparative testing of module features reveals the advantages of the high degree of flexibility of discontinuous PWM methods. The value of THD and UDB are calculated by using from (4) and (5) respectively.

$$THD = \frac{1}{V_1} \sqrt{\sum_2^\infty (V_n)^2} \quad (4)$$

$$UDB = \frac{\pi V_1}{2V_{dc}} \times 100\% \quad (5)$$

3. RESULTS AND DISCUSSION

Block diagram of THI is shown in Figure 4(a) and the methodology for THI is indicated in Figure 4(b), where the third harmonic component of modulating is added with Modulating waveform, to decrease the peak value of modulating waveform MATLAB/Simulink digital platform was used to demonstrate overmodulation techniques in MMCC. Figure 5 shows the Simscape model of MMCC. For analysis 8 sub-modules are used for each phase. In which 4 sub-modules are used for the upper arm and 4 sub-modules are used for the lower arm. A PWM generator has been used for generating gate-triggering pulses of submodules of MMCC. THI: one of the overmodulation PWM techniques used for explanation.

Overmodulation techniques are used at the controlling side of the PWM generation block of MMCC as shown in Figure 5. To compare various overmodulation techniques we created a model on MATLAB/Simulink software and the results are shown in Figures 6(a)-(e). Figure 6(a) indicates the conventional overmodulation technique in the range of linear modulation. i.e., $m_a=1$. From (2) and (3) modulation index increased to 1.155 as shown in Figure 6(b). As $m_a>1$ system goes into a nonlinear region as shown in Figure 3. To decrease the peak of modulating waveform, overmodulation techniques are implemented. Figure 6(c) represents the Flat-topped overmodulation PWM technique.

In this technique, the part of the three-phase input signal crossing values ± 1 is chopped. The three resulting signals are then added and removed from the original signal U_{ref} . The resulting modified signal U_{ref}^* is therefore a flat-top three-phase signal that contains zero-sequence triplen-harmonics. So, an outputs value range is between -1 and 1 . Figure 6(d) represented the min-max overmodulation PWM technique. In this technique, the minimum and maximum values of the three components of the input signal U_{ref} are summed and divided by two and then removed from the input signal. This resulting modified signal U_{ref}^* also contains zero-sequence triplen-harmonics. Figure 6(e) represents the THI overmodulation PWM technique, described in section 4.

Figure 7(a) indicates output waveforms obtained from the conventional PWM technique. Figure 7(b) indicates output waveforms obtained from the flat-topped overmodulation PWM technique. Figure 7(c) indicates output waveforms obtained from the min-max overmodulation PWM technique. Figure 7(d) indicates output waveforms obtained from the THI overmodulation PWM technique. All techniques are analyzed using the fast Fourier transform (FFT) tool of MATLAB/Simulink software. Figures 8(a) and (b) represent the FFT tool of the THI overmodulation PWM technique, where the simulation time was taken 1 second. FFT tool is used for the analysis of distortion (THD) of output waveforms of every overmodulation technique. Table 2 indicates the THD values of all techniques compared with the conventional PWM modulation technique.

