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Evaluation of the energy saving potential in electric motors applying a load-based voltage control method

Vladimir Sousa Santos [a,*], Juan J. Cabello Eras [b], Mario J. Cabello Ulloa [c]

[a] Department of Energy, Universidad de la Costa, Barranquilla, Colombia
[b] Mechanical Engineering, Faculty of Engineering, Universidad de Córdoba, Montería, Colombia
[c] IK4-IKERLAN Technology Research Centre, Gipuzkoa, Spain

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ABSTRACT

This paper studies the viability of energy savings in electric motors by adjusting the voltage according to load in motors that operate under significant load variations during their work cycles. The laboratory test program used a 1.1 kW electric motor to compare its measured efficiency operating without voltage control with the load-based voltage control method results. A neural network was developed, and a time series generator was used to model the motor and estimate the results of applying the method in its useful life in the load behavior of three operating regimes. The results show an energy saving potential of 2 %–5.2 % using the load-based voltage control method in motors operating with a load factor of less than 40 % during the simulated motor life cycle for the three operating regimes. Also, the economic feasibility of implementing the load-based voltage control method was evaluated on three industrial electric motors. Results indicated potential annual savings between $1227 and USD 1,549, with a projected investment payback period of less than three and a half years.

1. Introduction

Electric motors (EMs) have a high energy impact, representing between 43 % and 46 % of electrical energy consumption and 13 % of global CO_2 emissions [1]. In the industrial sector (IS), EMs consume between 60 and 70 % of electricity [2]. On the other hand, the potential to improve the energy efficiency of EMs is estimated between 20 % and 30 %, which could reduce global electricity consumption by approximately 10 % [3].

The main strategies to reduce electricity consumption in EMs are improving their technology to increase efficiency [4], mitigating power quality problems in electricity supply networks [5], using energy regeneration [6], and the use of motor control methods [7–9].

Speed regulation methods (SRM) and load-based voltage control methods (LVCM) are recognized as having additional energy-saving potential [7] because they aim to match the power supply conditions (i.e., voltage and frequency) to the mechanical load requirements, improving energy efficiency [2].

The SRM uses variable frequency drives (VFD), variable speed drives (VSD), adjustable frequency drives (AFD), or adjustable speed drives (ASD) to control the EM speed according to load requirements [10]. The electrical energy-saving potential of SRM is between 20 % and 50 %, depending on the torque behavior and speed reduction [2,11]. The SRM has been widely applied to save energy. However, it cannot be used where high-speed variation is not supported (for example, machine tools, conveyor belts, endless conveyors, and cane mills) as it affects production efficiency and extends process time [12]. In addition, its application requires control of many variables such as torque, speed, frequency, voltage, current, and starting time [13].

The LVCM reduces the supply voltage of the EM when operating at a low load factor (LF), improving its operating efficiency [14]. EM operation with a low LF is a common condition in the industry [15]. In the European Union, the average LF is estimated to be less than 60 %; in some sectors, it is around 25 % [16]. In the United States, it is estimated that 44 % of EMs work with an LF of less than 40 % [17]. Among the causes of EM over-dimensioning in the industry are [16]:

- Incorrect design of the Electric Motor Driven System because, in most applications, the torque-speed curves (mechanical characteristics) of the electric motor and mechanical load are unknown.
- Most designers apply significant tolerances or safety margins to avoid the risk of EM overload.
- The rated powers of commercially available EMs do not continuously cover the required power and rarely match the mechanical power

* Corresponding author.
E-mail address: vsousa1@cuc.edu.co (V. Sousa Santos).

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Nomenclature

Cf_i	cash flow ($USD)
D	discount rate (p.u)
E_i	expenses ($USD)
f	stator's frequency (Hz)
I	current (A)
Imeas	measured current (A)
In_i	income ($USD)
I_{NN}	current estimates with neural networks (A)
K	constant that depends on s, w, R_1, and R_2
k_0	Initial investment cost ($USD)
K_1	constant that depends on the winding factor and the number of turns per phase
LF	load factor (%)
n	lifespan of the motor (years)
NPV	Net Present Value ($USD)
Ø	magnetic flux (Wb)
PFmeas	measured power factor (p.u)
PF_{NN}	power factor estimates with neural networks (p.u)
P_{in}	electrical power (W)
P_{out}	mechanical power (W)
R_1	stator resistance (Ω)
R_2	rotor resistance (Ω)
R_{th}	Thévenin resistance
s	slip (p.u)
Subscript i	current year (year)
T	mechanical torque (Nm)
T_n	nominal mechanical torque (Nm)
V_1	voltage per phase (V)
Vmeas	measured line voltage (V)
Vn	rated voltage (V)
V_{NN}	voltage estimates with neural networks (V)
V_{th}	Thévenin voltage (V)
X_1	stator reactance (Ω)
X_2	rotor reactance (Ω)
X_m	magnetizing reactance (Ω)
X_{th}	Thévenin reactance
η	efficiency (%)
ω	electric motor shaft speed (rad/s)
ω_1	speed of the magnetic field (rad/s)

needed for the load. Therefore, EMs with a capacity several times higher than required by the load are usually selected.

