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Comparison of SPWM and THSPWM Control Techniquesin a HVDC Transmission System

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ABSTRACT
The comparison of the Sinusoidal PWM (SPWM) and Third Harmonic Sinusoidal PWM (THSPWM) control techniques used in Transmission System High Voltage Direct Current (HVDC) is made in this work. The control techniques are comparing in DC-AC Converter (Inverter). The simulation is done in PSCAD_EMTDC® software. The results are analyzed to determine which of the two control techniques is more efficient in HVDC Systems implementation.
KEYWORDS: *Sinusoidal PWM, Third Harmonic Sinusoidal PWM, HVDC Transmission System, Inverter.*

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I. INTRODUCTION

The transmission of electrical energy was originally carried out in direct current (DC), but the ease of transformation and transmission of alternating current (AC) led to its use and installation on a large scale, limiting the use of direct current to few applications. It was not until the second half of the twentieth century that the advances and development of semiconductor devices and Power Electronics gave the possibility of converting alternating current into continuous and vice versa, with high performance devices.

The main problem that the first semiconductor devices had was the low powers they were able to process and their high cost. For this reason, this technology began to be used only in those places where it presented advantages that could not be achieved with other technologies. Today the technological advance of semiconductors allows its use in the transmission of power over long distances or the interconnection of nearby electrical systems that operate at different frequencies. This technology is known as HVDC (High Voltage Direct Current). Its evolution has allowed to increase the powers to be transmitted, currently, there are operational transmission lines with powers around 3000MW and 800kV.

A HVDC transmission system is currently a consolidated technology, but in constant evolution, both for power electronics and for the technological advances of electrical conductors. These systems offer several advantages compared to transmission systems in HVAC (High Voltage Alternating Current). One of the most important qualities of this technology is that it considerably reduces transmission losses, as well as the environmental impact generated for its construction. The economic advantages of direct current transmission were known since its beginning; however, its applications had to wait for the development and sustainability of power electronics.

II. APPLICATIONS

A HVDC system is a technology that is being used to transport electrical energy over long distances. Another advantage is that this type of systems can have interconnection of electrical systems at different frequencies, thus forming asynchronous loops. It also considerably reduces the total transmission losses, as well as the environmental impact generated for its construction.

The most common applications of HVDC systems take place where the use of alternating current is not technically or economically viable and are:

- Long distance power transport
- Power transmission in underwater or underground environments
- Interconnection of asynchronous electrical systems
- Stabilization of electrical systems

III. COMPONENTS OF A HVDC SYSTEM

It is important to know the role that each component plays in an HVDC system, in order to understand the operation of this type of systems and thus correctly implement this type of technology, taking into account the required needs.

The main elements that make up an HVDC system can be seen in the diagram in Figure 1 and are the following:

- Transformers
- AC and DC Filters
- Lines of transmission
- Converter stations (rectifiers and inverters)

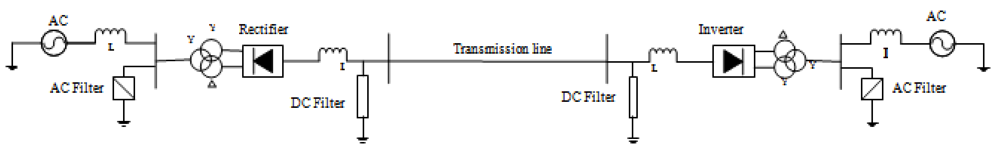


Figure 1.Elements of a HVDC System.

Transformers

The transformers in HVDC systemsare responsible for converting the AC voltage to a convenient level to connect the AC voltage to the input lines of the AC-DC converter. They also give the necessary isolation between the network and the converters.

These transformers are characterized by being designed to withstand the high harmonic content generated by the converter stations without overheating. In addition, they are designed to support the continuous premagnetization of the core, noise and other features of this type of assembly.

Filters

In HVDC systems there are two typesof filters: those of CD and those of AC, both in order to reduce the harmonic content.

- DC filters: are used to reduce the ripple content of the continuous signal to be obtained. Mainly they are low pass filters.
- AC filters: filter the harmonics generated in the rectifier; also provide part of the reactive power consumed in the converter.

