

A comprehensive analysis of SVPWM for a Five-phase VSI based on SiC devices applied to motor drives.

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Abstract—This paper presents a comprehensive analysis of SVPWM for a five-phase VSI based on SiC devices applied to motor drives. The modulation techniques analyzed use medium and large vectors to reach the reference vector. The 2L SVPWM uses two large space vectors, and the generated output signal contain low frequency harmonics. 2L+2M SVPWM uses two large and two medium space vectors. This technique provides good power loss distribution. 4L SVPWM works with the activation of four large space vectors. This modulation is able to generate low common-mode voltage. The performance and main features are analyzed using Matlab/Simulink and PLECS blockset software. Power losses, total harmonic distortion and common-mode voltage are compared and evaluated.

Keywords—Five-phase inverter, SVPWM, Total harmonic distortion, power losses, Common-mode Voltage, Silicon Carbide.

I. INTRODUCTION

Multi-phase machines are used in many applications, such as power generation, electric propulsion systems and power industrial applications [1]–[3]. Some of the advantages of the multi-phase machines are: the reductions in the amplitude of the torque pulsation, improves the torque per ampere, more degrees of freedom, better fault tolerance, improves the sharing of the power between the inverter phase legs, and higher reliability, among others [2], [4]–[6]. These machines are normally supplied from two-level voltage source inverters (VSI).

Carrier-based PWM (CBPWM) and space vector PWM (SVPWM) are the most used modulation techniques for the multi-phase inverter [2], [7]–[9]. Thus, each technique demonstrates different performance and advantages over each other, in terms of power losses distribution, common-mode voltage (CMV) [10]–[12], the harmonic content, and the shapes of the output voltage and current signal.

Efficiency in electric systems plays an important role in the design and implementation of electric inverters. Having a system with high efficiency depends on reducing the losses in the power semiconductor devices of the inverter. The power losses in the power semiconductor devices are divided into conduction and switching losses. Conduction losses result from the current passing through every device and the switching losses depends on the switching frequency [13]–[15].

Using wide bandgap (WBG) power devices allows the inverter to work with higher switching frequencies, while operating at high voltages and high-temperatures. One wide bandgap device is based on silicon carbide (SiC).

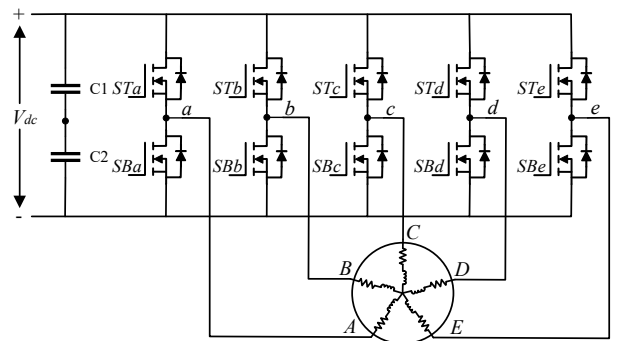


Fig. 1. Five-phase inverter

These devices perform better than the silicon (Si) devices, due to the low on-resistance R_{on} , thus resulting in power devices with better performance, also are able to operate with higher breakdown voltage, higher temperatures of up to 600°C, but actually the industrial SiC devices can operate up to 175 °C this due to that there are no high temperature packaging techniques [16], [17].

The objective of this work unlike others papers is to analyze the power losses, quantify CMV and study the harmonic content of a five-phase VSI based on SiC applied to an electric traction system under different modulation techniques. In order to analyze the converter a model based on Matlab Simulink/Plecs software has been developed. Fig. 1 shows the topology of the implemented two-level five-phase inverter with SiC power devices applied to a Permanent Magnet assisted Synchronous Reluctance Machine (PMA-SynRM). Fig. 2 shows the PWM techniques implemented in this paper: the *Two Large Vectors* (2L PWM) [2], [8], [18]–[20], *Two Large Two Medium Vectors* (2L+2M PWM) [2], [7], [8], [18], [20]–[22] and *Four Large Vectors* (4L PWM) [21], [23].

II. FIVE-PHASE VSI

In the multi-phase inverter, the number of states can be calculated by 2^n (where n is equal to the number of phases).

The five-phase inverter has 32 switching states, where two of these states are null or zero states. The switching states can be read like binary numbers with five digits where “1” means that the upper semiconductor device is closed and the lower device is open. The “0” state means that the lower device is closed and the upper device is open. Phase a is the most significant bit, and phase e is the least significant bit [4], [8], [24].

