# MATLAB/Simulink modeling of electric motors operating with harmonics and unbalance

**Adrián Bolaño Martínez[1], Isaac Jiménez Navarro[1], Vladimir Sousa[2], Enrique Ciro Quispe[3], Pablo Donolo[4]**
[1]Electrical Engineering Program, Universidad de la Costa, Barranquilla, Colombia
[2]Energy Department, Universidad de la Costa, Barranquilla, Colombia
[3]Grupo de Investigación en Energías, Energy and Mechanical Department, Universidad Autónoma de Occidente, Cali, Colombia
[4]Grupo de Electrónica Aplicada, Instituto de Investigación en Tecnologías Energéticas y Materiales Avanzados, Universidad Nacional de Río Cuarto-CONICET, Río Cuarto, Argentina

**Article Info**

***Article history:***

Received Oct 8, 2021
Revised May 21, 2022
Accepted Jun 5, 2022

***Keywords:***

Electric motor
Energy efficiency
Modeling
Power quality
Sequence components

**ABSTRACT**

This paper aims to present a simulation model for the analysis of the operational characteristics of electric motors (EMs). The model was developed on the Simulink platform of the MATLAB program and allows analysis in supply conditions with harmonics and voltage unbalance. The contribution of the model is that it considers the mechanical losses and provides for the study of the effect of each component of the electrical sequence of the harmonics and the voltage unbalance on the electromechanical characteristics of the EM. The model developed was tested in a 37.3 kW EM, operating under four power supply conditions: balanced sinusoidal voltages, balanced non-sinusoidal voltages (i.e., harmonics), unbalanced sinusoidal voltages, and non-sinusoidal unbalanced voltages. The results showed that under the conditions of harmonics and unbalance, the efficiency was reduced by 2%, respectively and that with the combined effects, the efficiency decreased by 4%. The results made it possible to quantify, from the current, voltage, and electrical power values of each sequence, the adverse effects caused by voltage unbalance and harmonics.



***Corresponding Author:***

Vladimir Sousa Santos
Energy Department, Universidad de la Costa
Calle 58 No.55-66, Barranquilla, Colombia
Email: vsousa1@cuc.edu.co.

## 1. INTRODUCTION

Analysis of the influence of power quality on the operation of electric motors (EMs) is essential due to their wide use. On average, EMs consume approximately 53% of global electricity consumption and between 60-70% of electricity consumption in the industrial sector, representing 5.5 Gton of $CO_{2eq}$ emissions [1]–[3]. The EMs, since their creation in 1888 by Nikola Tesla, has been designed to operate with balanced sinusoidal voltages close to their nominal value; therefore, any deviation from the nominal voltage can cause problems in its operation [4]–[6]

The most common steady-state power quality problems in distribution systems are voltage deviation, voltage unbalance, and harmonics. The voltage deviation is mainly produced by variations in the load and the incorrect selection of the connection point of the transformer (TAP) [7]. Unstable or unbalanced supply sources cause voltage unbalance, transformers connected in asymmetric banks, or the significant presence of single-phase loads [8], [9]. On the other hand, the presence of harmonics has increased significantly in industries due to the widespread use of electronic devices such as frequency inverters, static starters, and other power converters [10]–[12]. These power quality issues significantly affect the operational behavior of the EMs [13], [14].

Due to the energetic importance of EMs, it is crucial to develop simulation models that allow analyzing the effects of power quality on electrical and mechanical parameters and the efficiency of EMs [15]. Some studies that develop simulation models for the analysis of EMs. In study [16], a model developed on the Simulink platform of the MATLAB program (MATLAB/Simulink) is presented that allowed the simulation of different tests such as the generation of voltage variation by eliminating large loads, the use of three-phase nonlinear loads to simulate harmonics in the load side and capacitor bank switching, among other network disturbances. In this study, only an analysis of the detection of the signals in the network is made, and the effect of the disturbances on the efficiency of the EM is not emphasized.

In study [17], a simulation model is shown in MATLAB/Simulink to compare the effect of harmonics produced by multi-pulse converters (6, 12, and 24 pulses), using the total harmonic distortion (THD) as a comparative parameter. This article demonstrates how multiple pulse converters can improve power quality in the network by reducing harmonics. The effect of harmonics on EM efficiency is not analyzed in this study.

In study [18], a permanent magnet brushless direct current EM (PMBLDC) model is designed that allows its performance to be monitored in a steady and transient state. The model developed in MATLAB/Simulink provides for the analysis of various electromechanical characteristics of the EM when the speed varies at a constant mechanical load. The efficiency of the PMBLDC EM is not analyzed in this study.