Line of transmission

They can be aerial, underground and underwater transmission lines. The air transmission means involves transmission towers and conductors. The main difference between the transmission towers is the distance between lines, because in a common AC line, the distance between lines depends on the voltage between phases, while, on a DC line, the distance is determined by the voltage of phase and ground, which results in a smaller size in the towers.

Converter stations

These units are mainly used for AC-DC conversion and vice versa. They are located on both sides of the transmission. In aHVDC system the converters play an important role and the AC-DCconverters (rectifier) and the DC-AC converters (inverter) are used.

- **Types of converters**

A HVDC system requires an electronic converter for its ability of converting electrical energy from AC-DC or vice versa. There are two configuration types of three-phase converters possible for this conversion process: Current Source Converter (CSC), and Voltage Source Converter (VSC).

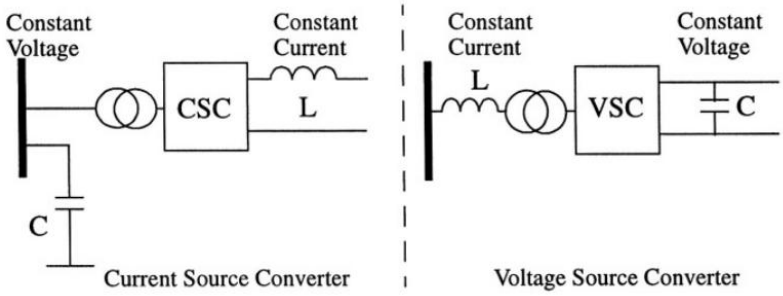


Figure 2.Types of converters in HVDC System.

The choice of converter type depends on the application. Approximately, during the period 1950-1990s, HVDC systems used the CSC configuration. Currently the most used technology is the VSC-HVDC; however, either of them can be used.

IV. VOLTAGE SOURCE CONVERTER (VSC)

Only VSC will be discussed because the comparison of PWM techniques is based on this type of converter. The commercial viability of high power and high voltage with the appearance of GTO and IGBT's devices offer a viable operation of VSC's in HVDC schemes.

Figure 3 shows a scheme of a VSC. VSC's use power switches such as GTO's and IGBT's, with which you can enable or disable them. Switching in a VSC can occur many times per cycle using forced switching switches. This feature allows the voltage/current in a VSC to be modulated to produce an almost sinusoidal output.

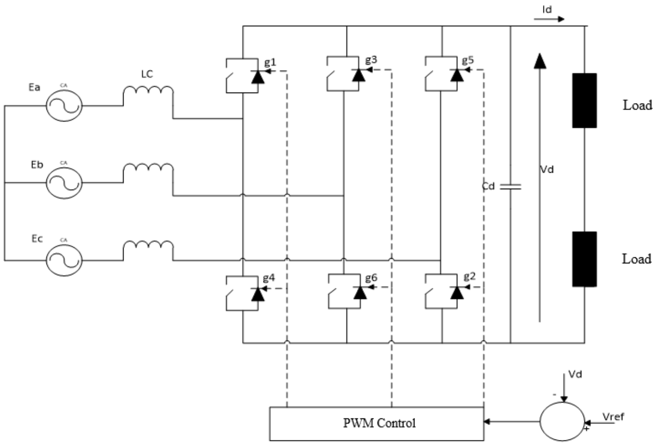


Figure 3.Scheme of the principle of operation of VSC.

On the DC side, the capacitor C_d and the AC side the inductor L_c are necessary elements of the VSC. On the DC side the voltage $V_d$is monitored and compared for a reference value V_{ref} to generate an error signal that controls the PWM. When on the DC side the current I_d is positive, the VSC works as a rectifier; The DC side capacitor is discharged to import power from the AC system. When the current $I_d$on DC is negative, the VSCworks as an inverter; The DCcapacitor is charged and to export the power to the AC system.
The different PWM techniques can be used to operate the VSC and have a sinusoidal output for the AC system. Next, the techniques used in this work are explained in summary.

V. PULSE WIDTH MODULATION (PWM)

To produce a sinusoidal output voltage waveform at the inverters, at a desired frequency, a sinusoidal control signal is compared to the desired frequency, with a triangular waveform as seen in Figure 4(a). The frequency of the triangular waveform sets the switching frequency of the inverter and is generally maintained at constant amplitude$\hat{V}_{tri}$.

