PWM Modulation Strategy for Common Mode Voltage reduction in five-phase machines

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Abstract: The three-phase machine is the most used, but alternating current machines with a number of phases greater than three have advantages over three-phase machines, such as extra degrees of freedom in the drive system; increase in useful torque by effective current value; among others. Static converters used to drive the machine introduce high frequency voltage components, which find a low impedance path to ground through the stray capacitances of the machine. Among the associated problems, mechanical failures in the bearings can be mentioned; increased levels of electromagnetic emissions; among others. A reduction in these problems can be achieved by reducing the common mode voltage in the drive system, as this is the voltage that powers the parasitic circuits of the machine. Among the solutions proposed in the literature for common mode voltage reduction and eddy current circulation, one can mention the use of passive filters associated with the inverter topology and/or the use of appropriate PWM modulation strategies. In this paper a new space vector modulation PWM (SVPWM) technique is presented to reduce common mode voltage for five-phase machines.

Keywords: Inverter, Bearing Currents, Common Mode Voltage, Polyphase Machines, Modulation Strategies.

1. INTRODUCTION

With advances in power electronics, microelectronics, microprocessor systems and control techniques, AC (Alternating Current) induction motors have taken the place of DC (Direct Current) motors in the field of drives. The drive of three-phase machines is the most common AC drive, but machines with more than three phases have some characteristics that are superior to those of three-phase machines, for example: decreased amplitude and increased torque pulse frequency; current decrease per phase without voltage increase per phase; increase in useful torque per effective current value compared to a three-phase machine with the same ferromagnetic volume; operation constancy, independent of one or more phases are fully open, without needing additional connections; flexibility in parameter estimation; reduction of current harmonics on the DC link; ease of activation as the extra phases provide an additional degree of freedom.

In drive systems, the static converters used introduce high-frequency voltage components, which find a low-impedance path to ground through the stray capacitances of the machine. Among the associated problems, mechanical failures in the bearings can be mentioned; increased levels of electromagnetic emissions; etc. A reduction in these problems can be achieved by reducing the common mode voltage (CMV) in the drive system, as this is the voltage supplying the parasitic circuits of the machine. Among the solutions proposed in the literature for common mode voltage reduction and eddy current circulation, the use of appropriate PWM modulation strategies can be mentioned Miranda (2007).

A problem that has been studied for decades is bearing currents. In da Silva et al. (2020) it is seen that the capacitances machine parasites have high impedance at low frequency making the CMV not a hindrance, but the sources switches that use pwm with the inverters, as seen above, introduce high frequencies that make these capacitances a low impedance path granting the circulation of bearing chains, these chains cannot damage the bearing directly, but can cause Lubrication fatigue and premature bearing failure. And as already done, to reduce the negative effects of high frequency it is necessary to reduce the CMV, a cost-free solution would be the application of new PWM techniques. In this paper, a new PWM vector modulation technique is presented to reduce the common mode voltage and bearing currents for five-phase machines.

2. MACHINE MODEL AND THE DRIVE SYSTEM

While the vector model of a three-phase machine relates vectors in the plane, in a five-phase machine the vectors present in the model are of dimension four. Taking only the first two spatial flux components (Fundamental and third harmonic), this four-dimensional model can be decomposed into two sets of tow-dimensional decoupled equations, that is, two planes: dq and xy. In Pereira et al. (2006) the modeling of a five-phase machine considering the presence of the third spatial harmonic of flow is discussed. The machine model obtained similarly to the one presented in Pereira et al. (2006) is given by:

$$\hat{\lambda}^s_{sdq} = l_{s1}\hat{i}^s_{sdq} + l_{m1}\hat{i}^s_{rdq} \tag{1}$$

$$\hat{\lambda}^s_{rdq} = l_{r1}\hat{i}^s_{rdq} + l_{m1}\hat{i}^s_{sdq} \tag{2}$$

$$\hat{v}^s_{sdq} = r_s\hat{i}^s_{sdq} + j\omega_{s1}\hat{\lambda}^s_{sdq} + \frac{d\hat{\lambda}^s_{sdq}}{dt} \tag{3}$$

$$0 = r_r\hat{i}^s_{rdq} + j(\omega_{s1} - \omega_r)\hat{\lambda}^s_{rdq} + \frac{d\hat{\lambda}^s_{rdq}}{dt} \tag{4}$$

$$\hat{\lambda}^s_{sxy} = l_{s3}\hat{i}^s_{sxy} + l_{m3}\hat{i}^s_{rxy} \tag{5}$$