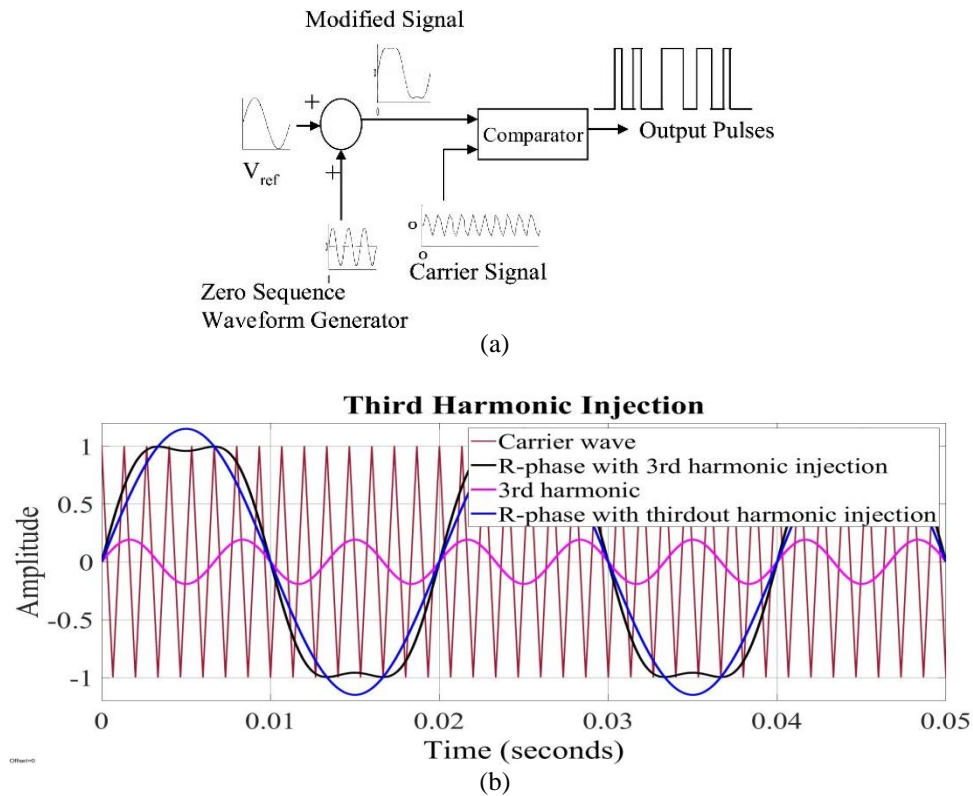


Figure 4. Third harmonic injection (a) block diagram modified of waveform conversion and (b) waveforms as per the basic theory