The frequency f_s of the triangular waveform v_{tri} is known as the switching frequency or carrier, figure 4(a). The control signal, $v_{control}$, is used to modulate the switch duty cycle and has a frequency f_1; This is the fundamental or modulation frequency of the inverter's output voltage.

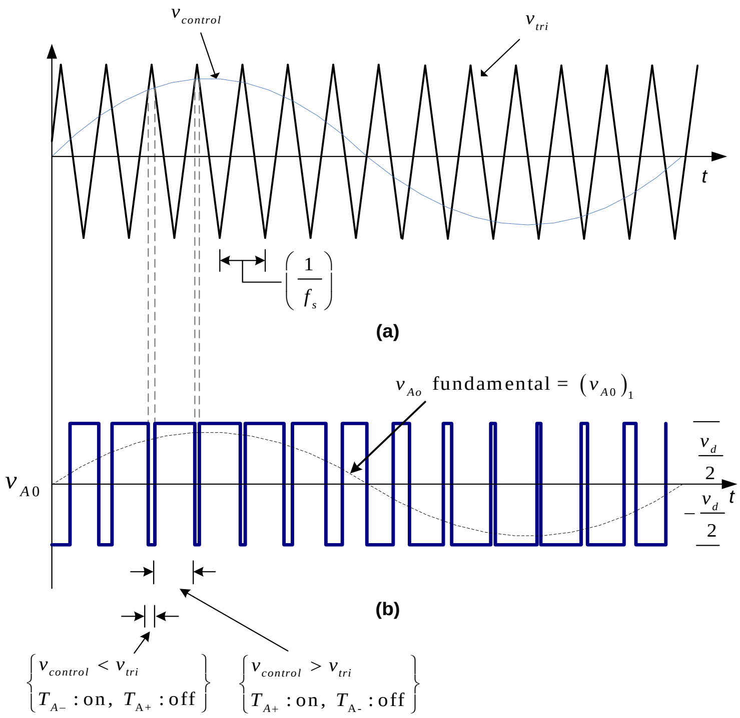


Figure 4. Voltage: a) Signal comparison. b) PWM sinusoidal output voltage.

The amplitude of the modulation ratio M is defined as:

$$M = \frac{\hat{V}_{control}}{\hat{V}_{tri}} \quad (1)$$

Where, $\hat{V}_{control}$is the peak amplitude of the control signal and $\hat{V}_{tri}$ the amplitude of the triangular signal. Thefrequencymodulation m_f ratio isdefined as:

$$m_f = \frac{f_s}{f_1} \quad (2)$$

It can be defined that, for a three-phase inverter, the modulating signals are a balanced three-phase sinusoidal system responsible for configuring the amplitude, frequency and phase at the output of the inverter and can be expressed algebraically as follows:

$$V_a(t) = m_f * A * sen(wt) \quad (3)$$
$$V_b(t) = m_f * A * sen(wt - 120°) \quad (4)$$
$$V_c(t) = m_f * A * sen(wt + 120°) \quad (5)$$

Where:
A - maximum amplitude of the modulating signal.
m_f - Modulation index.
w - angular frequency.

- **Thirdharmonic**

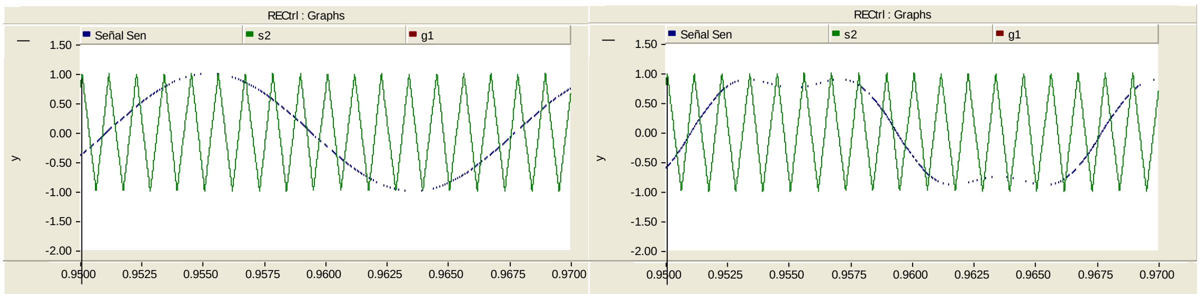
There is a variant of the PWM that consists of injecting the third harmonic to the desired signal with which the triangular signal is compared. In addition, this third harmonic has the property of being minimal when the main harmonic is maximum. This allows, with the same dynamic range of the bus voltage, to increase the power of the main harmonic.