$$\hat{\lambda}^s_{rxy} = l_{r3}\hat{i}^s_{rxy} + l_{m3}\hat{i}^s_{sxy} \tag{6}$$

$$\hat{v}^s_{sxy} = r_s\hat{i}^s_{sxy} + j\omega_{s3}\hat{\lambda}^s_{sxy} + \frac{d\hat{\lambda}^s_{sxy}}{dt} \tag{7}$$

$$0 = r_r\hat{i}^s_{rxy} + j(\omega_{s1} - 3\omega_r)\hat{\lambda}^s_{rxy} + \frac{d\hat{\lambda}^s_{rxy}}{dt} \tag{8}$$

$$T_e = Pl_{m1}\left[i^s_{rq}i^s_{sd} - i^s_{sd}i^s_{rq}\right] + 3Pl_{m3}\left[i^s_{ry}i^s_{sx} - i^s_{sx}i^s_{ry}\right] \tag{9}$$

Where:

$\hat{\lambda}^s_{sdq}$, $\hat{\lambda}^s_{rdq}$, $\hat{\lambda}^s_{sxy}$ e $\hat{\lambda}^s_{rxy}$ are the stator and rotor flux vectors in the $dqxy$ plane.
$\hat{v}^s_{sdq}$ e $\hat{v}^s_{sxy}$ are the stator voltage vectors in the $dqxy$ plane.
$\hat{i}^s_{sdq}$, $\hat{i}^s_{rdq}$, $\hat{i}^s_{sxy}$, $\hat{i}^s_{rxy}$ are the stator and rotor current vectors in the $dqxy$ plane.
l_{s1}, l_{r1} and l_{m1} are cyclic and mutual inductances from the stator and rotor to the fundamental component.
l_{s3}, l_{r3} and l_{m3} are cyclic and mutual inductances from the stator and rotor to the third harmonic component.
T_e and P are the torque and the number of pole pairs of the machine.
ω_{s1}, ω_{s3} and ω_r are the angular velocities.

The $dqxy$ components can be converted from and/or to the phase variables through:

$$\bar{x}_{12345} = \bar{A}_s\bar{x}_{dqxy} \tag{10}$$

and

$$\bar{x}_{dqxy} = \bar{A}_s^T\bar{x}_{12345} \tag{11}$$

On what,

$$\bar{A}_s = \sqrt{\frac{2}{5}}\begin{bmatrix} 1 & 0 & 1 & 0 \\ cos(2\pi/5) & sin(2\pi/5) & cos(4\pi/5) & sin(4\pi/5) \\ cos(4\pi/5) & sin(4\pi/5) & cos(8\pi/5) & sin(8\pi/5) \\ cos(6\pi/5) & sin(6\pi/5) & cos(12\pi/5) & sin(12\pi/5) \\ cos(8\pi/5) & sin(8\pi/5) & cos(16\pi/5) & sin(16\pi/5) \end{bmatrix} \tag{12}$$

The drive system using a five-phase induction motor is shown in Figure 1.

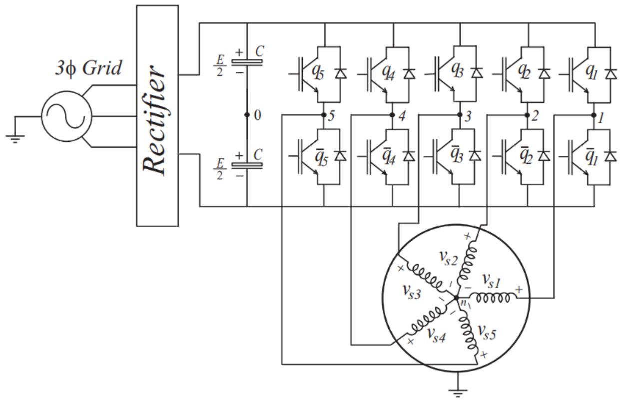

Figure 1. Five-phase machine drive system.

3. COMMON MODE VOLTAGE MITIGATION PWM STRATEGIES

In R.F. and M.J. (2004) and de Azevedo (2001), a sinusoidal source of symmetrical and balanced voltage operating in conditions normal has the vector sum of the three phases equal to zero, so at the neutral of the circuit will have a voltage equal to zero as well. But when using a PWM inverters similar to the one shown ta Figure 1, as a voltage source, the voltage resultant at neutral is not equal to zero, as pwm inverters use the voltage from the DC bus (E) switched on the three-phase motor terminals, to generate a voltage with component proper fundamental and frequency, so the motor line voltage is instantly +E/2 or -E/2 which results in the impossibility of summing the three voltages are zero at all instants of time, so the instantaneous sum of voltages that is not equal to zero is called the common mode voltage (CMV). This voltage can be expressed in terms of the machine neutral point voltage for the ground.