In study [19], a generalized dq axis model is developed in MATLAB/Simulink for a multiphase induction EM (5, 6, 7, 9, and 12 phases). The study performs the simulation for different load conditions, including the transient response analysis. This simulation model uses a set of blocks from the empower system of the MATLAB/Simulink software and focuses on models for non-conventional multiphase EMs, limiting the use of conventional EMs. The study does not analyze the efficiency of the EM, or the effects of harmonics and voltage unbalance.

In study [20], a system is developed using a graphical user interface of MATLAB to monitor and control three-phase induction EMs. The model uses EM data such as phase currents, phase voltages, active power, reactive power, temperature, speed, and power factor. The model allows to run the parameters of the induction EMs remotely, and if any fault occurs, the induction EM can be switched on/off at any time. While the model allows real-time monitoring of EM parameters to correct defects, it does not evaluate the efficiency or the effects of power quality problems.

In study [21], the effects of unbalanced voltage supply on induction EM current and torque are evaluated using a simulation model. For this, 16 cases of voltage unbalance are selected (8 types of voltage unbalance and two voltage unbalance factors (VUF)). The model focuses only on the voltage unbalance, without considering other problems such as harmonics.

In the present work, a model developed in MATLAB/Simulink [22] platform is proposed to analyze the operation of induction EMs when powered from sources with harmonics and voltage unbalance. The contribution of the model is that, in this case, the mechanical losses are considered, the effect of harmonics with the voltage unbalance is analyzed, and the impact of each sequence component on the electromechanical characteristics of the EM can be evaluated. The article is organized as follows. In section 2, the methodology is presented by describing each block of the model, the topology, the component data, the equations, and the characteristics of the applied scenarios. In section 3, the results are analyzed by comparing the performance of the efficiency obtained in each scenario and other parameters such as speed, torque, mechanical power, electrical power, and other parameters.

## 2. METHOD

### 2.1. Description of the model developed in MATLAB

The model developed for evaluating the effect of power quality on EMs was created on the MATLAB/Simulink [22]. The model is composed of blocks for power supply, EMs, measurement of electrical and mechanical parameters, and data and graph displays. In Figure 1, the general block diagram of the simulation model is shown that allows for determining the following parameters of EMs: electrical power, mechanical power, power factor, torque, speed, and efficiency. Each block of Figure 1 is described in sections 2.1.1, 2.1.2, and 2.1.3.

#### 2.1.1. Power supply block

The power supply block shown in Figure 2 comprises the adjustable power source that includes a harmonic signal generator, the EM with torque control, conductors, and electrical and mechanical measurement instruments. Table 1 shows the data of the supply source, including the nominal data, the harmonic signals generated, and the resistance to induce unbalance per phase. Harmonic voltages were programmed with the same phase angle (i.e., 0 degrees). Table 2 shows the data of the analyzed EM.