The instantaneous phase voltages of each leg are expressed as follows [2], [18]:

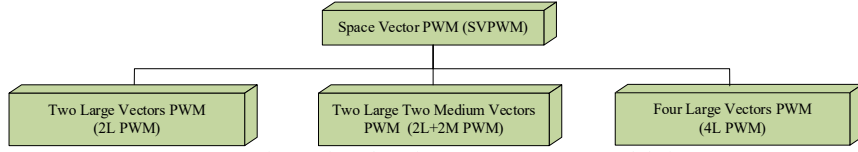


Fig. 2. Five-phase inverter space vector modulations.

$$\begin{aligned}
 V_a &= \frac{V_{dc}}{2} \left(\frac{4}{5} S_a - \frac{1}{5} [S_b + S_c + S_d + S_e] \right) \\
 V_b &= \frac{V_{dc}}{2} \left(\frac{4}{5} S_b - \frac{1}{5} [S_a + S_c + S_d + S_e] \right) \\
 V_c &= \frac{V_{dc}}{2} \left(\frac{4}{5} S_c - \frac{1}{5} [S_a + S_b + S_d + S_e] \right) \\
 V_d &= \frac{V_{dc}}{2} \left(\frac{4}{5} S_d - \frac{1}{5} [S_a + S_b + S_c + S_e] \right) \\
 V_e &= \frac{V_{dc}}{2} \left(\frac{4}{5} S_e - \frac{1}{5} [S_a + S_b + S_c + S_d] \right)
 \end{aligned} \quad (1)$$

where S_i ($i=a, b, c, d, e$) is the switching state of each one of the legs, V_i the instantaneous phase voltage, and V_{dc} the dc bus voltage.

III. SPACE VECTOR MODULATION (SVPWM)

The five-phase VSI has 32 switching states (i.e. vectors) for which 30 are active vectors and 2 are zero vectors. An n -phase system corresponds to an $n-1$ dimensional space (n it is assumed is odd, the load is balanced and star-connected). The 4-dimensional space where the vectors are projected can be divided into 2D subspaces by means of decoupling transformations. In this work, the Clarke Transformation (C_T) is applied as follows:

$$C_T = \frac{2}{5} \begin{bmatrix} 1 & \cos(\varphi) & \cos(2\varphi) & \cos(3\varphi) & \cos(4\varphi) \\ 0 & \sin(\varphi) & \sin(2\varphi) & \sin(3\varphi) & \sin(4\varphi) \\ 1 & \cos(2\varphi) & \cos(4\varphi) & \cos(\varphi) & \cos(3\varphi) \\ 0 & \sin(2\varphi) & \sin(4\varphi) & \sin(\varphi) & \sin(3\varphi) \\ 1/2 & 1/2 & 1/2 & 1/2 & 1/2 \end{bmatrix} \quad (2)$$

where $\varphi = 2\pi/5$ for the case of the five-phase VSI.

$$\begin{bmatrix} v_{d1} \\ v_{q1} \\ v_{d2} \\ v_{q2} \\ v_z \end{bmatrix} = C_T^* \begin{bmatrix} v_a \\ v_b \\ v_c \\ v_d \\ v_e \end{bmatrix} \quad (3)$$

By applying (2) to the five sinusoidal references, we can obtain two 2D subspaces with ten sectors for each one of them. Fig. 3 shows the first subspace d_1-q_1 , which contains the fundamental component and the $10k \pm 1$ ($k = 0, 1, 2, \dots$) harmonics. The second subspace d_2-q_2 , contains the harmonics on the order of $10k \pm 3$. The $5k$ harmonics cannot exist in this case because of the star configuration of the load.

The subspace d_1-q_1 contains four-types of space vectors of different sizes. In Fig. 3, the small (green) and large (blue) vectors are formed by the combination of three legs of the VSI in the turn-on state and two legs in turn-off (11100), or vice versa (00011). Medium (red) vectors are formed by four legs turned-on and one turned-off (11110) or vice versa (01111). The zero vectors are all the legs turned-on (11111) or turned-off (00000).