Therefore:

$$v_{in} = \frac{1}{5}(v_{s10} + v_{s20} + v_{s30} + v_{s40} + v_{s50}) \tag{13}$$

Each combination of switching states creates a four-dimensional vector, whose projections on the planes dq and xy are shown in Figure 2. There are 32 vectors, of which two are null and thirty are active.

Figure 2 shows the common mode voltage produced by each vector. It can be seen that the null vectors are

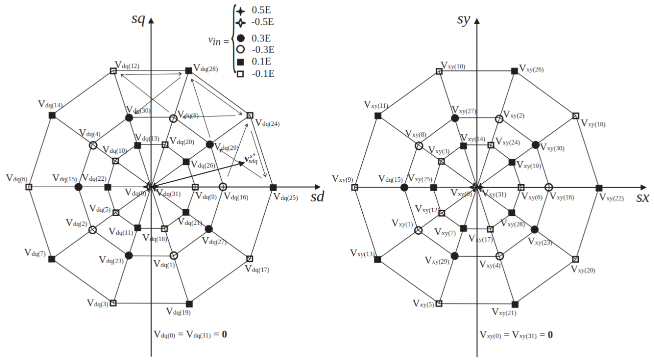

Figure 2. dq and xy plans.

responsible for the highest levels of common mode voltage, 50% of the bus voltage. The vectors whose projections in the dq planes are the largest and those whose projections are the smallest produce common-mode voltage levels 10% of the bus voltage, while the ten vectors whose projections in the dq plane are average produce voltage of common mode equal to 30% of the bus voltage.

With zero reference connection in the xy plane, there is a sinusoidal drive of the machine. For sinusoidal drive, the so-called conventional modulation strategy or conventional space vector modulation PWM (Conventional SVPWM) uses the four vectors whose projections in the dq plane are adjacent to the reference vector and have large and medium amplitudes (Vectors with smaller projections are not used). There are therefore ten distinct sectors. The first of these defined by the vectors $V_{dq(25)}$, $V_{dq(24)}$, $V_{dq(16)}$ and $V_{dq(29)}$. The application time of these vectors, for a reference located in this sector, is calculated by:

$$V^{*}_{sdqxy} = \frac{t_a}{\tau}V_{dq(16)} + \frac{t_b}{\tau}V_{dq(24)} + \frac{t_c}{\tau}V_{dq(25)} + \frac{t_e}{\tau}V_{dq(29)}, \quad (14)$$

or separating in the equations in each plane:

$$V^{**}_{sdq} = \frac{t_a}{\tau}V_{dq(16)} + \frac{t_b}{\tau}V_{dq(24)} + \frac{t_c}{\tau}V_{dq(25)} + \frac{t_e}{\tau}V_{dq(29)} \quad (15)$$

$$V^{**}_{sxy} = \frac{t_a}{\tau}V_{xy(16)} + \frac{t_b}{\tau}V_{xy(24)} + \frac{t_c}{\tau}V_{xy(25)} + \frac{t_e}{\tau}V_{xy(29)} \quad (16)$$

Such equations correspond to a 4×4 equations system given by:

$$\begin{bmatrix} V_{d(16)} & V_{d(24)} & V_{d(25)} & V_{d(29)} \\ V_{q(16)} & V_{q(24)} & V_{q(25)} & V_{q(29)} \\ V_{x(16)} & V_{x(24)} & V_{x(25)} & V_{x(29)} \\ V_{y(16)} & V_{y(24)} & V_{y(24)} & V_{y(29)} \end{bmatrix} \begin{bmatrix} t_a \\ t_b \\ t_c \\ t_e \end{bmatrix} = \tau \begin{bmatrix} v^{*}_{sd} \\ v^{*}_{sq} \\ 0 \\ 0 \end{bmatrix} \quad (17)$$

To ensure that the inverter operates with constant switching frequency, τ, is filled with the null vectors $V_{(0)}$ and $V_{(31)}$. The total time of application of the null vectors is t_o,

$$t_o = \tau - t_a - t_b - t_c - t_e \quad (18)$$

The time interval t_o, can be split at the beginning, t_{oi}, and at the end, t_{of} , of the switching period. By introducing the distributing factor $\mu = t_{oi}/t_o$, it follows that,

$$t_{oi} = \mu t_o \quad (19)$$

$$t_{of} = (1 - \mu)t_o \quad (20)$$

Table 1 shows the vectors chosen for each sector.

