# Alternative Feedback Quantizer Using Space Vector Modulation

Matias Veillon
*Dept. of Electrical Engineering*
*Universidad Catolica de la Santisima Concepcion*
Concepcion, Chile
mveillon@magister.ucsc.cl

Eduardo Espinosa
*Dept. of Electrical Engineering*
*Universidad Catolica de la Santisima Concepcion*
Concepcion, Chile
eespinosa@ucsc.cl

Ricardo Lizana
*Dept. of Electrical Engineering*
*Universidad Catolica de la Santisima Concepcion*
Concepcion, Chile
ricardolizana@ucsc.cl

Pedro Melin
*Dept. of Electrical and Electronic Engineering*
*Universidad del Bío-Bío*
Concepcion, Chile
pemelin@ubiobio.cl

Galina Mirzaeva
*School of Engineering*
*The University of Newcastle*
Callaghan, Australia
galina.mirzaeva@newcastle.edu.au

Marco Rivera
Dept. of Electrical Engineering
Universidad de Talca
Curicó, Talca
marcoriv@utalca.cl

Neil Sepulveda
*Dept. of Computer Science*
*Universidad Catolica de la Santisima Concepcion*
Concepcion, Chile
nsepulveda@magister.ucsc.cl

***Abstract*— Feedback Quantizer is a closed-loop modulation scheme with low harmonic content at low frequency and good tracking of the voltage reference at the fundamental frequency. In electrical systems where power converters and transformers interact, the modulation technique must be capable of not generating low-frequency harmonic components in order to avoid transformer saturation. This paper presents an alternative for applying FBQ using Space Vector Modulation to obtain higher accuracy in tracking the reference and improve the harmonic content of this technique at low sampling times. The simulated results show the fulfillment of the objectives satisfactorily.**

***Keywords—Voltage Source Inverter* (VSI)*, Feedback Quantizer* (FBQ)*, Space Vector Modulation* (SVM).**

## I. INTRODUCTION

AC/DC or DC/AC power conversion is now essential because of the new changes in the energy matrix and the global context of generating clean energy. Thanks to technological advances, researchers have created various converter topologies, modulation, and control schemes to meet the needs of each application [1]. These applications include AC motor drives, renewable energies, HVDC systems, and electromobility.

The power converters use a pulse width modulation (PWM) scheme for on/off power semiconductors devices. However, different modulation schemes have been implemented in the literature [2], and each focuses on different points of interest, such as switching frequency optimization, semiconductor losses, harmonic distortion, system response speed, or voltage reference tracking at the fundamental frequency.

In this paper, we work with the Feedback Quantizer (FBQ) modulation scheme as a basis, which is a closed-loop modulation scheme with good voltage reference tracking at the fundamental frequency and natural behavior of mitigating low-frequency harmonics obtained weighted harmonic distortions (WTHD) better than other modulation schemes [3][4]. Another advantage of this modulation scheme is its easy implementation of notch filters to the system [5][6] to improve the reference tracking or mitigation of some low-order harmonics that may be detrimental to electrical machines [7].

This technique, thanks to its low harmonic content at low frequency, can be applied to grid-connected systems or systems with transformers, thus avoiding transformer saturation and increasing the lifetime of this equipment [8][9][10].

The FBQ scheme and the predictive control method (MPC) do not have a fixed switching frequency, creating a harmonic spectrum dispersed in time [11]. Also, these techniques depend on a small sampling time to obtain good results, which leads to high switching frequencies [12] and associated losses.

There are works where space vectors have been used to optimize MPC control techniques, decreasing the iterations related to its cost function or replacing this function entirely with only one algorithm [13][14].

From the above, the proposal was born to implement the Space Vector Modulation scheme to the FBQ scheme in a two-level voltage source converter to improve the tracking of the voltage reference at the fundamental frequency and improve the harmonic content of this technique at low sampling times.

The structure of this document consists of the first instance with section II, which introduces the conventional FBQ modulation scheme, showing its mathematical development in detail. Then, in section III, the proposal of the SVM to FBQ modulation scheme is introduced. Section IV.