In applying (2), the *signal reference* is transformed into a rotary vector (V_{ref}) positioned in the d_1-q_1 subspace. To apply the different SVPWM techniques, it is necessary to calculate the magnitude and position of the reference vector as follows:

$$V_{ref} = \sqrt{V_{d1}^2 + V_{q1}^2} \quad (4)$$

$$\alpha = \tan^{-1} \left(\frac{V_{d1}}{V_{q1}} \right) \quad (5)$$

With the position and magnitude of the reference vector obtained from (4) and (5), the activation time of each switch combination can be calculated in order to reach the reference vector.

A. Two Large Vectors (2L SVPWM)

2L SVPWM use two large vectors plus the zero vectors to reach the reference vector. Applying 2L SVPWM, the inverter can supply more current than the other modulation techniques. This is able to maximize the modulation index ($m = 1.2311$).

The activation sequence of the space vectors in the 2L SVPWM technique depends on whether the location of the reference vector is an odd or an even sector.

Fig. 4 (b) shows the switching sequence for an odd sector that is $V_0, V_B, V_A, V_{31}, V_A, V_B, V_0$. For an even sector the switching sequence is $V_0, V_A, V_B, V_{31}, V_B, V_A, V_0$.

B. Two Large Two Medium Vectors (2L+2M SVPWM)

Unlike the 2L SVPWM modulation, the 2L+2M SVPWM combines two large and two medium vectors plus the zero vectors. This modulation has a maximum modulation index of $m=1.0515$. This modulation technique eliminates the low frequency harmonics in the voltages and the currents of the inverter[8].

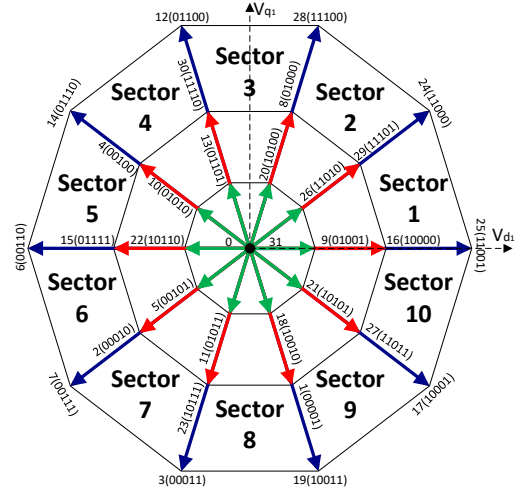


Fig. 3. 2D subspace vectors d_1-q_1 .

Fig. 5 (b) shows the switching sequence for an odd sector $V_0, V_{AM}, V_{BL}, V_{AL}, V_{BM}, V_{31}, V_{BM}, V_{AL}, V_{BL}, V_{AM}, V_0$. For an even sector, the switching sequence is $V_0, V_{BM}, V_{AL}, V_{BL}, V_{AM}, V_{31}, V_{AM}, V_{BL}, V_{AL}, V_{BM}, V_0$.

C. Four Large Vectors PWM (4L SVPWM)

The 4L PWM like the 2L+2M PWM, is formed by four active vectors plus two zero vectors, but the difference is that it has only large vectors. This technique uses the two vectors of the sector where the reference vector is located and the large vector from the previous and next sector. 4L PWM modulation has a modulation index of $m=1.0515$.

Fig. 6 (b) shows the switching sequence for an odd sector that is $V_0, V_{CL}, V_{AL}, V_{BL}, V_{DL}, V_{31}, V_{DL}, V_{BL}, V_{AL}, V_{CL}, V_0$. For an even sector the switching sequence is $V_0, V_{DL}, V_{BL}, V_{AL}, V_{CL}, V_{31}, V_{CL}, V_{AL}, V_{BL}, V_{DL}, V_0$.

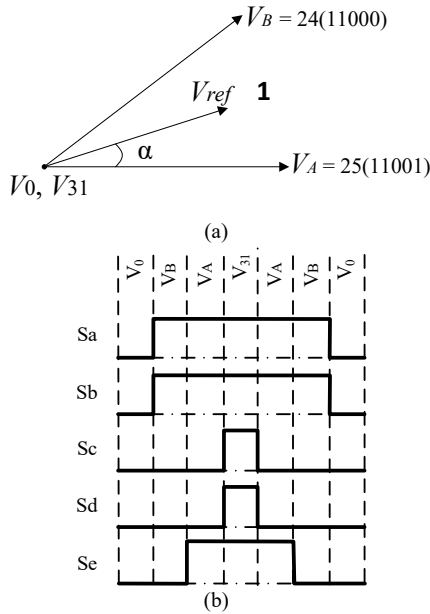


Fig. 4. 2L SVPWM Sector 1: (a) space vectors and (b) switching sequence.