Table 1. Vectors of each Sector for Switching.

Sectors	Selected Vectors
I	V0, V16, V24, V25, V29, V31
II	V0, V29, V28, V24,V8 V31
III	V0, V8,V12,V28,V30, V31,
IV	V0, V30,V14,V12,V4, V31
V	V0, V4,V6, V14, V15,V31
VI	V0,V15,V7,V6,V2 , V31
VII	V0,V2,V3,V7,V23, V31
VIII	V0,V23,V19,V3,V1 , V31
IX	V0, V1,V17, V19,V27, V31
X	V0,V27,V25,V17,V16, V31

Where $V = V_{sdqxy}$. Figure 3 shows the behavior of CMV voltage for conventional modulation strategy. In Durán

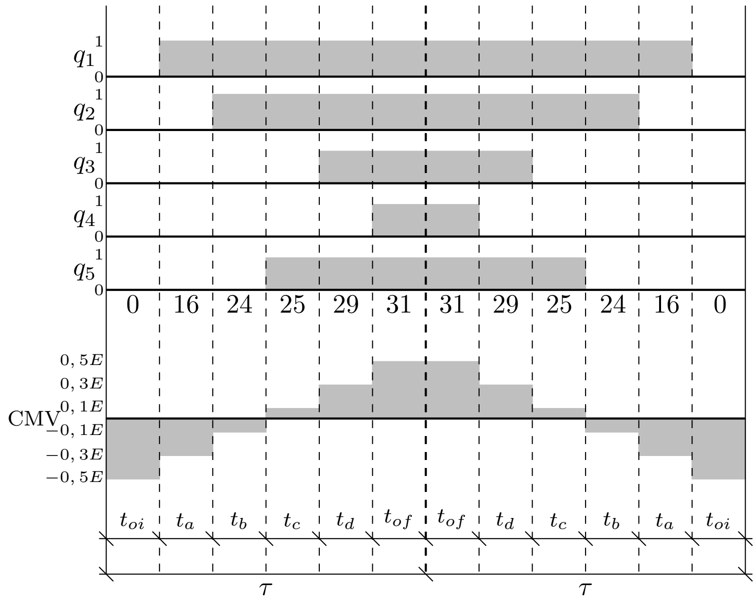

Figure 3. CMV voltage for conventional modulation strategy, sector I.

et al. (2013) are presented techniques of SVPWM (Space Vector Modulation PWM) strategies capable of reducing the peak-to-peak common mode voltage between 40% and 80% in a five-phase drive system. In Freitas et al. (2007) a strategy for a five-phase machine is proposed in which the null vectors are replaced by opposite active vectors applied for equal periods of time, so that the average applied voltage is zero. In this way, the null is emulated by using active vectors, which in turn contribute with lower common mode voltage values. In the literature this type of modulation is commonly called AZPWM (*Active Zero State Pulse-Width Modulation*), like the solution for a three-phase machine presented in Ali et al. (2014). In Ahmad and Miao (2015) the common mode voltage reduction and the voltage/frequency control stability (V/F) are presented when AZPWM is applied.

In Yu et al. (2019) a predictive control method based on virtual vectors is presented that is applied in the five-phase

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inverter making the mean and zero vectors not exist in the application, so the common mode voltage can be reduced by 80%.

Another solution present in the literature for three-phase systems is to use the active vector closest to the reference accompanied by the two adjacent active vectors Ün and Hava (2007) and Ün and Hava (2009). Such solutions avoid the use of null vectors, but are only applicable to high modulation indices. Such strategies are named in the cited NSPWM (*Near State Pulse-Width Modulation*) references. In Dabour et al. (2019) he presents a modulation strategy for driving the five-phase machine based on the three-phase NSPWM called CMVR3 for common mode voltage reduction. This strategy consists of using the five adjacent vectors to generate the reference vector that is find the $\pm 18°$ of the active vector from the center of the set as in Figure 4 for sertor I.

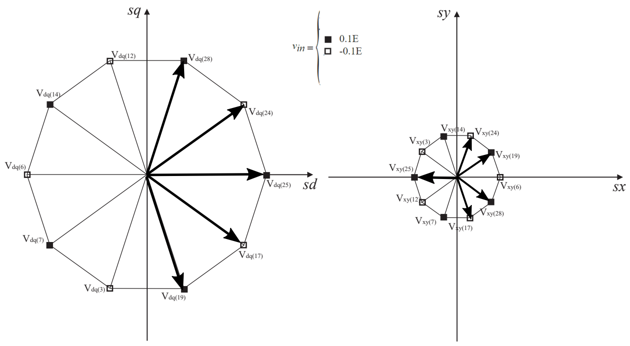

Figure 4. For sector I.