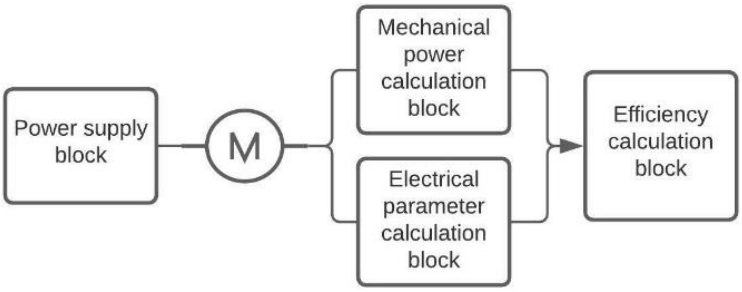



Figure 1. Simulation block diagram

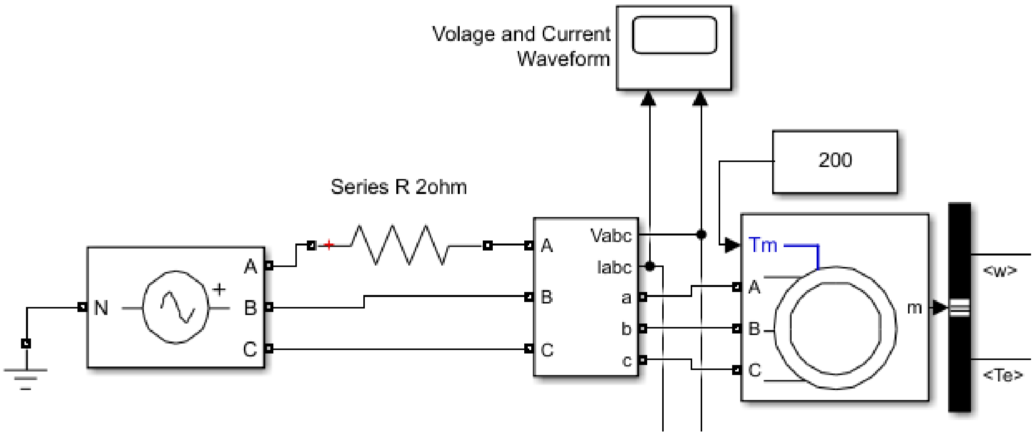



Figure 2. Power supply block

Table 1. Power supply data

| Power supply data for each condition | | | |
|---|---|---|---|
| Nominal condition | | | |
| Line RMS Voltage (V) | Phase | Freq (Hz) | |
| 460 | -30 | 60 | |
| Harmonics conditions | | | |
| Order | Amp (p.u) | Phase | Seq |
| 5 | 0.15 | 0 | 2 |
| 7 | 0.14 | 0 | 1 |
| Unbalance condition | | | |
| Resistors in phase A (2Ω) | | | |

Note: Freq is the frequency (Hz), seq is the sequence, Amp is the amplitude of the signal (p.u)

Table 2. Specifications of sample motor

| $P_{out}$ (kW) | Volt (V) | Speed (rpm) | Poles (No.) | Rs (Ω) | Lls (H) |
|---|---|---|---|---|---|
| 37.3 | 460 | 1780 | 4 | 0.09961 | 0.000867 |
| Rr’ (Ω) | Llr’ (H) | Lm (H) | F (Nms) | J (kgm²) | Torq (Nm) |
| 0.05837 | 0.000867 | 0.03039 | 0.02187 | 0.4 | 200 |

Where: $P_{out}$ is the mechanical output power (kW), Volt is the terminal voltage (V), Rs is the stator resistance (Ω), Lls is the stator leakage inductance (H), Lm is the magnetizing inductance (H), Rr is the rotor resistance (Ω), Llr is the rotor leakage inductance (H), F is the friction (Nms), J is the moment of inertia (kgm$^2$), and Torq is the load torque (Nm).

### 2.1.2. Mechanical power calculation block

Figure 3 shows the block diagram for calculating the mechanical power. The simulation model equations are described in (1)-(5). From the angular velocity (ω) and torque (T_ag) parameters obtained from the multiple output bus to the EM, the mechanical power can be calculated.

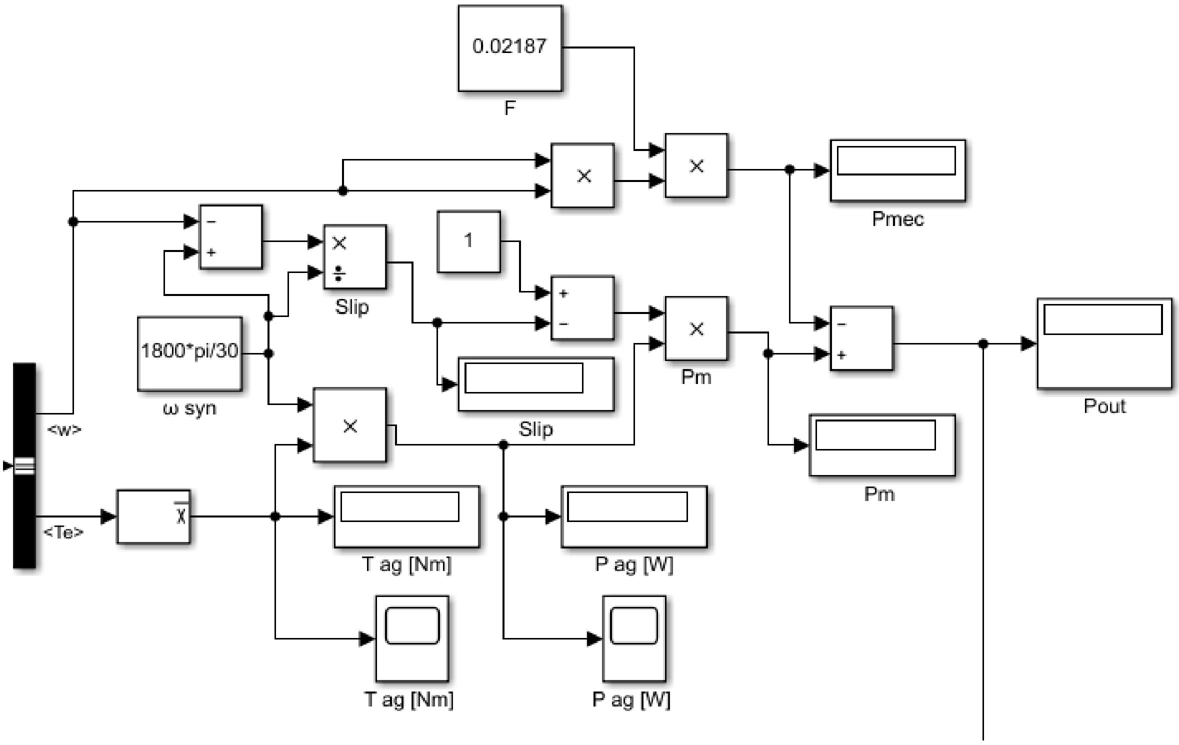



Figure 3. Block diagram for the calculation of mechanical parameters

Motor slip is calculated as (1). The air gap power is calculated with (2) [23]. The developed mechanical power is calculated with (3). The mechanical losses are calculated with (4) [24] and the mechanical output power is obtained with (5) [23].