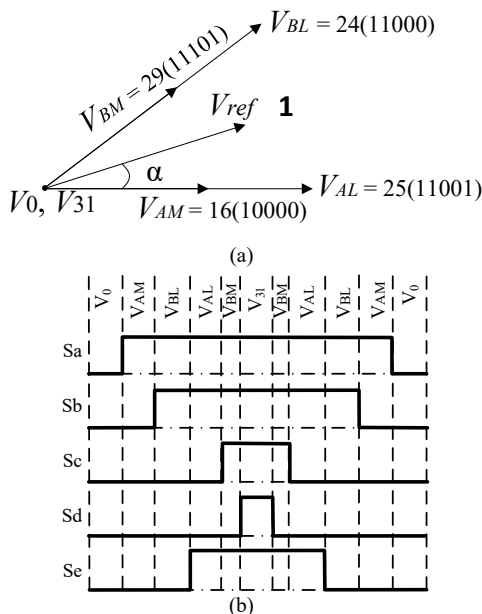


Fig. 5. 2L+2M SVPWM Sector 1: (a) space vectors and (b) switching sequence.

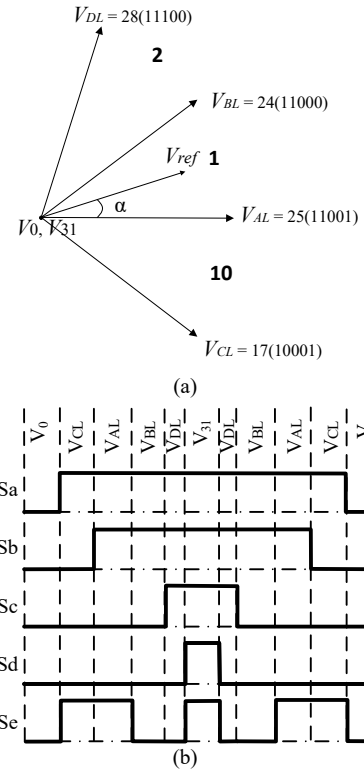


Fig. 6. 4L SVPWM Sector 1: (a) space vectors and (b) switching sequence.

IV. SIMULATION RESULTS

In order to study the different modulation techniques and compare them, the following characteristics have been evaluated: A) the harmonic content, B) the CMV generated and C) the power losses.

A. Harmonic content

The output voltages and currents are evaluated using the total harmonic distortion (THD) and the weighted total harmonic distortion (WTHD). The parameters are defined as follows:

$$THD(\%) = 100 \sqrt{\frac{\sum_{n=2}^{\infty} V_{n,RMS}^2}{V_{1,RMS}^2}} = 100 \sqrt{\left(\frac{V_{RMS}}{V_{1,RMS}}\right)^2 - 1} \quad (6)$$

$$WTHD(\%) = 100 \sqrt{\frac{\sum_{n=2}^{\infty} \left(\frac{V_{n,RMS}}{n}\right)^2}{V_{1,RMS}^2}} \quad (7)$$

B. Power Losses

1) Conduction losses

Conduction occurs when the MOSFET is in the on-state. These losses are defined in the form:

$$P_{condloss} = \frac{1}{T_s} \int_0^{T_s} (V_{F0} + R_{on} I_F) * I_F dt \quad (8)$$

Where V_{F0} is the threshold voltage, R_{on} is the on resistance, T_s is the period of the fundamental frequency and I_F is the forward current.

2) Switching losses

These losses are generated during the turn-on and turn-off switching processes of the power devices, and they are defined in the following form:

$$P_{Swtloss} = \frac{1}{T_s} \sum_{j=1}^{nT_s} [E_{on_j}(I_F, V_{offs}) + E_{off_j}(I_F, V_{offs})] \quad (9)$$

where E_{on} and E_{off} are the turn-on and turn-off energy dissipated during the change of state, nT_s is the number of transitions in one fundamental period, I_F is the on-state current running through the power devices and V_{offs} is the voltage in the off-state.

3) Efficiency

Efficiency is defined in the following form:

$$\eta(\%) = \left(\frac{P_{tot} - P_{condloss} - P_{swtloss}}{P_{tot}} \right) * 100 \quad (10)$$

where P_{tot} is the inverter total power.