On the other hand, the LVCM has a broader field of application than the SRM since the speed of the driven load varies very little. Furthermore, only torque and speed data are required for the operation of the LVCM. Therefore, it is easier to implement than the SRM [8]. While direct measurement of mechanical torque under field conditions remains challenging, it can be estimated with an accuracy of less than the 5 % suggested in Refs. [18–20] for engineering applications by applying some of the methods investigated in Refs. [21,22].

Few studies have evaluated the LVCM and mainly focused on developing optimization models that allow obtaining the minimum voltage as a torque function to achieve the EM maximum efficiency [8,23–25]. The models presented in Refs. [8,23] use internal parameters of EMs (e.g., resistance and reactance) and data such as electromagnetic power, which are difficult to obtain under industrial conditions. Other models are based on complex mathematical methods or indirect calculations that make their application difficult [26].

The equivalent circuit methods have been applied in other studies but are only successful in sinusoidal and balanced voltage supply conditions [8,24]. A constant frequency control technology based on a silicon-controlled rectifier (SCR) is applied to adjust the EM voltage according to the torque demand [14]. In Ref. [12], a voltage phase control technology is used to improve the energy efficiency of a belt-driven centrifugal fan. In Ref. [27], reducing the voltage for low LF by changing delta to star connection is proposed as an energy-saving measure. However, this method is limited as it allows discrete change in a single step (i.e., 58 % of the rated star voltage).

The studies reported so far focus on obtaining optimization models for applying LVCM and presenting technologies based on LVCM without evaluating their energy-saving potential in the industry. Therefore, this study's objective and main contribution is to evaluate the energy-saving potential of LVCM in the life cycle of an EM with different operating regimes. Other contributions of the study consist of using neural networks (NN) and time series as an alternative to the simulation of EM parameters and for the energy evaluation of the LVCM in the EM life cycle.

The study is relevant because the LVCM has been little implemented and may have a greater field of application than other saving measures, such as using SRM. Also, evaluating the impact of an energy-saving measure in the life cycle of an EM is essential due to its high incidence of energy consumption. It is estimated that the EMs can operate in a continuous regime of around 6000 h/year for a period between 15 and 20 years [28]. In addition, the study presented by Ref. [29] demonstrated the importance of evaluating energy-saving measures in EM under actual or quasi-real operating conditions to avoid overestimating the energy-saving potential of these measures.

2. Materials and methods

2.1. LVCM principle

The principle of the LVCM is based on the relationship between motor torque and voltage according to equation (1) [30]:

$$T=\frac{3\bullet R_2\bullet V_{TH}^2}{s\bullet\omega_1\bullet\left[(R_{TH}+R_2/s)^2+(X_{TH}+X_2)^2\right]} \tag{1}$$

where:

$$V_{TH}=V_1\bullet\left(\frac{X_M}{X_1+X_M}\right) \tag{2}$$

$$R_{TH}=\frac{R_1\bullet X_M}{X_1+X_M} \tag{3}$$

$$X_{TH}=\frac{X_1\bullet X_M}{X_1+X_M} \tag{4}$$

in a steady-state condition, the parameters s, ω_1, R_1, R_2 X_1 and X_M remain nearly constant [30], thus establishing the constant K as depicted in equation (5).

$$K=\frac{3\bullet R_2\bullet\left(\frac{X_M}{X_1+X_M}\right)}{s\bullet\omega_1\bullet\left[(R_{TH}+R_2/s)^2+(X_{TH}+X_2)^2\right]} \tag{5}$$

Substituting equation (5) into equation (1) gives equation (6):

$$T=K\bullet V_1{}^2 \tag{6}$$

From equation (6), voltage and torque are related according to equation (7):