$$\mathbf{s} = \frac{\omega_{syn} - \omega}{\omega_{syn}} \quad (1)$$

Where: $s$ is the slip, $\omega_{syn}$ is the synchronous speed (rad/s), and ω is the supply frequency (rad/s).

$$P_{ag} = T_{ag} \cdot \omega_{syn} \quad (2)$$

Where: $P_{ag}$ is the air gap power in (kW) and $T_{ag}$ is air gap torque in (Nm).

$$P_m = (1 - s) \cdot P_{ag} \quad (3)$$

Where: $P_m$ is developed mechanical power in (kW).

$$P_{mec} = \omega^2 \cdot F \quad (4)$$

Where $P_{mec}$ is mechanical losses in (kW), ω is the supply frequency (rad/s), and F is the coefficient of friction.

$$P_{out} = P_m - P_{mec} \quad (5)$$

### 2.1.3. Block of electrical parameter measurements for each harmonic sequence component

Figure 4 shows the block diagram that allows obtaining the electrical power for each phase sequence. In the block diagram, sequence analyzers are used that allow decomposing the waveform of the voltage and current of the power supply into the magnitudes and angles of each harmonic of its sequence or the opposite sequence. In this case, the sequence analyzers were programmed to filter the signals of the proper and opposite sequence of the fundamental component and the 5th and 7th order harmonics. The signal of the opposite sequence is helpful in the case of a power supply with harmonics and voltage unbalance.

The results obtained by each sequence analyzer are processed by multiplication blocks that allow the electrical and apparent power to be calculated. To find the total electrical and apparent power consumed by the motor, all the electrical and apparent powers of the fundamental component and each harmonic are added using a block according to (6) and (7) [25], [26]:

$$P_{apar.} = \sum \sqrt{3} \cdot V_k \cdot I_k \quad (6)$$

$$P_{elec.} = \sum \sqrt{3} \cdot V_k \cdot I_k \cdot \cos\theta \quad (7)$$

where $V_k$ is the voltage for each harmonic order (V), $I_k$ is the current for each harmonic order (A) and $\theta$ is the phase angle.

A division block divides the total electrical power over the total apparent power to obtain the power factor, according to (8):

$$fp = \frac{P_{elec.}}{P_{aper.}} \quad (8)$$

where *fp* is the power factor. Figure 5 shows the block diagram that calculates electrical power, apparent power, and power factor. Figure 6 shows the diagram for calculating efficiency. The efficiency is calculated by applying (9) [23].

$$\eta = \frac{P_{out.}}{P_{elec.}} . 100 \quad (9)$$

where $\eta$ is the motor efficiency in (%).