PWM algorithms with injection of the third harmonic increase the three-phase output voltage of an inverter by up to 15% without leaving the linear zone. In this method it is proposed to add a signal with amplitude 1/4 of the fundamental signal and three times the fundamental frequency ($3w_m$). The equations are:

$$V_a(t) = m_f * A * sen(wt) + A3 * sen(3wt) \quad (6)$$
$$V_b(t) = m_f * A * sen(wt - 120°) + A3 * sen(3wt - 3 * 120) \quad (7)$$
$$V_c(t) = m_f * A * sen(wt + 120°) + A3 * sen(3wt + 3 * 120) \quad (8)$$

VI. SPWM AND THSPWM CONTROL TECHNIQUES

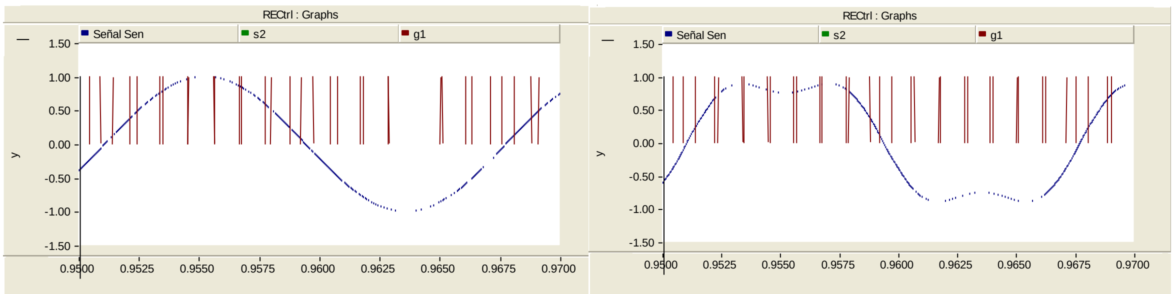
In this work the implementation of the control techniques in the PSCAD-EMTDC®software is done. The comparison of the SPWM and THSPWM control techniques is made with the objective of verifying which of the two techniques has better use of the DCsource, in this case, the transmission voltage. Figure 5 shows the sinusoidal and sinusoidal signals plus third harmonic, compared with a triangular signal for the generation of PWM's.



(a) (b)

Figure 5. Sinusoidal signals with 100% amplitude: (a) SPWM and (b) THSPWM.

The injection of the third harmonic deforms the sine wave. As can be seen in Figure 6, the difference between the two techniques is in the ridges and at the ends of each wave. The ridge of the THSPWM method decreases, but the voltage at the ends increases with respect to the sine wave. This deformation increases the conduction time of the transistors, which increases the average output voltage of the inverter. It can see the PWM's generated with each of the techniques, figure 6. The THSPWM technique has a larger pulse width than the SPWM technique, which allows for greater voltage gain when these signals control the inverter.