Table 2 shows the vectors chosen for each sector and CMV levels for this strategy. Let us continue to call this strategy NSPWM.

Table 2. Vectors of each Sector for Switching and common mode voltages of NSPWM.

Sectors	Selected Vectors	Common Mode Voltage
I	V28,V24,V25,V17,V19	$\pm 0.1E$
II	V24,V25,V17,V19,V3	$\pm 0.1E$
III	V25,V17,V19,V3,V7	$\pm 0.1E$
IV	V17,V19,V3,V7,V6	$\pm 0.1E$
V	V19,V3,V7,V6,V14	$\pm 0.1E$
VI	V3,V7,V6,V14,V12	$\pm 0.1E$
VII	V7,V6,V14,V12,V28	$\pm 0.1E$
VIII	V6,V14,V12,V28,V24	$\pm 0.1E$
IX	V14,V12,V28,V24,V25	$\pm 0.1E$
X	V12,V28,V24,V25,V17	$\pm 0.1E$

Figure 5 shows the behavior of CMV voltage for strategy NSPWM.

By calculating the cycle ratios, it is observed that depending on the magnitude of the reference vectors, some cycle ratios can become negative. The following equation was defined:

$$M = \frac{\left|V_{dq}^{*}\right|}{E_{dc}} \tag{21}$$

Where $\left|V_{dq}^{*}\right|$ is the reference vector and E_{dc} is the bus voltage. Where a principle can be considered to be the modulation index.

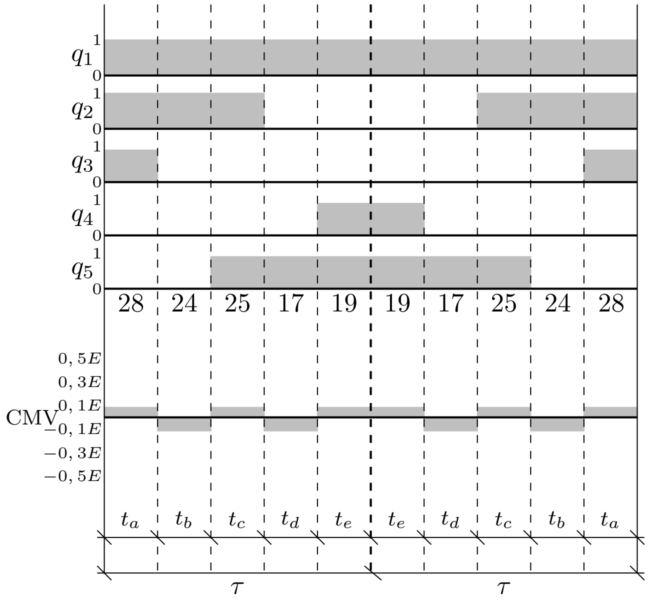

Figure 5. CMV voltage for strategy NSPWM, sector I.

Manipulating the cycle ratios again, a value for M is obtained making the PWM not saturate, so we can define the modulation index for this strategy as:

$0.69798 \leq M \leq 0.83126$.

Any value of M outside this range has PWM saturation.

Another strategy present in the literature for three-phase systems uses two sets with three active vectors each set, out of phase with each other by 120° Cacciato et al. (1999). Such strategies are called 3AVPWM (*Three Active Vectors PWM*) and only apply to low modulation rates. In Iqbal et al. (2014) he presents a modulation technique for the activation of the five-phase machine based on the three-phase 3AVPWM. This strategy consists of using two groups with five large vectors out of phase with each other by 72°. The group used will be the one for which the reference vector is tangent to one of the vectors of that group, the groups that define this strategy are shown in Figures 6 and 7.

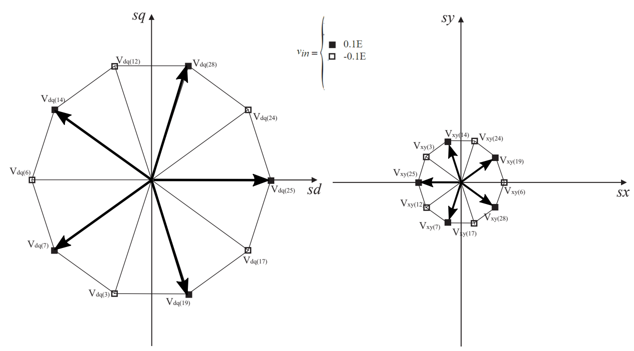

Figure 6. For sectors I, III, V, VII and IX.