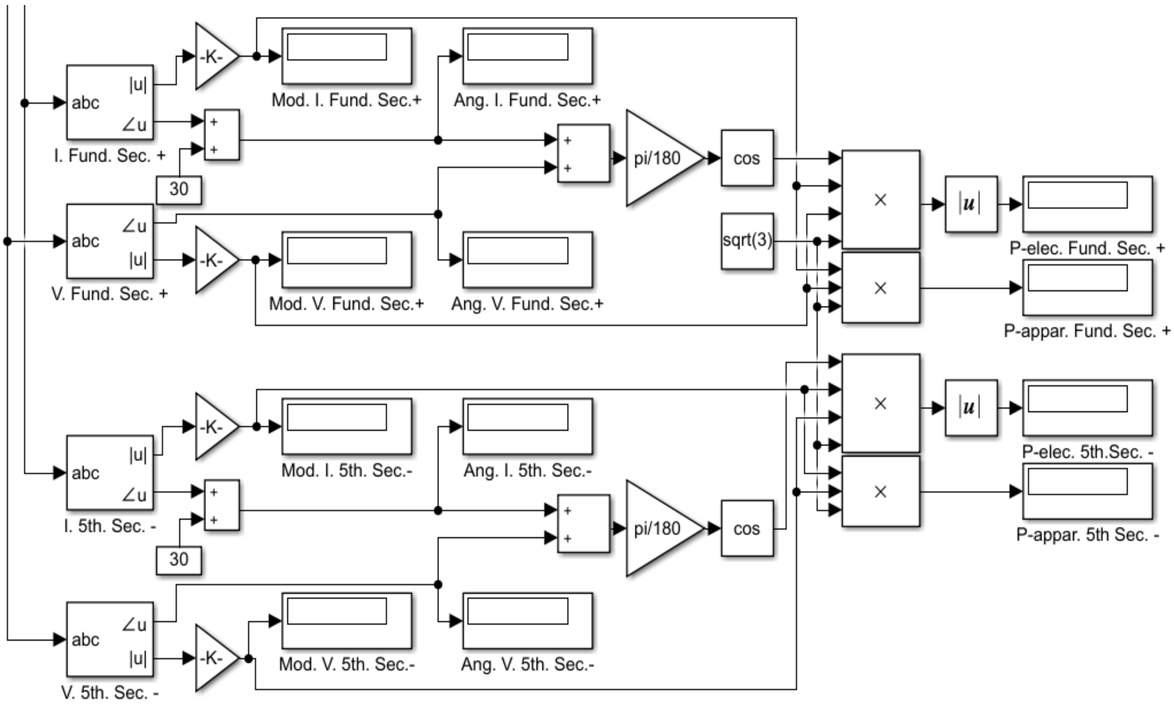



Figure 5. Block diagram for the calculation of electrical parameters

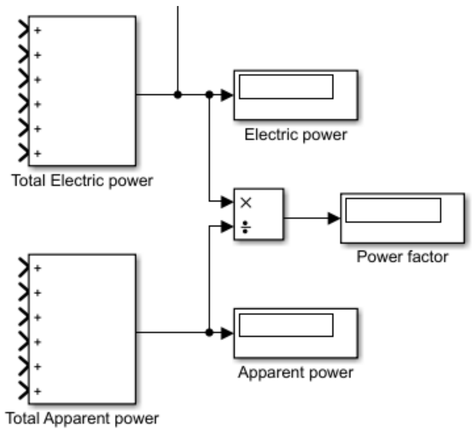



Figure 6. Block diagram for calculating electric power, apparent power, and power factor

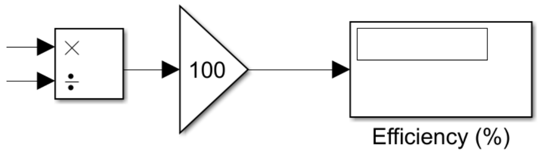



Figure 7. Block diagram for the calculation of efficiency

### 2.2. Description of the analyzed conditions

With the developed model, the efficiency of the EM under study was analyzed in the following four power supply conditions. In condition 1, the electrical supply is at nominal voltage without harmonics or unbalance between phases. In condition 2, the EM is supplied with balanced three-phase voltages with harmonics of order 5 with a magnitude of 15% of the fundamental voltage and harmonics of order 7 with a magnitude of 14% of the fundamental voltage. In condition 3, the EM is fed with a sine wave with no harmonics, with a 2 Ohm resistor in series to one of the phases to induce the unbalanced voltage. In condition 4 the EM is fed with conditions 2 and 3 simultaneously.

## 3. RESULTS AND DISCUSSION

Table 3 shows the electrical parameters of power, voltage and current for the four conditions. Table 4 shows the results of the electrical, mechanical and efficiency parameters of the EM for the four conditions. In Table 3 the parameters of own and opposite sequence are represented.

Table 3. Electric parameters for all conditions

| Parameters | Cond. 1 (Nom.) | Cond. 2 (Harm.) | Cond. 3 (Umb.) | Cond 4 (Harm. Umb.) |
|---|---|---|---|---|
| V1 sec (+) (V) | 460 | 460 | 414.8 | 415.2 |
| V1 sec (-) (V) | - | - | 46.26 | 45.05 |
| I1 sec (+) (A) | 56.94 | 56.94 | 62.55 | 62.57 |
| I1 sec (-) (A) | - | - | 40.85 | 40.68 |
| P1 sec. (+) (kW) | 39.48 | 39.5 | 39.19 | 39.15 |
| P1 sec. (-) (kW) | - | - | 1.38 | 1.23 |
| V5$^{th}$ sec (+) (V) | - | - | - | 14.16 |
| V5$^{th}$ sec (-) (V) | - | 69.04 | - | 65.14 |
| I5$^{th}$ sec (+) (A) | - | - | - | 2.45 |
| I5$^{th}$ sec (-) (A) | - | 12.36 | - | 12.02 |
| P5$^{th}$ sec. (+) (kW) | - | - | - | 0.046 |
| P5$^{th}$ sec. (-) (kW) | - | 0.0658 | - | 0.471 |
| V7$^{th}$ sec (+) (V) | - | 64.4 | - | 64.33 |
| V7$^{th}$ sec (-) (V) | - | - | - | 3.314 |
| I7$^{th}$ sec (+) (A) | - | 8.23 | - | 7.803 |
| I7$^{th}$ sec (-) (A) | - | - | - | 1.44 |
| P7$^{th}$ sec. (+) (kW) | - | 0.879 | - | 0.661 |
| P7$^{th}$ sec. (-) (kW) | - | - | - | 0.00358 |