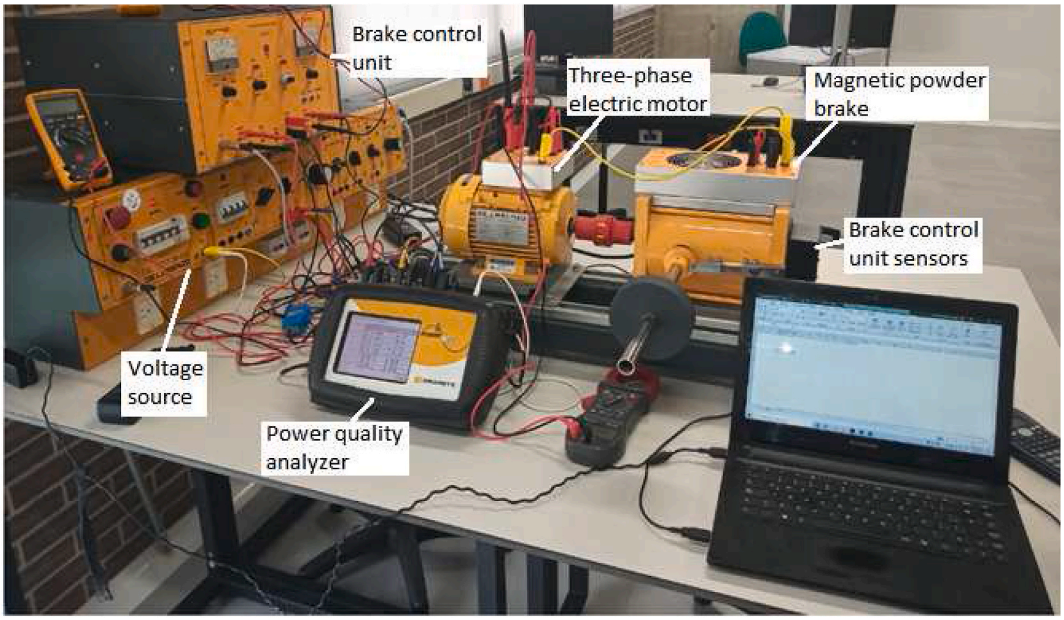


Fig. 1. Experimental installation.

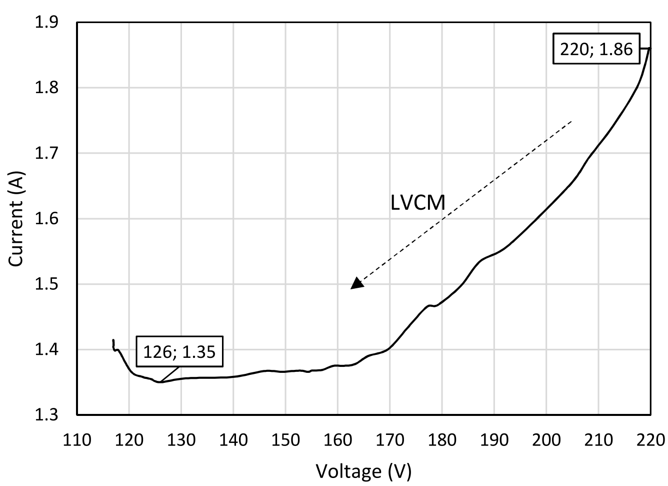


Fig. 2. LVCM application at 15 % LF.

Table 1
EM parameters.

Parameter	Value
Stator resistance (R_1)	6.1 Ω
Rotor resistance (R_2)	6.2 Ω
Magnetizing reactance (X_m)	174.7 Ω
Stator reactance (X_1)	8.3 Ω
Rotor reactance (X_2)	8.3 Ω

$$V_1 = \sqrt{\frac{T}{K}} \tag{7}$$

Furthermore, the magnetic flux in the EM core is related to voltage and frequency as [30]:

$$\varnothing = K_1 \bullet \frac{V_1}{f} \tag{8}$$

According to equation (7), the voltage can be reduced if the load torque decreases. However, from equation (8), if the voltage is reduced to a value lower than that indicated in equation (7), the magnetic flux of the EM is weakened, causing an increase in the current demand to continue driving the mechanical load [30,31].

Table 2
Voltage and current measurements for each LF are at rated voltage and applied to the LVCM.

LF (%)	Vn (V)	I at Vn (A)	V at LVCM (V)	I at LVCM (A)
5	220.0	1.77	81.0	0.89
10	220.0	1.81	106.0	1.13
15	220.0	1.86	126.0	1.35
20	220.0	1.92	142.0	1.55
25	220.0	2.00	152.0	1.74
30	220.0	2.09	159.0	1.93
35	220.0	2.20	165.0	2.11
40	220.0	2.31	174.0	2.29
45	220.0	2.43	220.0	2.43
50	220.0	2.56	220.0	2.56
55	220.0	2.70	220.0	2.70
60	220.0	2.84	220.0	2.84
65	220.0	2.98	220.0	2.98
70	220.0	3.12	220.0	3.12
75	220.0	3.26	220.0	3.26
80	220.0	3.40	220.0	3.40
85	220.0	3.55	220.0	3.55
90	220.0	3.71	220.0	3.71
95	220.0	3.88	220.0	3.88
100	220.0	4.08	220.0	4.08

The efficiency of the EM is calculated by equation (9) [32]:

$$\eta = \frac{P_{out}}{P_{in}} \bullet 100 \ \ (\%) \tag{9}$$

The difference between electrical power and mechanical power is the losses. The EM losses are stator copper losses, rotor copper losses, iron losses, mechanical losses, and additional losses [31]. EM losses are related to LF and voltage as follows:

Relationship between EM losses and LF at rated voltage [10]:

- Mechanical and iron losses practically do not change with the LF.
- Stator copper losses, rotor copper losses, and additional losses vary proportionally with the LF.