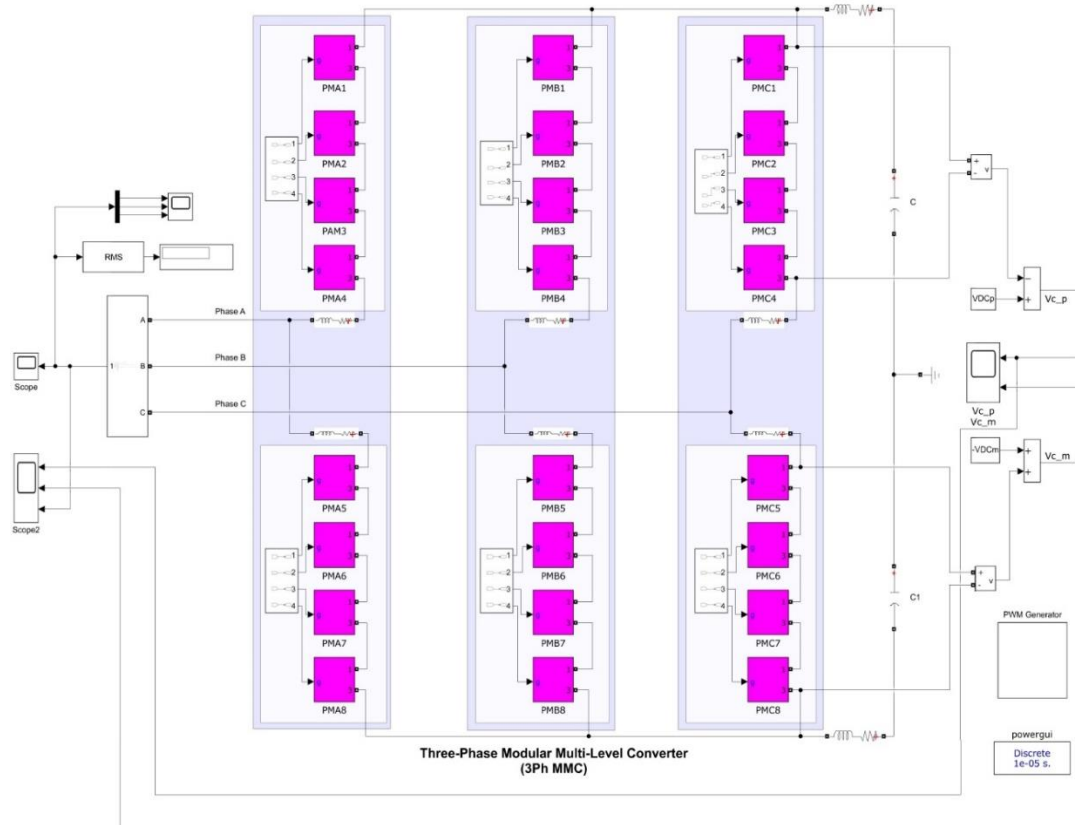


Figure 5. Simscape model of MMCC

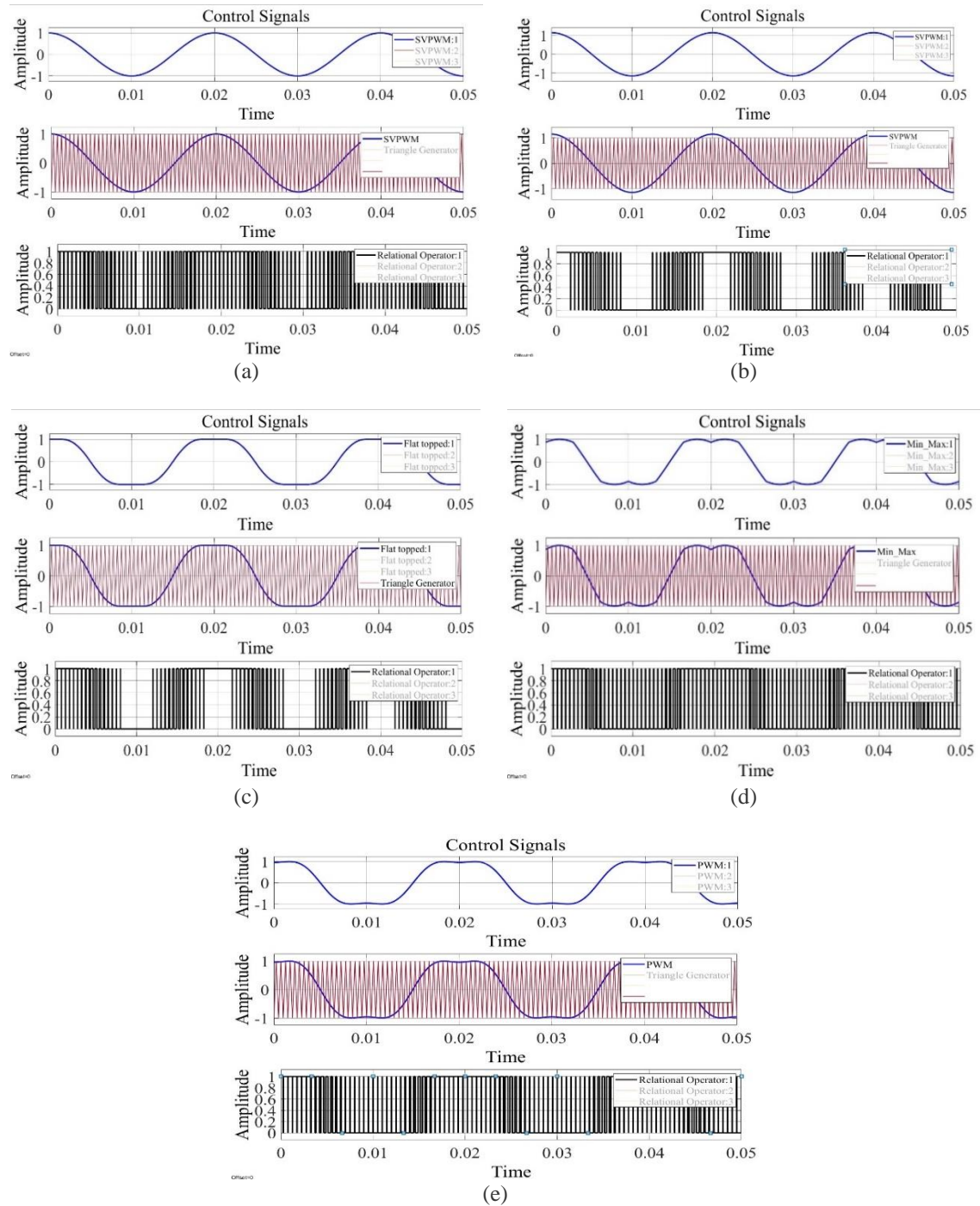


Figure 6. Various overmodulation techniques (a) conventional PWM, (b) over modulated PWM $m_a=1.155$, (c) flat-topped overmodulation PWM $m_a=1.155$, (d) min-max overmodulation PWM $m_a=1.555$, and (e) THI overmodulation PWM $m_a=1.155$

Table 2. THD comparison of overmodulation techniques

Overmodulation technique	THD (%)
Conventional PWM	27.31
PWM overmodulation	26.27
Flat topped	23.61
Min-max	29.41
THI	25.86