Table 3 shows the vectors chosen for each sector and CMV levels for this strategy. We will call this strategy of 5AVPWM.

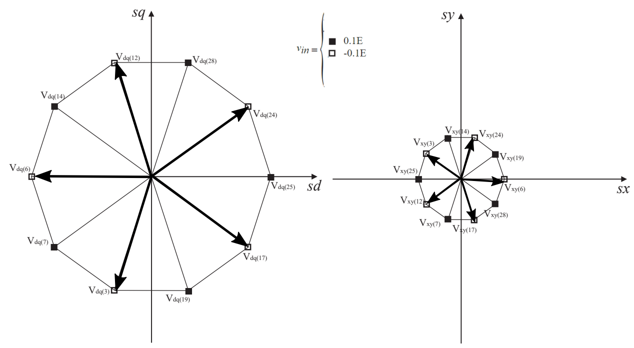

Figure 7. For sectors II, IV, VI, VIII e X.

Table 3. Vectors of each Sector for Switching and common mode voltages of 5AVPWM.

Sectors	Selected Vectors	Common Mode Voltage
I, III, V, VII, IX	V25,V19,V7,V14,V28	$0.1E$
II,IV,VI,VIII,X	V17,V3,V6,V12,V24	$0.1E$

Figure 8 shows the behavior of CMV voltage for strategy 5AVPWM.

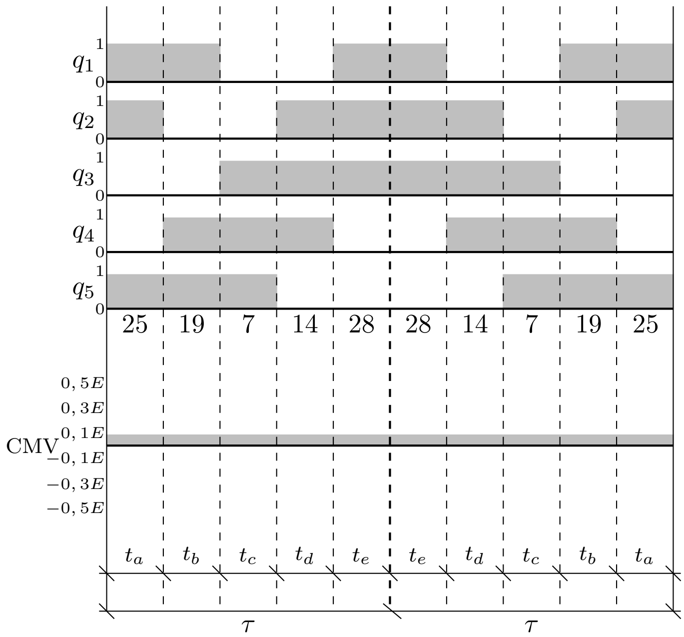

Figure 8. CMV voltage for strategy 5AVPWM, sector I, III, V, VII, IX.

Performing the same procedure seen in the previous strategy to obtain the modulation index, it was obtained:

$0 \leq M \leq 0.538$.

For M values above 0.538, the saturation of the PWM is obtained. Therefore, this modulation applies to low modulation indices.

These two strategies discussed earlier do not require the use of null vectors, as the application time of the five vectors will be equal to the sampling period ($t_a + t_b + t_c + t_e + t_g = \tau$).

In da Silva et al. (2020) a hybrid approach between NSPWM and 3AVPWM for three-phase drive system allows expanding the use of modulation indices across the entire range.

4. PROPOSED PWM TECHNIQUE

4.1 Proposed SVPWM

This strategy is based on the Figure 4 technique, but instead of using five close vectors in 36°, there will be three close vectors in 36° and two vectors in 72° as shown in Figure 9.

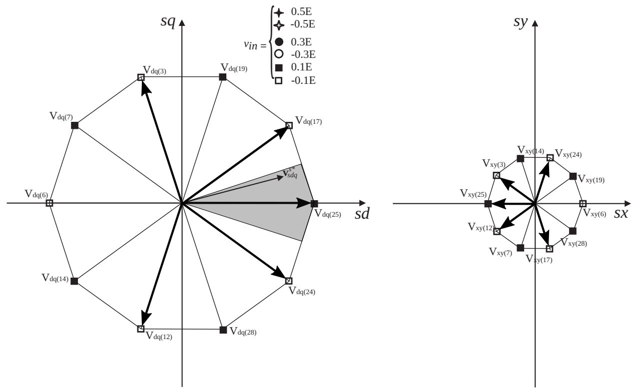

Figure 9. For sector I of the proposed SVPWM.