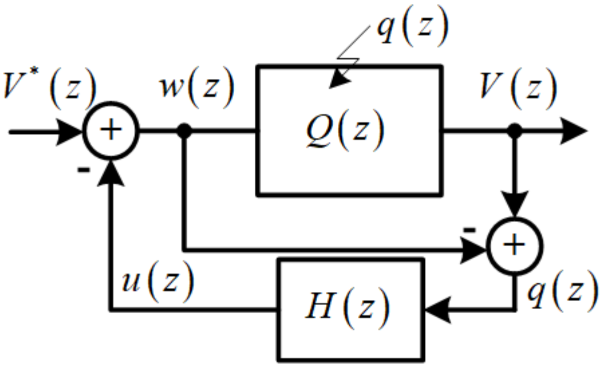


Fig. 1 Scheme Feedback Quantizer.

shows the results obtained by simulation and compares the conventional scheme with the proposed one in terms of harmonic distortion, switching frequency, voltage reference tracking at the fundamental frequency, and efficiency. Finally, in the last section V, we proceed to the conclusions of this work.

## II. CONVENTIONAL FEEDBACK QUANTIZER

A Feedback Quantizer is a closed-loop modulation scheme that allows the model of the system's quantized noise and obtains a low harmonic content at low frequencies [6]. Considering the scheme of this technique, Fig. 1, a perfect tracking of the reference can be theoretically obtained (1). In the given scheme, $V(z)$ the quantized output voltage $V^*(z)$ is the reference voltage, and $q(z)$ is the quantized noise of the system.

$$V(z) = V^*(z) + q(z) - q(z) = V^*(z) \tag{1}$$

The above is possible with an H($z$) = 1, but this is not possible due to causality properties; for this property to be fulfilled, the minimum H(z) to use is $H(z) = z^{-1}$ which is the optimal function to use since it provides ease of calculations and analysis of the system, compared to other possible functions [9]. Therefore, the scheme would be modeled as follows:

$$V(z) = V^*(z) + (1 - H(z))q(z) \tag{2}$$

Replacing $H(z) = z^{-1}$ in (2), we obtain:

$$V(z) = V^*(z) + \left(\frac{z-1}{z}\right)q(z) \tag{3}$$

From (2), we can obtain the quantized voltage sensitivity function:

$$S(z) = 1 - z^{-1} \tag{4}$$

For the analysis of the sensitivity system at the frequency plane, $z = e^{j\omega_n}$ the magnitude of the system can be obtained:

$$|1 - \mathrm{H}(e^{j\omega_n})| = \sqrt{2 - 2\cos(\omega_n)} \tag{5}$$

From the magnitude obtained in (5) and Fig. 2, we can observe the natural behavior of the FBQ system, where it tends to mitigate the low-frequency harmonics. In addition, it can be observed from (3) that having a zero at $z$ = 1, the system will not have DC components in the voltages produced by the converter.

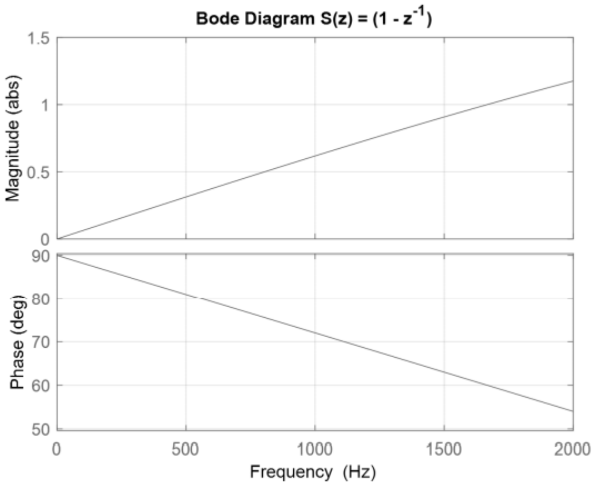


Fig. 2 Bode diagram $S(z) = 1 - z^{-1}$

Then, the quantizer Q($z$) is defined for choosing the optimal switching states by measuring the distances of the vectors associated with the reference and the measured vector. The distance between these is defined as:

$$D_i = \sqrt{\left(V_\alpha^* - V_{i\alpha}\right)^2 + \left(V_\beta^* - V_{i\beta}\right)^2} \tag{6}$$

Where $\left(V_\alpha^*, V_\beta^*\right)$ and $\left(V_{i\alpha}, V_{i\beta}\right)$ are the voltages in Clark coordinates of the reference and switching state at instant $i$. For example, a two-level voltage source inverter has eight valid switching states, in Fig. 3, which can be seen in detail in [3][6].