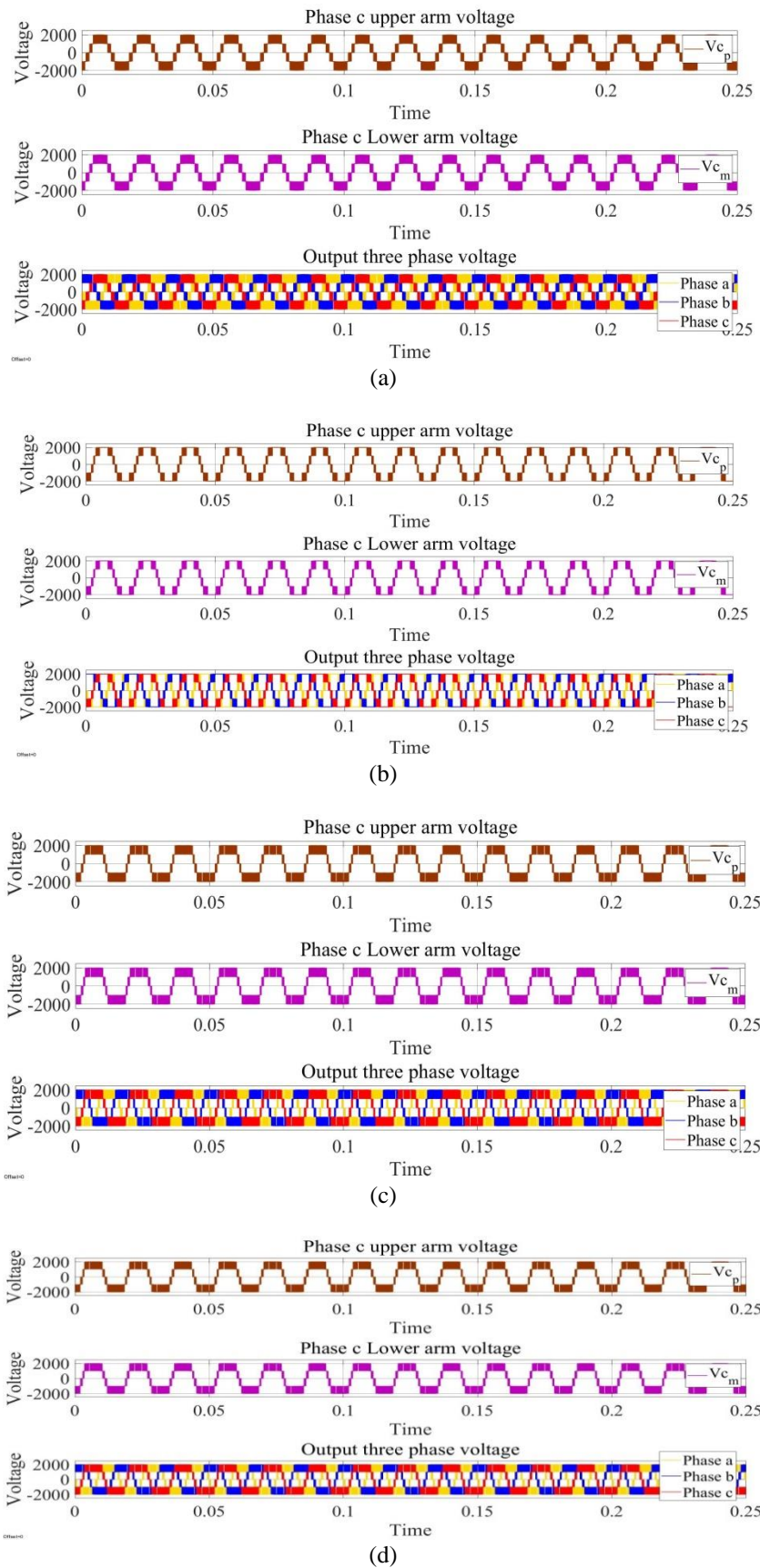


Figure 7. Overmodulation PWM outputs (a) conventional PWM output waveforms, (b) flat-topped overmodulation PWM, (c) min-max overmodulation PWM, and (d) THI overmodulation PWM

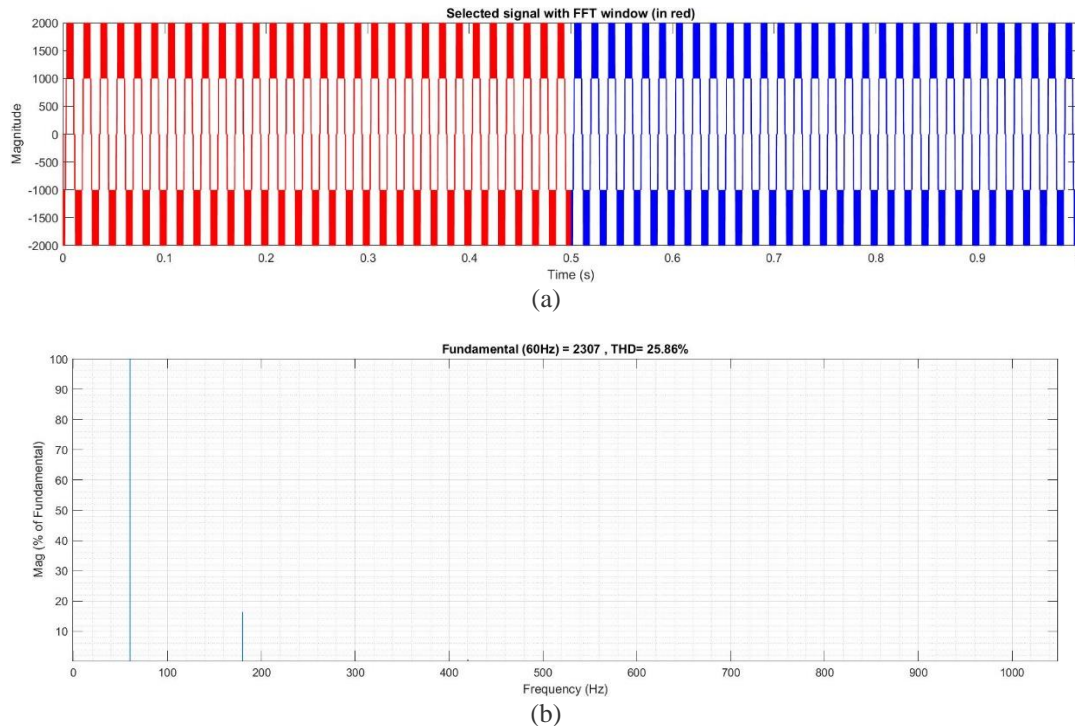


Figure 8. FFT tool window (a) selected signal: 30 cycles and (b) THI overmodulation PWM

4. CONCLUSION

MMCC is a widely used controller in HVDC, STATCOM, and many applications. A comparative analysis was conducted on MATLAB/Simulink digital platform. As we increase the modulation index system goes into overmodulation or nonlinear region, to maintain the linearity of the system various PWM techniques are used. Some popular overmodulation techniques are discussed in this article. Comparative analysis has been done based on THD, and UDB. The flat-topped overmodulation technique gives the lowest THD among other overmodulation PWM techniques followed by THI-PWM overmodulation Conventional PWM and then the min-max PWM technique. Further increase in the Modulation increases THD of output waveform up to square waveform formation. Filters are required to reduce lower-order harmonics. Flat-topped waveform gives the least THD but has less span area of modulation index range. THI has a wider area as compared to a Flat-topped waveform. THI is compatible with a wider range of operations in a power grid.