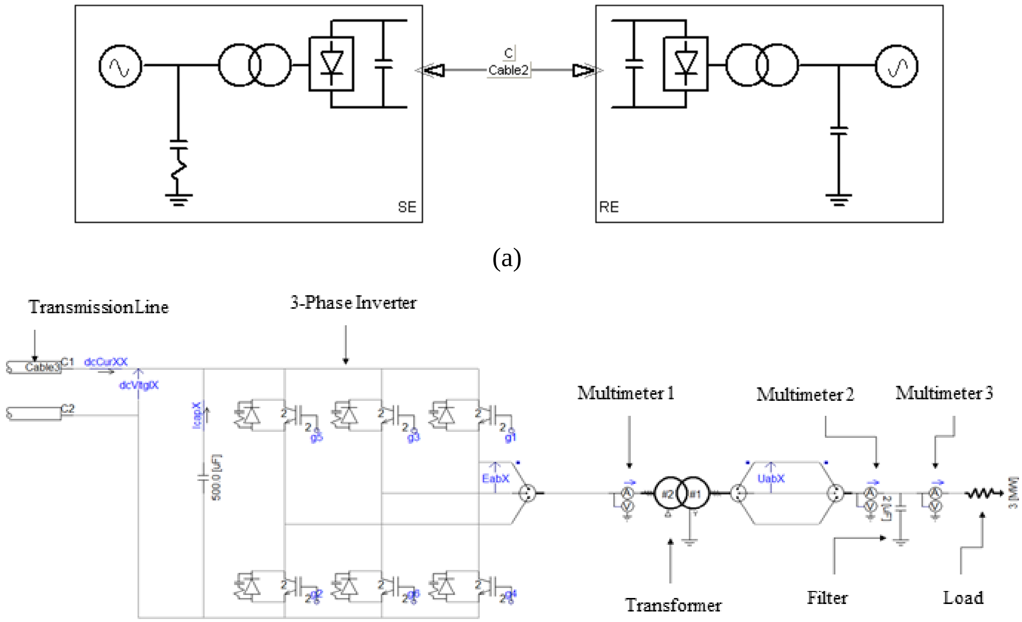
(a) (b)

Figura 6. PWM differences: (a) SPWM y (b) THSPWM.

VII. SIMULATION

Figure 7 shows the scheme of the HVDC system included in PSCAD/EMTDC® used in this work. The block on the left (SE) contains mainly the power supply, the transformer and the rectifier, the block on the right (RE) contains the inverter, another transformer and the load, both blocks are linked by the transmission system, DC cable. It is important to mention that this example was taken as a base and is preloaded in the

PSCAD/EMTDC® libraries, adjustments were made to this system and control techniques were designed that were integrated into the inputs of the inverter block, figure 7(b).



(a)

(b)

Figure 7.Schematic: (a) Block diagram of a HVDC system, (b) Internal diagram of the RE block.

The inverter side of the system was modified and consists of a direct current transmission line, a three-phase inverter, a three-phase transformer, a filter, three multimeters, and a three-phase load. The parts that were modified from the original HVDC system are:

- Elimination of the alternating voltage source
- The installation of a three-phase load.
- The replacement of the three-phase inverter GTO's byIGBT's.
- The elimination of the block to simulate faults.

VIII. RESULTS

The comparison of SPWM and THSPWM techniques is made by varying the amplitude modulation index M. The parameters considered in the comparison of the two techniques are measured and recorded in tables and some are shown in graphs. The comparison and analysis of the two techniques is done considering the numerical and graphical results of the simulations for the test cases. The three-phase load in the simulation is 3MW, connection Y and three-phase RMS voltage of 70.7 kV.

Tests are performed with amplitude modulation indices of 0.25, 0.5, 0.75, 1, 1.1 and 1.25. Considering that the switching frequency of the inverter transistors in HVDC systems ranges from 1 to 2 kHz, and that the frequency of the carrier signal must be an integer multiple of the frequency of the reference signal to reduce harmonic distortion in voltage of the inverter's output, the frequency modulation index is maintainedfixed, equal to 33 (1980 Hz).Values of M>1 are proposed to observe the relationship between the voltage and current parameters at the inverter's output. Magnitudes will be determined as: RMS magnitude of the fundamental component, total harmonic distortion, active and reactive powers. From this test the following results were obtained:

Table 1 shows the magnitudes of the parameters, measured in the simulations, with the SPWM technique, varyingthe amplitude modulation index M.

Table 1. Magnitudes obtained in the tests of the HVDC system with the SPWM technique, varying M.