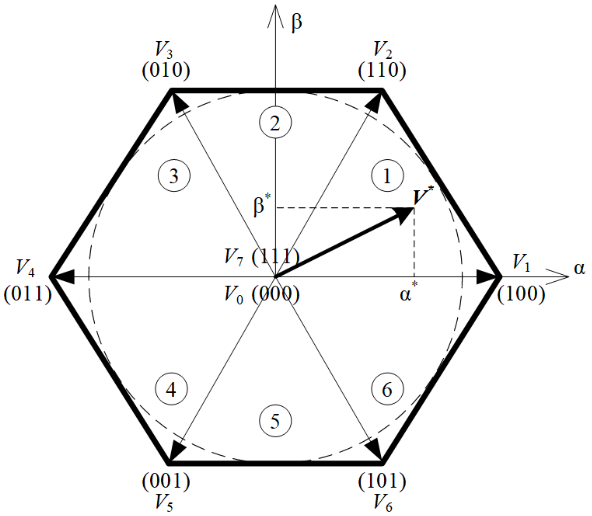


Fig. 3 Valid switching states, two-level converter.

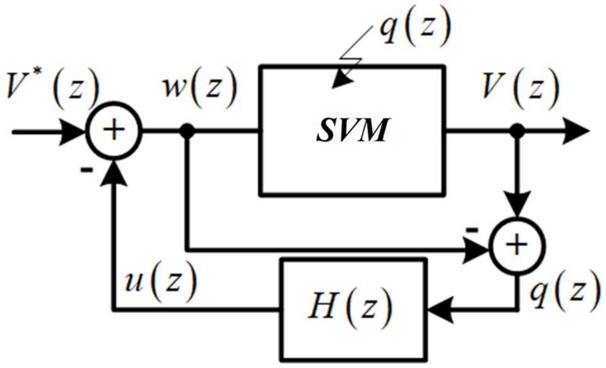


Fig. 4 Feedback Quantizer Scheme with Space Vector Modulation.

## III. PROPOSED FEEDBACK QUANTIZER WITH SPACE VECTOR MODULATION

The proposed scheme seeks to change the cost function (6) to the SVM modulation scheme, as shown in Fig. 4, to improve the tracking of the voltage reference at the fundamental frequency and obtain a decrease in the switching frequency of the system.

The operation FBQ scheme was explained in the previous chapter. Therefore, we now proceed to mention the steps followed in the SVM block.

First, the reference $V^*(z)$ is defined in the same way as the conventional method, which is obtained from the mathematical model of the converter, working in Clark coordinates and discretizing by the forward Euler method (7).

$$v_r^{\alpha\beta}(kT) = \left( i_s^{\alpha\beta}(kT+T) - i_s^{\alpha\beta}(kT)\left[1 - \frac{T_s R_L}{L_L}\right]\right)\frac{L_L}{T_s} \tag{7}$$

Then the SVM scheme's input is the voltage reference's subtraction with the quantized feedback noise $w(z)$. From the quantized voltage, the angle (8) and magnitude (9) are obtained to place them within the vector space of the optimal states of the inverter in Fig. 3.