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BIOGRAPHIES OF AUTHORS






Dr. Mohan P. Thakre    received the B.Tech. and M. Tech degrees in electrical power engineering from Dr. Babasaheb Ambedkar Technological University (Dr. Batu), Maharashtra, India, in 2009 and 2011 respectively, and the Ph.D. degree in electrical engineering from Visvesvaraya National Institute of Technology, (VNIT), Nagpur, Maharashtra, India in 2017. Currently, he is an Assistant Professor at the Department of Electrical Engineering, K. K. Wagh Institute of Engineering Education & Research, Nashik, India. His research interests include flexible AC transmission systems (FACTS) and power system protection. He can be contacted at email: mohanthakre@gmail.com.






Jayesh A. Gangurde    received the B.E. degree in electrical engineering and M.E. degrees in electrical power system branch from Savitribai Phule Pune University (SPPU), Maharashtra, India, in 2018 and 2022 respectively. Currently, he is student at the Department of Electrical Engineering, K. K. Wagh Institute of Engineering Education & Research, Nashik, India. His research interests in flexible AC transmission systems (FACTS), power electronics converters and control drives, artificial intelligence, and machine learning. He can be contacted at email: gangurdejyesh77@gmail.com.






Dr. Rakesh Shriwastava    obtained Ph.D. degree in electrical engineering specializing in power electronics and drives from RTM Nagpur University, (India) in 2017. He occupied various positions to serve the engineering institutes for about 24 years. He is currently working as Professor in the Department of Electrical Engineering, Matoshri College of Engineering & Research Center, Nashik. His research interests include the analysis and control of electrical drives, particularly in hybrid and electric vehicle applications. He has several publications in national and international journals. He attended International and National conferences and also worked as a jury member. He is a member of professional bodies such as ISTE and IAENG. He can be contacted at email: rakesh_shriwastava@rediffmail.com.






Dr. Deepak P. Kadam    received the B.E from Government College of Engineering, Amarawati and M.E degrees in electrical power system from Walchand College of Engineering, Sangli, Maharashtra, India, in 1997 and 2005 respectively, and the Ph.D. degree in electrical engineering from Savitribai Phule Pune University, Pune Maharashtra, India in 2015. Currently, he is an Associate Professor at the Department of Electrical Engineering, Bhujbal Knowledge City, MET Institute of Engineering, Nashik, India. His research interests include renewable energy technology, power quality, and power system. His total teaching experience is around 23 years. He can be contacted at email: dpkadam@gmail.com.



Dr. Sunil Somnath Kadlag    did B.E in Electrical Engineering from Dr. Babasaheb Ambedkar, Marathwada University, Aurangabad (Dr. B.A.M.U) in 1997 and M.E in Electrical Engineering (control system) from Government College of Engineering Pune (Pune University) in 2005. He had done a Ph. D in Electrical Engineering from Suresh Gyan Vihar University Jaipur (Rajasthan) in 2021. His research area is an electric vehicle. He is presently working as Associate Professor & Head, Department of Electrical Engineering, Amrutvahini College of Engineering, Sangamner, Savitribai Phule Pune University, Pune, Maharashtra, India. He can be contacted at email: Sunilkadlag5675@gmail.com.



Haridarshan S. Sonawane    is working as an Assistant Electrical Inspector in the Electrical Inspectorate wing of the Government of State of Maharashtra, India. He is in service to the government since 2012. He graduated his engineering with a first-class B. Tech degree in Electrical from the Government College of Engineering, Pune, and Maharashtra, India in 2010. He received a Master's degree in power system (electrical), from the University of Pune, Maharashtra, India. His research interests are in the areas of transmission line protection and renewable energy. He can be contacted at email: haridarshanss@gmail.com.