Table 4 shows the vectors chosen for each sector and CMV levels for this strategy.

Table 4. Vectors of each Sector for Switching and common mode voltages of the proposed strategy.

Sectors	Selected Vectors	Common Mode Voltage
I	V12,V24,V25,V17,V3	$\pm 0.1E$
II	V28,V25,V17,V19,V7	$\pm 0.1E$
III	V24,V17,V19,V3,V6	$\pm 0.1E$
IV	V25,V19,V3,V7,V14	$\pm 0.1E$
V	V17,V3,V7,V6,V12	$\pm 0.1E$
VI	V19,V7,V6,V14,V28	$\pm 0.1E$
VII	V3,V6,V14,V12,V24	$\pm 0.1E$
VIII	V7,V14,V12,V28,V25	$\pm 0.1E$
IX	V6,V12,V28,V24,V17	$\pm 0.1E$
X	V14,V28,V24,V25,V19	$\pm 0.1E$

Figure 10 shows the behavior of CMV voltage for proposed SVPWM.

This strategy has a modulation index range given by: $0.538 \leq M \leq 0.69798$.

Thus obtaining modulation in the regions where the other two strategies previously seen saturated.

5. SIMULATION RESULTS

A specified model for the common mode voltage and bearing currents in the machine's drive system is discussed in Chen et al. (1996). The current bearing model is simplified as shown in Figure 11. The proposed technique for reducing the CMV plus the 5AVPWM and NSPWM were simulated and applied to the circuit of Figure 11 with the parameters given in Table 5, taken from Chen et al.

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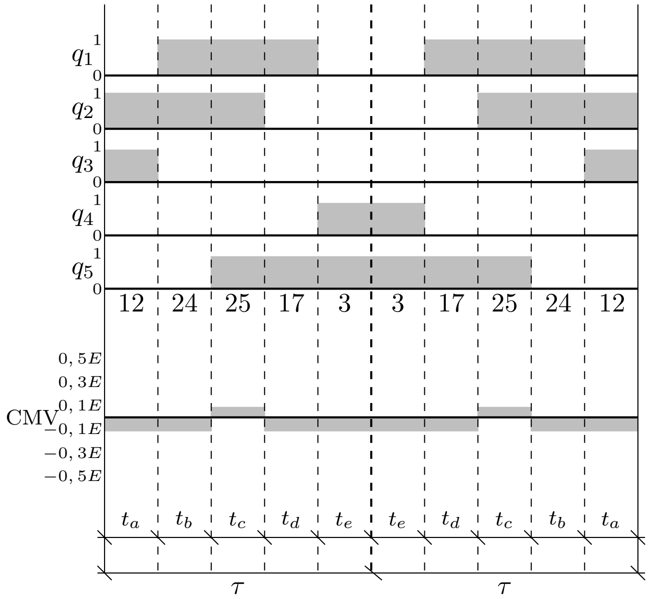

Figure 10. CMV voltage for proposed SVPWM, sector I.

(1996). This simulation aimed to show the reduction of currents due to stray capacitances for the proposed method comparing with the 5AVPWM and NSPWM methods.

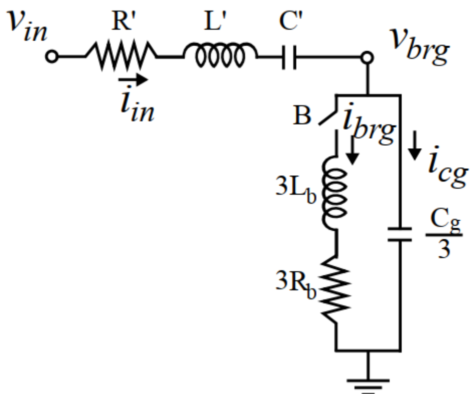

Figure 11. Bearing currents model shown in Chen et al. (1996).

Table 5. Paramaters for the Bearing Currents Model.

$R' = 200\Omega$	$L' = 300\mu H$	$C' = 20pF$
$L_b = 150nH$	$R_b = 6.5\Omega$	$C_g = 800pF$

For bearing model simulation, as seen in the Figure 11, the switch B was considered permanently closed in the simulation of bearing currents. Although this assumption introduces a significant error in the bearing current compared to actual values due to the switching characteristic of B, this error is also introduced in all strategy simulations. So, for comparisons proposes among the different strategies this assumption is adequate.