Each sector is divided by 60°.

$$\theta = \arg\left(w^{\alpha\beta}(k)\right) \tag{8}$$

$$\| w^{\alpha\beta}(k) \| = \sqrt{w_\alpha^{\ 2} + w_\beta^{\ 2}} \tag{9}$$

Next, calculating the semiconductor activation times for the given sector i, $T_i$, $T_{i+1}$, and $T_0$, Fig. 6, with a sampling time of the SVM, $T_z$.

$$T_i = \frac{\sqrt{3}V_{ref}}{V_{dc}} T_z \sin\left(\frac{\pi}{3} - \phi\right) \tag{10}$$

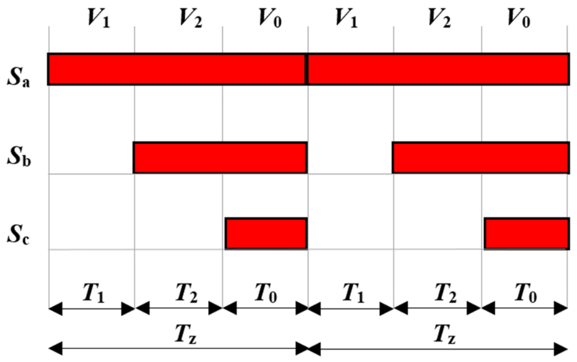


Fig. 5 Asymmetric Switching Sequence, Sector 1.

$$T_{i+1} = \frac{\sqrt{3}V_{ref}}{V_{dc}} T_z \sin(\phi) \tag{11}$$

$$T_0 = T_z - T_i - T_{i+1} \tag{12}$$

$$\phi = \theta - (\text{sector} - 1)\frac{\pi}{3} \tag{13}$$

Once the trigger times $T_i$, $T_{i+1}$, and $T_0$ have been obtained, the SVM switching sequence is chosen. In this case, an asymmetric sequence of three segments was chosen to reduce switching losses. The switching sequence is shown in Fig. 5.

## IV. STUDY CASE

### A. Simulated Results

The two-level voltage source inverter is simulated using PSIM 2020a®, with the parameters shown in TABLE I. Harmonic distortion indicators were calculated up to harmonic 51.

In the first instance, we have the simulation of the conventional FBQ scheme, Fig. 7(a) shows the voltage of phase "*a*" generated by the converter with its respective harmonic spectrum, where you can notice its dispersed behavior and mitigation of low order harmonics, due to the FBQ scheme. This is also reflected in the phase current shown in Fig. 7(b).