M	0.25	0.5	0.75	1	1.1	1.25
Eab1CompF [kV]	13.3166	26.2629	39.0513	51.3596	54.4422	57.1639
Eab2CompF[kV]	24.6764	48.8964	72.4896	95.4713	101.154	106.179
Eab1THD	0.973	0.802	0.594	0.489	0.467	0.463
Eab2THD	0.02676	0.03239	0.03955	0.04671	0.059	0.068
Ea1RMS[kV]	43.3296	42.956	42.468	41.1952	41.2614	41.6369
Ea2RMS[kV]	14.5026	28.282	41.575	55.4341	58.5636	61.4150
Ea3RMS[kV]	14.5026	28.282	41.575	55.4341	58.5636	61.4151
Ia1RMS[A]	39.16433	112.12471	99.69479	168.04332	184.8	187.522
Ia2RMS[A]	26.89159	60.22240	46.63468	96.08384	99.59	94.471
Ia3RMS[A]	8.70417	16.97453	24.95256	33.27198	35.149	36.860
P0[MW]	1.26	2.28	3.9	6	6.65	7.2
P1[MW]	0.4475	1.56	3.325	5.6	6.3	6.9
P2[MW]	0.364	1.445	3.18	5.5	6.22	6.8
P3[MW]	0.36592	1.437	3.19	5.4815	6.165	6.8
Q1[MVAR]	-0.440	-1.65	-3.5	-5.9	-6.65	-7.3
Q2[MVAR]	-0.4583	-1.8	-4	-6.96	-7.81	-8.45
Q3[MVAR]	0	0	0	0	0	0

Table 2 shows the magnitudes of the parameters measured in the simulations of the HVDC system, with the THSPWM technique, varyingM.

Table 2. Magnitudes obtained in the tests of the HVDC system with the THSPWM technique, varying M.

M	0.25	0.5	0.75	1	1.1	1.25
Eab1CompF[kV]	15.247	30.1348	44.5329	58.6059	61.7755	60.7356
Eab2CompF[kV]	28.345	56.0416	82.8646	108.832	114.698	112.828
Eab1THD	0.965	0.767937	0.54351	0.419	0.400	0.36853
Eab2THD	0.026	0.028986	0.03427	0.040	0.064	0.08017
Ea1RMS[kV]	43.2835	42.5416	41.8	41.564	41.3	41.4016
Ea2RMS[kV]	16.6574	32.1194	48.0275	62.846	65.2403	66.4229
Ea3RMS[kV]	16.6574	32.1194	48.0274	62.846	65.2393	66.4229
Ia1RMS[A]	43.910	113.307	81.828	176.74049	174.5	164.750
Ia2RMS[A]	31.217	52.006	70.003	85.47043	83.750	80.135
Ia3RMS[A]	9.997	19.277	28.825	37.71945	39.252	39.866
P0[MW]	1.38	2.71	4.84	7.5	7.96	8.25
P1[MW]	0.575	2.025	4.29	7.25	7.8	8
P2[MW]	0.48	1.885	4.14	7.14	7.7	7.95
P3[MW]	0.48275	1.8871	4.1262	7.117	7.67	7.95
Q1[MVAR]	-0.58	-2.2	-4.7	-7.9	-8.6	-8.7
Q2[MVAR]	-0.604	-2.37	-5.185	-8.95	-9.5	-9.69
Q3[MVAR]	0	0	0	0	0	0

To make the interpretation of the results of the previous tables easier, some parameters are plotted. The graphs in figure 8 allow comparing the rms magnitudes of the fundamental components of the phase voltages Eab1CompF, recorded by EabX at the output of the inverter, see figure 7. In this graph, it is observed that the fundamental component of the voltage in Eab1CompF inverter output of the system, for both SPWM and THSPWM control techniques.This as a consequence of the increase in the modulation index M.

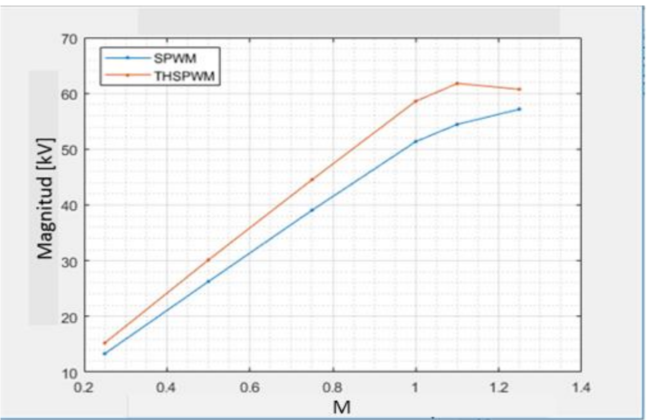


Figure 8.Fundamental components of the voltages at the output of the inverter.