Table 4. Results data for all conditions

| Parameters | Cond. 1 (Nom.) | Cond. 2 (Harm.) | Cond. 3 (Umb.) | Cond 4 (Harm. Umb.) |
|---|---|---|---|---|
| Electric power (kW) | 39.48 | 40.437 | 40.58 | 41.57 |
| Power Factor (p.u) | 0.87 | 0.85 | 0.84 | 0.82 |
| Torque (Nm) | 200.23 | 200.27 | 202.10 | 201.97 |
| Speed (rpm) | 1779 | 1779 | 1770 | 1771 |
| Mechanical power (kW) | 37.302 | 37.31 | 37.46 | 37.457 |
| Efficiency (%) | 94.47 | 92.27 | 92.32 | 90.11 |

In the first condition analyzed, it can be observed that the EM works with the highest efficiency (94.47%) since it is powered by balanced and sinusoidal nominal voltages. In the second condition, a considerable increase in the electrical power of the EM is observed due to the presence of harmonics of the fifth and seventh order. The reduction in power factor due to the increase in apparent power can also be observed. In the third condition, the effects of the voltage unbalance in the EM are evidenced, which causes the creation of two rotating fields in the air gap, a magnetic field flux in direct sequence and another that opposes it, causing the EM to increase in current, electrical power and consequently a reduction of the efficiency. In the fourth condition, with unbalance and harmonics, it is evident that the electrical power concerning the aforementioned conditions will increase much more. In the same way, the lower value (90.11%) of efficiency and the power factor is shown.

With these results, it can be shown that the EM parameters most affected when poor power quality occurs electrical power, power factor, and EM efficiency. The affectation is because the EM will always try to supply the mechanical power required by the load. In turn, it must counteract the opposite electromagnetic field produced by harmonics and voltage unbalance.

In summary, it was observed that under harmonic and unbalance conditions, the efficiency decreased by 2%, respectively, and that with the combined effects, the efficiency decreased by 4%. The results allowed quantifying that in condition 2, the summation of the electrical power produced by the harmonics was 945 W. In condition 3, the summation of the negative sequence electrical power produced by the voltage unbalance was 1,380 W. In condition 4, the consumption of 2411.5 W is shown by combining harmonics and voltage unbalance. These consumptions are lost because of power quality problems and are essential information for the energy quantification of these problems and evaluating technical measures for their mitigation.

## 4. CONCLUSION

The high incidence in the energy consumption of electric EMs reinforces the importance of developing tools that allow the analysis of their energy efficiency. On the other hand, the new changes in the electrical power systems, where the use of electronic equipment is increasing, together with the unbalance of the loads, increase the problems of harmonics and voltage unbalance in the electrical networks. Considering that these problems affect the operation of electric EMs, in this work, a simulation model was presented in MATLAB that allows the analysis of the operational characteristics of this equipment in various conditions of electrical power supply.

Unlike other simulation models presented in the scientific literature, this model considers mechanical losses and allows for the analysis of the effect of each electrical sequence component on the electromechanical characteristics of the EM. As a result of implementing the model in four electrical power supply conditions, it was possible to quantify the losses caused by harmonics and voltage unbalance and the reduction in efficiency caused by these problems in a 37.3 kW EM. In this case, an efficiency reduction of 2% was observed, caused by the increase in losses due to harmonics and voltage unbalance, and a 4% decrease in efficiency due to the combined effect of the two problems-power quality. The simulation model developed is essential as a tool for electromagnetic analysis of the operation of large electric EMs in different operating conditions, which can hardly be evaluated in real working conditions.

## REFERENCES

[1] M. J. S. Zuberi, A. Tijdink, and M. K. Patel, "Techno-economic analysis of energy efficiency improvement in electric motor driven systems in Swiss industry," *Applied Energy*, vol. 205, pp. 85–104, Nov. 2017, doi: 10.1016/j.apenergy.2017.07.121.

[2] K. He and L. Wang, "A review of energy use and energy-efficient technologies for the iron and steel industry," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 1022–1039, Apr. 2017, doi: 10.1016/j.rser.2016.12.007.