C. Common-Mode Voltage (CMV)

The CMV in motor applications can cause bearing currents that lead to bearing failures, electromagnetic interference (EMI), damage to the winding insulation, and mechanical vibration. Table I shows the CMV generated for each of the different space vectors [11], [25].

TABLE I. CMV FOR EACH VECTOR TYPE.

Vector type	Common-Mode Voltage
Zero	$0.5 * V_{dc}$
Small	$0.1 * V_{dc}$
Medium	$0.3 * V_{dc}$
Large	$0.1 * V_{dc}$

Applying the Fast Fourier Transform (FFT) to the CMV signal, and the sum of the all the components of the FFT spectrum squared and divided between the half of the dc bus V_{dc} , we can obtain the normalized energy analysis of the CMV. The above mentioned is represented as follows:

$$E_{norm} \approx \sum_{i=1}^{\infty} \left[\frac{x(i)}{(V_{dc}/2)} \right]^2 \quad (11)$$

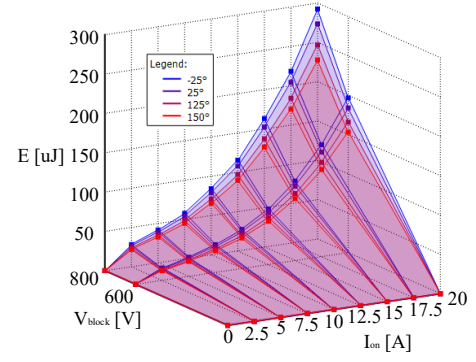
where E_{norm} is the normalized energy of the CMV, i the number of elements of the FFT spectrum and x the FFT spectrum of the CMV.

D. Simulation

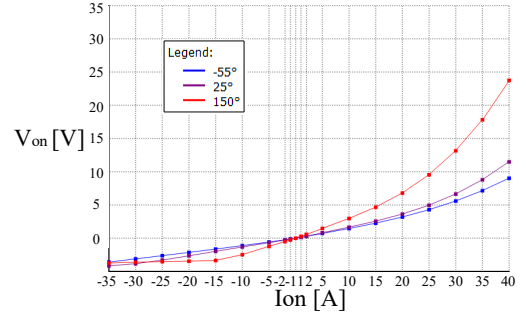
All the modulation techniques and the five-phase VSI are implemented in Matlab/Simulink and PLECS blockset software. Fig.7 (a) and (b) shows the switching energy and conduction losses of the SiC MOSFET C2M0160120D used in this analysis. Table II shows the simulation parameters of the system.

TABLE II. SIMULATION PARAMETERS

Inverter Switching frequency (f_s)	100 kHz
Inverter dc bus link (V_{dc})	550 V
Inverter temperature (T)	125°C
Motor Stator Resistance	2.05Ω
Motor Stator Inductance	59.89 mH
Motor Nominal Power	3 kW
Motor Nominal Torque	7 Nm
Motor Nominal Speed	4000 rpm
Motor Pair of poles	6

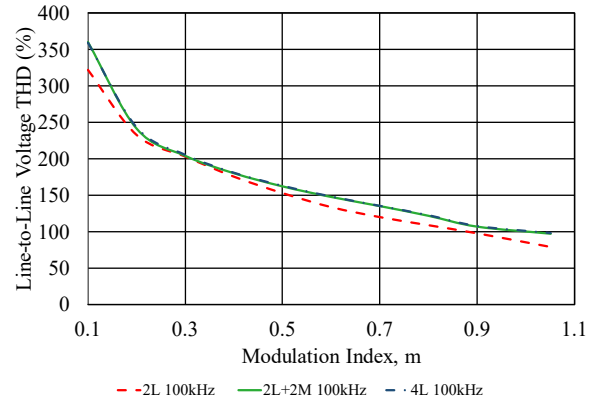


(a)

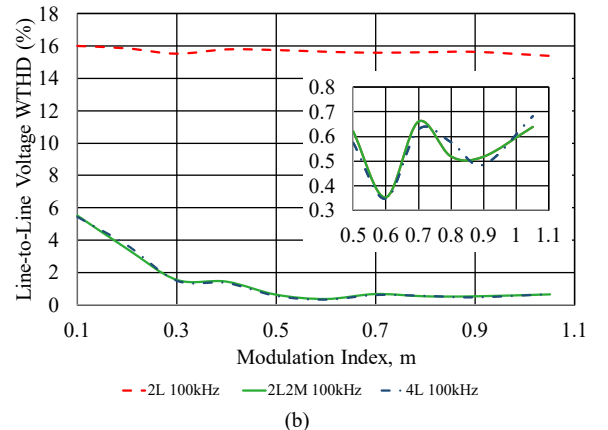


(b)

Fig. 7. PLECS lookup tables for the MOSFET C2M0160120D: (a) Switching and (b) conduction losses.