Figure 9 shows that the fundamental components of the output voltages of the inverter, Eab2CompF,registered by UabX at the output of the transformer, see figure 7. The SPWM and THSPWM techniques are proportional to the index of modulation M.

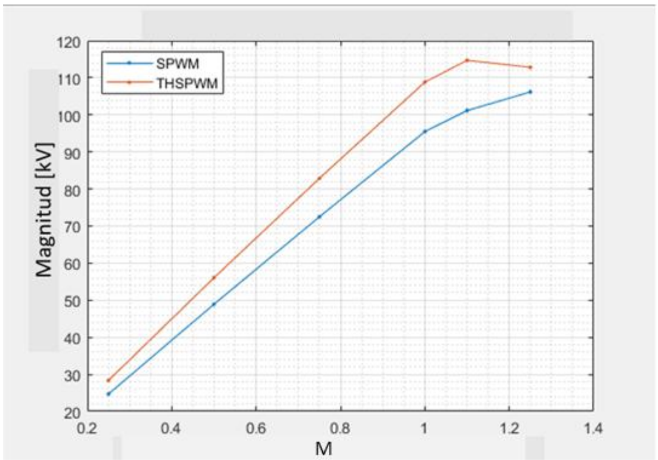


Figure 9.Fundamental components of the voltages at the output of the transformer.

It can be seen that while M≤1, the fundamental components of the voltages at the output of the inverter and the transformer are directly proportional to M. It is also observed that these voltages are always higher with the THSPWM technique, so, the THSPWM technique is always better from the point of view of the fundamental components of the inverter and transformer output voltages, respectively.

The Total Harmonic Distortion (THD) at the inverter's output decreases with both techniques as M increases, however, it can be seen that it decreases more with the THSPWM technique, Figure 10. That is, the THSPWM technique is better from the point of view of the total harmonic distortion of the inverter's output voltage.

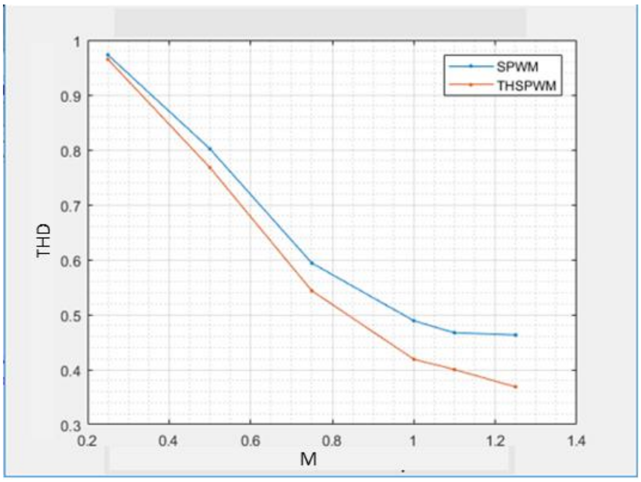


Figure 10.The THD of the voltage at the output of the inverter.

In Figure 11, it is observed that the phase voltages at the load input (Ea3RMS) also increase as M increases. These voltages are always higher with the THSPWM technique. It has greater performance with respect to the phase voltages at the input of the load.

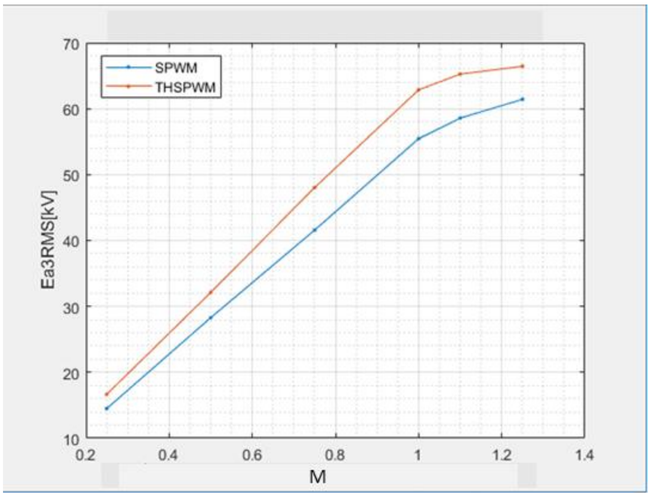


Figure 11. Phase voltages at the load input (Ea3RMS).