In Figure 12, the proposed SVPWM is compared to the conventional SVPWM, 5AZPWM and NSPWM in relation to THD, and in Figure 13 in relation to the rms values of the bearing current. Therefore, it is possible to verify that the 5AVPWM generates a lower rms value of bearing current and consequently a lower common mode voltage when compared to other techniques. The problem is that the 5AVPWM strategy only works at low modulation index. The proposed technique obtained THD lower than 5AVPWM and slightly higher than NSPWM, the conventional SVPWM obtained THD lower than all of them.

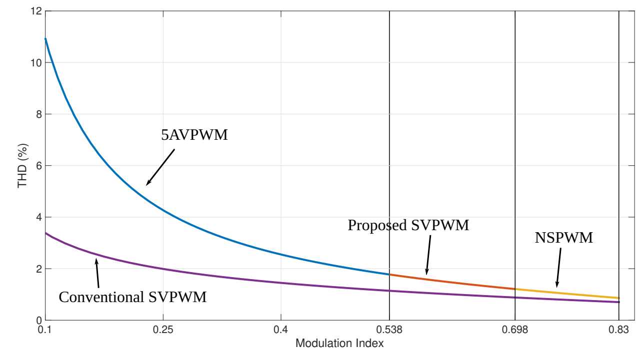

Figure 12. Proposed SVPWM, 5AVZPWM, NSPWM and Conventional SVPWM comparation regarding THD.

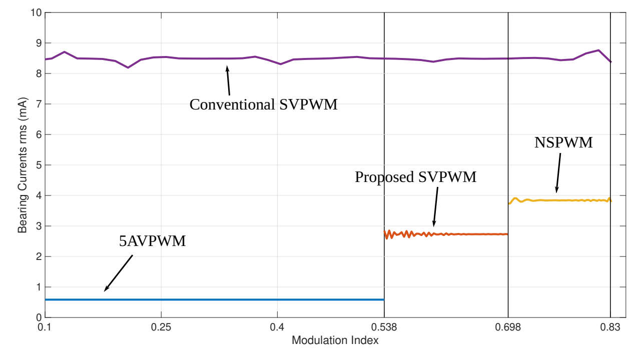

Figure 13. Proposed SVPWM, 5AVZPWM, NSPWM and Conventional SVPWM comparation regarding bearing current.

In the Figure 14 we can see the output voltages (phase and line) of the 5AVPWM strategy, NSPWM strategy and the proposed strategy.

6. CONCLUSION

In this paper an SVPWM technique is proposed that allows the minimization of common mode voltages and bearing currents that operate in regions where the 5AVPWM and NSPWM techniques saturate. It is compared to conventional SVPWM, 5AVPWM and NSPWM. The proposed technique presents the second smallest amplitude of the bearing currents when compared to the others, obtaining a lower value than the NSPWM strategy. The THD simulation was also satisfactory, again reaching the second position among the strategies. The objective of this proposed strategy is to be an option for operation with low levels of common mode voltage and bearing currents in the modulation index ranges where the 5AVPWM and NSPWM strategies saturate.

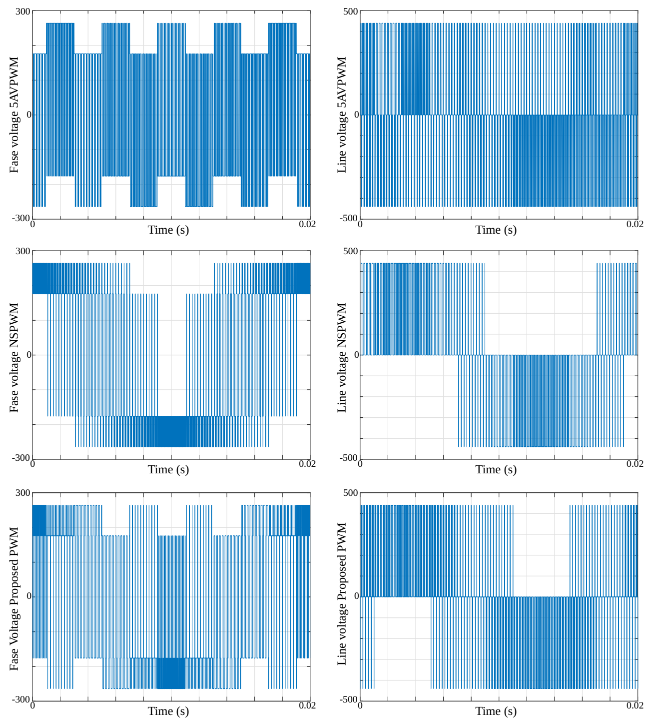

Figure 14. Phases voltages and lines voltages

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