(a)



(b)

Fig. 8. Line-to-line voltage harmonic distortion: (a) THD and (b) WTHD.

Fig. 8 (a) and (b) show the THD and WTHD for the first two thousand harmonics of the line-to-line voltage. The 2L SVPWM is 9 to 38% smaller compared with the other two modulations. However, the WTHD for the 2L SVPWM as

much as to 10 to 15% greater than the 2L+2M and 4L SVPWM, due to the presence of low order harmonics in the 2L SVPWM.

Fig. 9 (a) and (b) show the THD and WTHD of the current output for 2L, 2L+2M and 4L SVPWM. The 2L+2M and 4L SVPWM have similar values with a slight difference. However, compared with the 2L SVPWM that has a 6 to 10% THD greater and a 2.5 to 3% greater WTHD, we can see that these results are also due to the presence of low order harmonics.

In Fig. 10, can be observed the CMV energy comparison. 4L SVPWM has the lowest energy and this decreases according to the increase in the modulation index. The energy decreases in the three different modulations because the activation time of the zero vectors is reduced when the modulation index increases. Table III shows the maximum reduction in the CMV of the modulations.

TABLE III. CMV REDUCTION PERCENTAGE.

2L SVPWM	60-80%
2L+2M SVPWM	62%
4L SVPWM	80 %

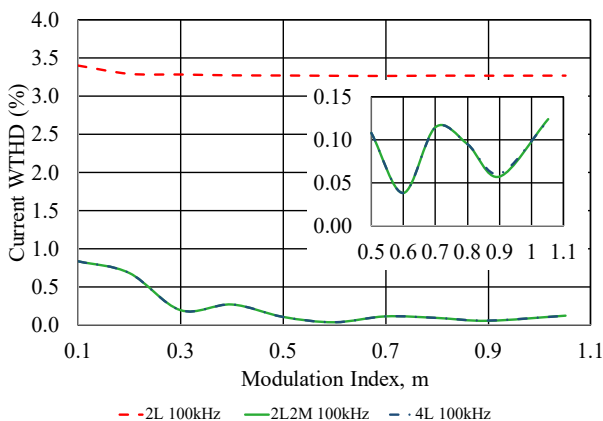
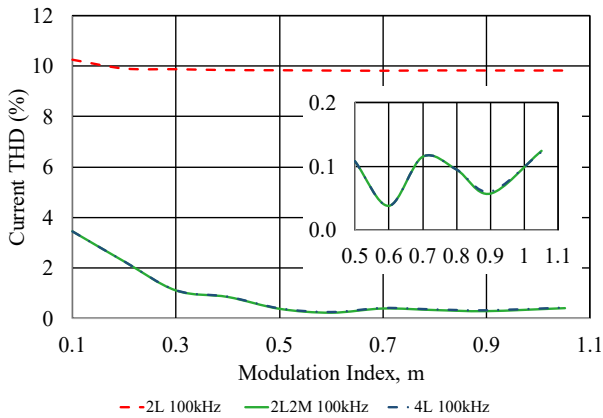


Fig. 9. Current harmonic distortion: (a) THD and (b) WTHD.

Fig. 11 (a), provides the efficiency comparison of the modulations, according to the change in motor speed using the nominal torque. The 4L SVPWM has the lowest efficiency. Meanwhile the 2L and 2L+2M SVPWM have a similar efficiency.

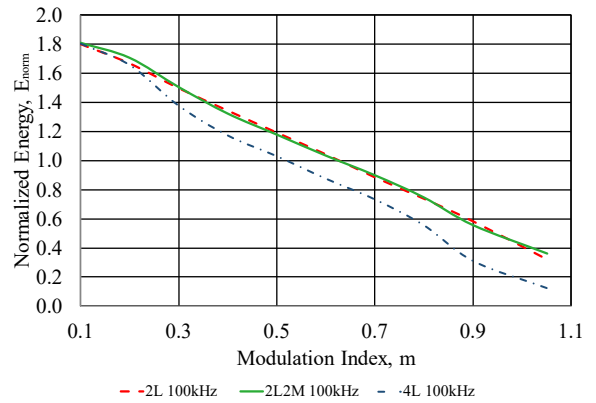


Fig. 10. Energy analysis of the FFT CMV.