The currents at the load input (Ia3RMS) in the system, are directly proportional to M when M≤1, linear zone. It is also observed that these currents are always higher with the THSPWM technique.

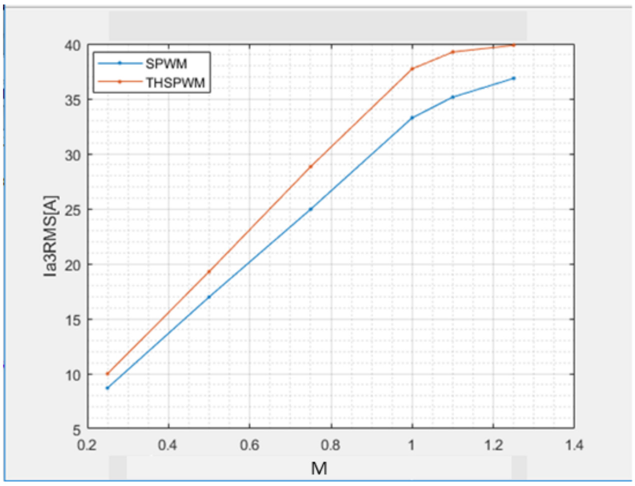


Figure 12. Load input currents (Ia3RMS).

The active powers (P_0) at the input of the system inverter is proportional to M, figure 13. It is also observed that these active powers are always greater with the THSPWM technique.

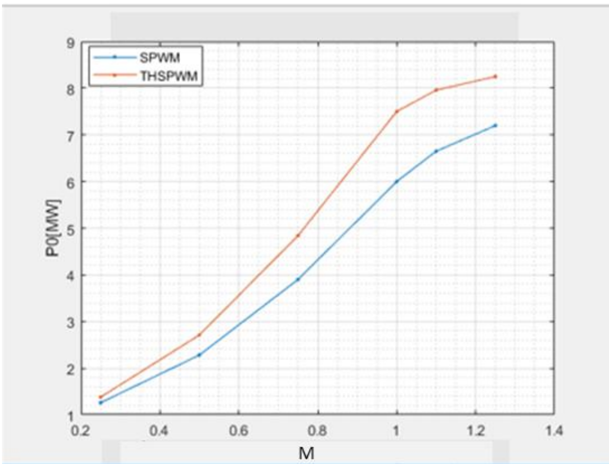


Figure 13.Active powers at the input of the inverter (P0).

IX. CONCLUSIONS

From the simulations made and the respective observations mentioned in the previous results, it is observed that, in general, the HVDC system with the THSPWM technique has greater performance, considering the magnitudes of the parameters measured when M is varied. In Tables 1 and 2 it is possible to see that some of the parameters are sometimes better with the SPWMthan the THSPWM technique, depending on the amplitude modulation index. However, the parameters measured in the final load are always better with the THSPWM technique. Therefore, it is concluded that, that the THSPWM technique has a better performance; the source is used better, in this case the transmitted voltage.

The THSPWM technique is generally considered to be more convenient, since the measured electrical parameters (voltages, currents, active powers, total harmonic distortion, among others) at the inverter's output, the secondary of the transformer and load terminals, are quantitatively better with the THSPWM than SPWM technique.

To support the above statement, regarding the advantages of the THSPWM technique, it can be said that:

- The fundamental component of the inverter and transformer output voltages is greater when THSPWM is used, approximately 14~15% higher with respect to SPWM.
- The phase voltage at the load input is higher with THSPWM, approximately 13 ~ 15% higher with respect to SPWM with linear modulation, and 8~11% higher with respect to SPWM with overmodulation.
- The THD of the inverter output voltage is lower with THSPWM, between1~20% lower than SPWM.
- The active power supplied to the load is always greater with THSPWM, approximately 22~32%.

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