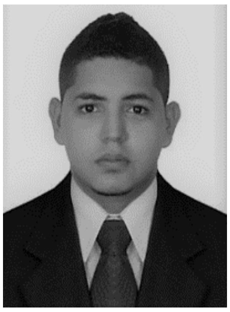
[3] J. R. Gómez *et al.*, "Assessment criteria of the feasibility of replacement standard efficiency electric motors with high-efficiency motors," *Energy*, vol. 239, Jan. 2022, doi: 10.1016/j.energy.2021.121877.

[4] P. R. Viego, J. R. Gómez, V. Sousa, J. P. M. Yanes, and E. C. Quispe, "Reducing torque pulsations in PMa-SynRM: a way for

improving motor performance," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 12, no. 1, pp. 67–79, Mar. 2021, doi: 10.11591/ijpeds.v12.i1.pp67-79.
[5] J. M. Tabora, M. E. de L. Tostes, E. O. de Matos, T. M. Soares, and U. H. Bezerra, "Voltage harmonic impacts on electric motors: a comparison between IE2, IE3 and IE4 induction motor classes," *Energies*, vol. 13, no. 13, Jun. 2020, doi: 10.3390/en13133333.
[6] A. Trianni, E. Cagno, and D. Accordini, "A review of energy efficiency measures within electric motors systems," *Energy Procedia*, vol. 158, pp. 3346–3351, Feb. 2019, doi: 10.1016/j.egypro.2019.01.964.
[7] Institute of Electrical and Electronics Engineers, *IEEE Std 1159 - IEEE recommended practice for monitoring electric power quality*. 2009.
[8] F. J. T. E. Ferreira, J. Alberto, and A. T. de Almeida, "Voltage unbalance impact on coil-side temperature rise in a delta-connected, dual-winding induction motor," in *2020 IEEE International Conference on Industrial Technology (ICIT)*, Feb. 2020, vol. 2020-Feb, pp. 925–930, doi: 10.1109/ICIT45562.2020.9067201.
[9] D. Wang, X. Yuan, and M. Zhang, "Power-balancing based induction machine model for power system dynamic analysis in electromechanical timescale," *Energies*, vol. 11, no. 2, Feb. 2018, doi: 10.3390/en11020438.
[10] M. D. Faraby, O. Penangsang, R. S. Wibowo, and A. Fitriati, "Coordinated planning in improving power quality considering the use of nonlinear load in radial distribution system," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 11, no. 6, pp. 4610–4621, Dec. 2021, doi: 10.11591/ijece.v11i6.pp4610-4621.
[11] IEEE, "Recommended practices and requirements for harmonic control in electrical power systems," *IEEE Std 519-1992*, vol. 1992. pp. 1–101, 1992, doi: 10.1109/IEEESTD.1993.114370.
[12] F. E. Hoyos Velasco, J. E. Candelo, and J. I. Silva Ortega, "Performance evaluation of a DC-AC inverter controlled with ZAD-FPIC," *INGE CUC*, vol. 14, no. 1, pp. 9–18, Jan. 2018, doi: 10.17981/ingecuc.14.1.2018.01.
[13] A. G. Siraki and P. Pillay, "An in situ efficiency estimation technique for induction machines working with unbalanced supplies," *IEEE Transactions on Energy Conversion*, vol. 27, no. 1, pp. 85–95, Mar. 2012, doi: 10.1109/TEC.2011.2168563.
[14] P. Phumiphak and C. Chat-uthai, "Nonintrusive method for estimating field efficiency of inverter- fed induction motor using measured values," in *2008 IEEE International Conference on Sustainable Energy Technologies*, Nov. 2008, pp. 580–583, doi: 10.1109/ICSET.2008.4747074.
[15] L. C. Solar, A. A. C. Montiel, M. V. Llanes, V. S. Santos, and A. C. Colina, "A new exact equivalent circuit of the medium voltage three-phase induction motor," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 6, pp. 6164–6171, Dec. 2020, doi: 10.11591/ijece.v10i6.pp6164-6171.
[16] P. V. Dhote, B. T. Deshmukh, and B. E. Kushare, "Generation of power quality disturbances using MATLAB-Simulink," in *2015 International Conference on Computation of Power, Energy, Information and Communication (ICCPEIC)*, Apr. 2015, pp. 301–0305, doi: 10.1109/ICCPEIC.2015.7259479.
[17] A. Panchbhai, S. Parmar, and C. Vaghasiya, "THD comparison for power quality (MATLAB simulation and hardware)," in *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Jul. 2016, pp. 1–4, doi: 10.1109/ICPEICES.2016.7853339.
[18] M. J. A. Hasan and P. C. Biswas, "Design and evaluation of a MATLAB Simulink block of permanent magnet brushless DC motor," in *2019 5th International Conference on Advances in Electrical Engineering (ICAEE)*, Sep. 2019, pp. 789–794, doi: 10.1109/ICAEE48663.2019.8975476.
[19] G. Renukadevi and K. Rajambal, "Generalized model of multi-phase induction motor drive using MATLAB/simulink," in *ISGT2011-India*, Dec. 2011, pp. 114–119, doi: 10.1109/ISET-India.2011.6145366.
[20] V. C. Khairnar and K. Sandeep K, "Induction motor parameter monitoring system using ZigBee protocol MATLAB GUI : automated monitoring system," in *2018 Fourth International Conference on Advances in Electrical, Electronics, Information, Communication and Bio-Informatics (AEEICB)*, Feb. 2018, pp. 1–6, doi: 10.1109/AEEICB.2018.8480992.
[21] R. N. Dash, S. Sahu, and C. K. Panigrahi, "Effect and analysis of unbalanced voltage on induction motor torque," in *2018 International Conference on Recent Innovations in Electrical, Electronics and Communication Engineering (ICRIEECE)*, Jul. 2018, pp. 2698–2703, doi: 10.1109/ICRIEECE44171.2018.9009287.
[22] MathWorks, "MATLAB. (R2019a)," *Mathworks*. https://la.mathworks.com/products/new_products/release2019a.html (accessed Dec. 01, 2021).
[23] S. J. Chapman, *Electric machinery fundamentals*, 5th ed. New York: McGraw-Hill Education, 2012.
[24] H. G. Beleiu, V. Maier, S. G. Pavel, I. Birou, C. S. Pică, and P. C. Dărab, "Harmonics consequences on drive systems with induction motor," *Applied Sciences*, vol. 10, no. 4, Feb. 2020, doi: 10.3390/app10041528.
[25] E. de Graaff and A. Kolmos, "Challenging models and perspectives of problem-based learning," in *Management of Change*, BRILL, 2007, pp. 9–29.
[26] J. Grainge and W. Stevenson, *Power system analysis*. New York: McGraw Hill, 1994.