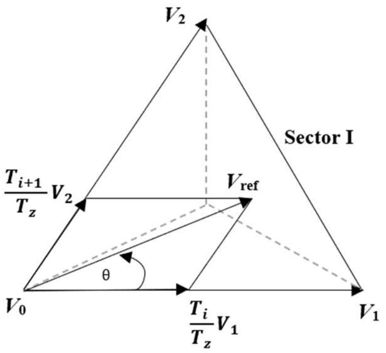
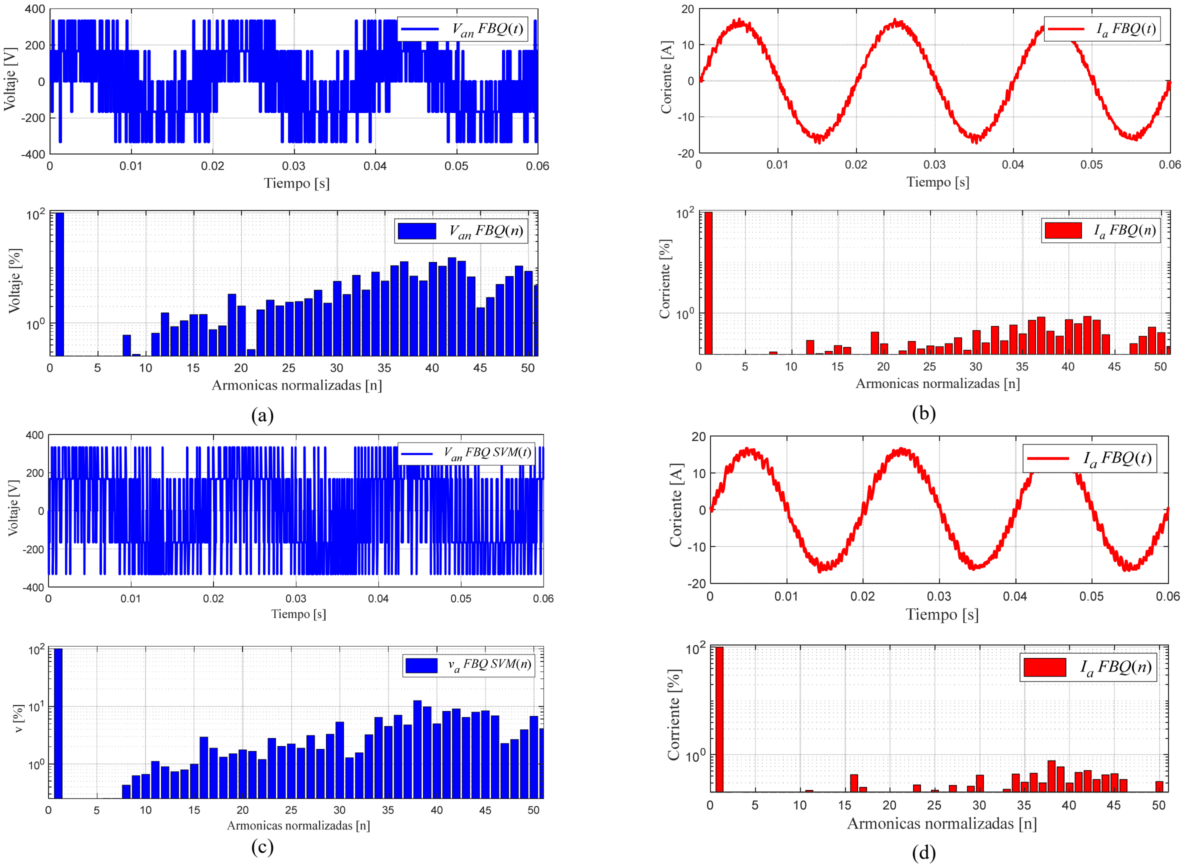


Fig. 6 $V_{ref}$ synthesized by Voltages Sector and Dwell Times, Sector 1.



(a) (b)

(c) (d)

Fig. 7. Simulated key results. (a) Phase "$a$" voltage of the Converter with FBQ. (b) Phase "$a$" current of the Converter with FBQ, (c) Phase "$a$" voltage of the Converter with FBQ-SVM, (d) Phase "$a$" current of the Converter with FBQ-SVM.

Then, Fig. 7(c) and 7(d) show the simulated voltage and current of the proposed scheme, FBQ-SVM, at 100[µS], where the behavior of the dispersed type harmonics and the low-order harmonics mitigation provided by the FBQ can be seen.

The summary of the results regarding harmonic distortion can be seen in Table II, where the proposed scheme has better harmonic content, analyzed for sampling times of 100[µS] and 200[µS]. This improvement can be seen in greater detail in the indicators obtained with a sampling time equal to 200[µS], thus achieving the objective of achieving a better harmonic behavior at a shorter sampling time since this technique depends on short sampling times to obtain a better performance.

TABLE I. SIMULATION PARAMETERS VSI

| **Symbol** | **Parameters** | |
|---|---|---|
| | ***Quantity*** | ***Value*** |
| $R_L$ | Load resistance | 10 [Ω] |
| $L_L$ | Load inductance | 15 [mH] |
| $V_{dc}$ | Voltage DC | 500 [V] |
| $T_s$ | Sampling time | 100/200 [µS] |
| $T_z$ | Sampling time SVM | 100/200 [µS] |
| $f$ | Network frequency | 50 [Hz] |

The voltage reference tracking at fundamental frequency was also analyzed, considering the fundamental component obtained from an SPWM modulation as a reference. The conventional FBQ scheme reflects excellent reference tracking with 99.5%, and the proposed scheme slightly improves it to 99.8%.

Finally, the average frequency of the techniques was analyzed, where we can observe in Table II that for both sampling times, the proposed scheme obtained an increase in the switching frequency of approximately 25% with respect to the conventional scheme.