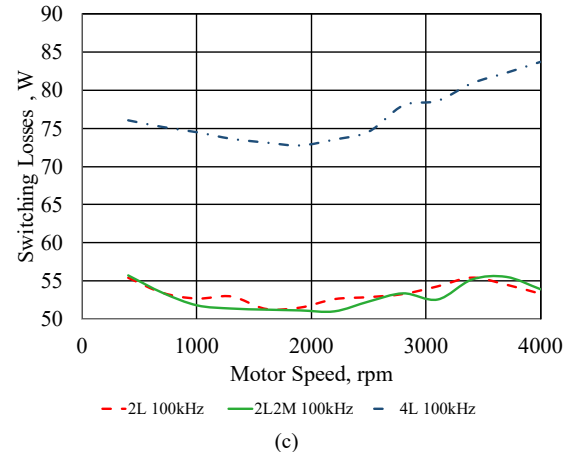
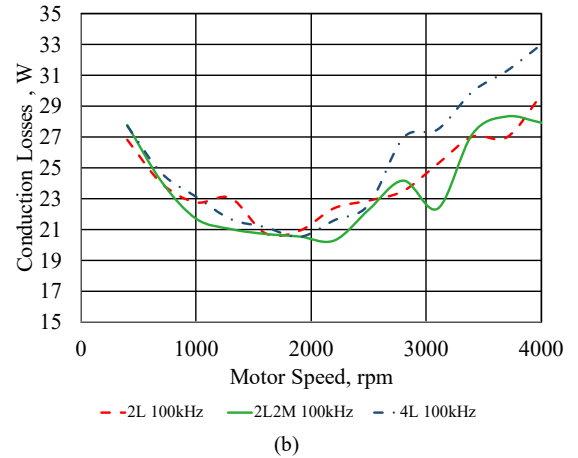
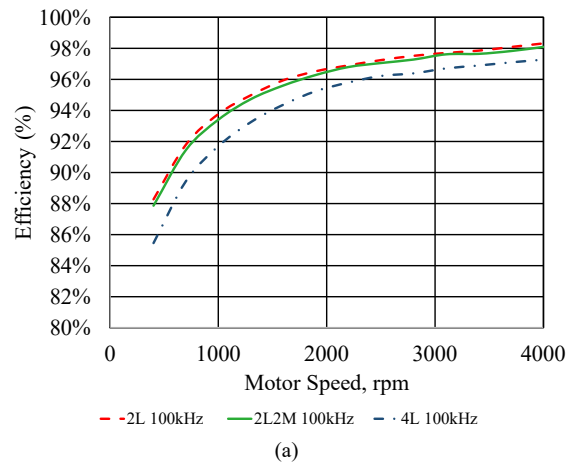


Fig. 11 Modulations comparison on: (a) Efficiency, (b) Conduction Losses and (c) Switching Losses.

Fig. 11 (b) shows the conduction losses of the modulations. These losses are similar but the 4L SVPWM can have up to 6 to 18% more losses than the other modulations.

In the Fig. 11 (c), can be observed the switching losses. The main reason that the 4L SVPWM has the lowest efficiency is due to the switching losses. The 4L SVPWM has between 36 to 55% more losses than the other modulations. On the other hand, the 2L and 2L+2M have similar losses, and depending on the operating zone, one can have a few more losses using one over the other.

V. CONCLUSIONS

Depending on the application of the multiphase machine or the characteristic that one wants to improve, each of these modulation techniques has advantages and disadvantages. The 4L SVPWM allows us to reduce the CMV, and thus reduce the bearing currents in the multiphase machine, although the efficiency of the inverter becomes compromised. The 2L+2M modulation has good WTHD content. We therefore have a good current waveform and lower power losses, but the reduction in CMV is lower than that of 4L SVPWM. Finally, the 2L SVPWM can provide almost the same reduction in CMV while at the same time it has less losses than the 4L SVPWM, but with the disadvantage that its current THD and WTHD is higher due to the presence of low order harmonics.

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