## BIOGRAPHY OF AUTHORS

**Adrián Bolaño Martínez** was born in Barranquilla, Colombia, on December 15, 1998. Currently a 10th semester student of Electrical Engineering from the Universidad de la Costa, Colombia. His areas of interest are electrical installation design, industrial maintenance, and final use of energy. He can be contacted at email: abolano16@cuc.edu.co.



**Isaac Jimenez Navarro** was born in Barranquilla, Colombia, on January 4, 1997. Active student of Electrical Engineering at the Universidad de la Costa. He has worked in industrial electromechanical maintenance, electric motor maintenance. He has also worked in the design of electrical panels. His area of interest includes electrical machines, generation, and transmission of electrical energy. He can be contacted at email: ijimenez13@cuc.edu.co.

**Vladimir Sousa Santos** was born in Cienfuegos, Cuba, on November 21, 1980. Received a B.Sc. in Electrical Engineering from the Universidad Central de Las Villas, Cuba in 2004. M.Sc. in Energy Efficiency from Universidad Cienfuegos, Cuba in 2004. PhD. in Electrical Engineering from Universidad Central de Las Villas, Cuba, in 2014. He has published articles on induction motors, power quality and energy efficiency in high impact journals indexed in Scopus and Web of Science. His area of interest includes electric machines, power quality, and energy efficiency. He can be contacted at email: vsousa1@cuc.edu.co

**Enrique Ciro Quispe** was born in Lima, Perú, on January 20, 1956. He received the B.Sc. in Electrical Engineering from the Universidad Nacional de Ingeniería, Perú in 1980. M.Sc. in Electrical Engineering, M. Eng. in Industrial Automation and Ph.D. in Electrical Engineering from Universidad del Valle, Colombia in 1994, 1997 and 2011, respectively. Since 1992, he has been with Universidad Autónoma de Occidente, Cali, Colombia, where he is currently Full Professor in the Department of Energy and Mechanics and the Director of the Energy Research Group. His current research interests include the analysis of electrical machines and drives, power quality and management and energy efficiency. He is an IEEE Senior Member. He can be contacted at email: ecquispe@uao.edu.co.

**Pablo Daniel Donolo** was born in Rio Cuarto, Argentina, on March 31, 1982. Received his Electrical Engineering degree (2006), his MS degree in Engineering Sciences (2013), and his Doctorate in Engineering Sciences (2014) from Universidad Nacional de Río Cuarto, Argentina. In 2005, he joined the Grupo de Electrónica Aplicada, Universidad Nacional de Río Cuarto. He is currently First Assistant at Universidad Nacional de Río Cuarto and Assistant Researcher at Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina. His research interests include energy efficiency, power quality and fault diagnosis on electric machines. He can be contacted at email: pdonolo@ing.unrc.edu.ar.