## B. *Efficiency Analysis*

Semiconductor losses were considered and divided into switching and conduction losses for the efficiency analysis study. The semiconductors are nonlinear elements; therefore, we work with linear approximations obtained from the characteristic curves of the on and off processes and the diode dynamics, as in [15-17]. The

TABLE II. COMPARISON OF TECHNIQUES

| Indicator | Technique | | | |
|---|---|---|---|---|
| | **FBQ 100[μS]** | **FBQ SVM 100[μS]** | **FBQ 200[μS]** | **FBQ SVM 200[μS]** |
| THD $i_L^a$ [%] | 2.56 | 2.05 | 5.53 | 3.47 |
| THD $v_r^a$ [%] | 41.08 | 36.46 | 67.63 | 37.39 |
| WTHD $i_L^a$ [%] | 0.13 | 0.11 | 0.30 | 0.24 |
| WTHD $v_r^a$ [%] | 1.06 | 0.85 | 2.27 | 1.4 |
| Switching frequency [Hz] | 4566 | 5890 | 2230 | 3240 |
| Reference tracking [%] | 99.54 | 99.80 | 99.56 | 99.88 |
| Efficiency [%] | 94.1 | 93.4 | 95.4 | 95.1 |

parameters used for the efficiency calculation were considering the IGBT KM600GB126D semiconductor [18].

As these schemes depend on the sampling time of the system, it has a high switching frequency. This is reflected in the distribution of energy losses shown in Figure 8. For example, the efficiency obtained with the conventional scheme was 94.1% and 95.4%, while with the proposed scheme, an efficiency of 93.4% and 95.1% were obtained with a sampling time of 100[μS] and 200[μS], respectively as shown in Table II.

## V. CONCLUSIONS

An alternative form of the feedback quantizer modulation scheme has been presented, introducing the space vector modulation scheme, obtaining a slight improvement in the tracking of the voltage reference at the fundamental frequency and better performance at low sampling times with an increase of approximately 35% in the switching frequency. Finally, the efficiency obtained did not decrease more than 1% with respect to the efficiency of the conventional scheme.

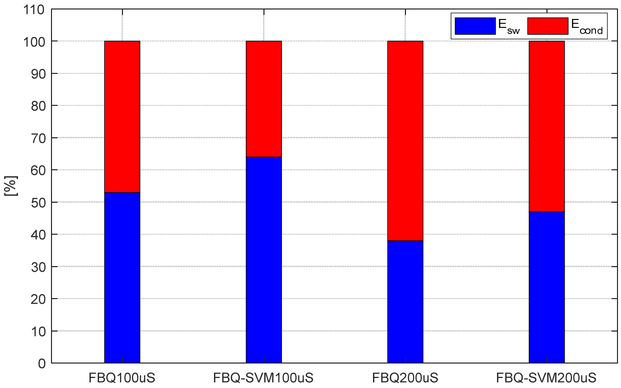


Fig.8 Semiconductor losses distribution.

## REFERENCES

[1] H. Akagi, "Multilevel Converters: Fundamental Circuits and Systems," in *Proceedings of the IEEE*, vol. 105, no. 11, pp. 2048-2065, Nov. 2017, doi: 10.1109/JPROC.2017.2682105.

[2] J. I. Leon, S. Vazquez and L. G. Franquelo, "Multilevel Converters: Control and Modulation Techniques for Their Operation and Industrial Applications," in *Proceedings of the IEEE*, vol. 105, no. 11, pp. 2066-2081, Nov. 2017, doi: 10.1109/JPROC.2017.2726583.

[3] Galina Mirzaeva; Graham Goodwin; "Introducing Feedback Quantizer – a Novel Pulse-Width Modulation Strategy for Voltage Source Inverters," *in Conf. Rec.* AUPEC 12, vol. 1, pp. 1 – 6, 2012.

[4] Galina Mirzaeva; Graham Goodwin; "The use of Feedback Quantizer PWM for shaping inverter noise spectrum," *in Conf. Rec.* EPE/PEMC 12, vol. 1, pp. DS3c.10-1 – DS3c10-7, 2012.

[5] G. Mirzaeva and G. Goodwin, "Advanced noise shaping and filter design with Feedback Quantizer PWM," 2013 *IEEE International Conference on Industrial Technology* (*ICIT*), Cape Town, 2013, pp. 469-474.

[6] M. Veillon *et al.*, "Feedback Quantizer and Non Linear Control Applied to Multi-Cell AFE Rectifier," *2021 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)*, 2021, pp. 1-6, doi: 10.1109/CHILECON54041.2021.9702974.

[7] H. Funato, C. Sasaki, Y. Chiku, and S. Ogasawara, "Analysis of loss of receiving transformer caused by harmonic current and voltage for loss reduction," *Proceedings of 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010*, 2010.

[8] J. A. C. Forrest and B. Allard, "Thermal problems caused by harmonic frequency leakage fluxes in three-phase, three-winding converter transformers," in *IEEE Transactions on Power Delivery*, vol. 19, no. 1, pp. 208-213, Jan. 2004, doi: 10.1109/TPWRD.2003.820223.

[9] O. A. Mohammed, N. Y. Abed, and S. Liu, "Investigation of the harmonic behavior of three phase transformer under nonsinusoidal operation using finite element and wavelet packets," in *IEEE Transactions on Magnetics*, vol. 42, no. 4, pp. 967-970, April 2006, doi: 10.1109/TMAG.2006.872467.

[10] J. Smajic, J. Hughes, T. Steinmetz, D. Pusch, W. Monig and M. Carlen, "Numerical Computation of Ohmic and Eddy-Current Winding Losses of Converter Transformers Including Higher Harmonics of Load Current," in *IEEE Transactions on Magnetics*, vol. 48, no. 2, pp. 827-830, Feb. 2012, doi: 10.1109/TMAG.2011.2171926.

[11] S. Kouro, P. Cortes, R. Vargas, U. Ammann, and J. Rodriguez, "Model Predictive Control—A Simple and Powerful Method to Control Power Converters," in *IEEE Transactions on Industrial Electronics*, vol. 56, no. 6, pp. 1826-1838, June 2009, doi: 10.1109/TIE.2008.2008349.

[12] J. Henríquez *et al.*, "A performance and efficiency comparison of an AFE rectifier with Finite Control Set – Model Predictive Control and Feedback Quantizer," *2021 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON)*, 2021, pp. 1-7, doi: 10.1109/CHILECON54041.2021.9702994.

[13] N. H. Saad, A. El Meged and A. M. A. Mahmoud, "Comparison of state space vector PWM schemes for a voltage source inverter," *2008 International Conference on Computer Engineering & Systems*, 2008, pp. 303-308, doi: 10.1109/ICCES.2008.4773017.

[14] J. J. Silva, J. R. Espinoza, J. A. Rohten, E. S. Pulido, F. A. Villarroel and M. L. Andreu, "A Novel Simplified Implementation of Finite-Set Model Predictive Control for Power Converters," in *IEEE Access*, vol. 9, pp. 96114-96124, 2021, doi: 10.1109/ACCESS.2021.3094864.

[15] E. Espinosa, P. Melín, C. Baier, J. Espinoza, and H. Garcés, "An Efficiency Analysis of 27-Level Single-Phase Asymmetric Inverter without Regeneration," Energies, vol. 14, no. 5, p. 1459, Mar. 2021, doi:10.3390/en14051459.

[16] A. D. Rajapakse, A. M. Gole and P. L. Wilson, "Electromagnetic transients simulation models for accurate representation of switching losses and thermal performance in power electronic systems," in *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 319-327, Jan. 2005, doi: 10.1109/TPWRD.2004.839726.

[17] S. Kouro, M. Perez, H. Robles, and J. Rodriguez, "Switching loss analysis of modulation methods used in cascaded H-bridge multilevel

converters," *2008 IEEE Power Electronics Specialists Conference*, 2008, pp. 4662-4668, doi: 10.1109/PESC.2008.4592703.

[18] https://www.semikron-danfoss.com/dl/service-support/downloads/download/semikron-datasheet-skm600ga126d-21915720.pdf