Relationship between EM losses and voltage at full load [14]:

Table 3
Data was used to train the NN at rated voltage.

T (Nm)	Vn (V)	n at Vn (rpm)	I at Vn (A)	PF at Vn (p.u)	Pin at Vn (W)
0.15	220.0	3567	1.77	0.21	144
0.31	220.0	3562	1.81	0.29	199
0.46	220.0	3556	1.86	0.36	254
0.61	220.0	3549	1.92	0.42	308
0.77	220.0	3542	2.00	0.48	364
0.92	220.0	3533	2.09	0.53	422
1.07	220.0	3524	2.20	0.57	480
1.23	220.0	3514	2.31	0.61	541
1.38	220.0	3504	2.43	0.65	602
1.54	220.0	3494	2.56	0.68	663
1.69	220.0	3485	2.70	0.70	724
1.84	220.0	3476	2.84	0.73	785
2.00	220.0	3467	2.98	0.74	844
2.15	220.0	3459	3.12	0.76	903
2.30	220.0	3451	3.26	0.77	961
2.46	220.0	3443	3.40	0.79	1018
2.61	220.0	3435	3.55	0.80	1077
2.76	220.0	3425	3.71	0.80	1138
2.92	220.0	3413	3.88	0.81	1204
3.07	220.0	3397	4.08	0.82	1277

Table 4
Data was used to train the NN to apply the LVCM.

T (Nm)	V at LVCM (V)	n at LVCM (rpm)	I at LVCM (A)	PF at LVCM (p.u)	Pin at LVCM (W)
0.15	81.0	3498	0.89	0.78	97
0.31	106.0	3503	1.13	0.80	165
0.46	126.0	3503	1.35	0.75	221
0.61	142.0	3499	1.55	0.73	278
0.77	152.0	3493	1.74	0.74	340
0.92	159.0	3485	1.93	0.76	405
1.07	165.0	3478	2.11	0.78	469
1.23	174.0	3471	2.29	0.77	534
1.38	220.0	3504	2.43	0.65	602
1.54	220.0	3494	2.56	0.68	663
1.69	220.0	3485	2.70	0.70	724
1.84	220.0	3476	2.84	0.73	785
2.00	220.0	3467	2.98	0.74	844
2.15	220.0	3459	3.12	0.76	903
2.30	220.0	3451	3.26	0.77	961
2.46	220.0	3443	3.40	0.79	1018
2.61	220.0	3435	3.55	0.80	1077
2.76	220.0	3425	3.71	0.80	1138
2.92	220.0	3413	3.88	0.81	1204
3.07	220.0	3397	4.08	0.82	1277

- Stator copper losses and mechanical losses practically do not change with voltage.
- The iron losses are proportional to the square of the voltage.
- Rotor copper losses and additional losses are inversely proportional to the voltage.

With the implementation of LVCM, energy is saved because when the load is reduced below the nominal load, the current consumption of the rotor and stator is reduced. Therefore, the copper losses of the rotor and stator are reduced. Additional. Suppose the voltage is also reduced under these conditions. In that case, core losses will also be significantly reduced, which reduces total losses and improves the efficiency of the electric motor compared to maintaining the nominal voltage at a low load.

According to equation (7), the voltage can be reduced as a torque function in low load conditions without increasing the rotor and stator currents since the magnetic flux is unaffected. However, as stated in equation (8), the magnetic field would weaken for a lower voltage value, and the motor would increase current consumption.

This is the operating principle applied in Refs. [8,12,14]. It is also the method based on which the IEEE Std 112™-2017 standard [31] applies no-load tests to determine mechanical and core losses in three-phase induction motors.

2.2. Assessment method

The study was carried out in the following three stages:

- In the first stage, the electromechanical behavior of a 1.1 kW EM was experimentally evaluated under both conditions, at rated voltage and applying the LVCM. The evaluation was carried out at different LFs, and the parameters of voltage, speed, current, power factor, and electric power were recorded, and the efficiency was calculated.
- In the second stage, two neural networks (NN) were developed from the experimental data, one at rated voltage and the other with the application of LVCM. These NNs allowed the EM to be modeled in different operating regimes. These NN allowed us to model the operation of the EM in different operational regimes and compare the efficiency of the EM operating at rated voltage with when the voltage can be reduced at a low load factor. The developed NNs have the advantage of not using internal EM parameters such as resistance and reactance used in Refs. [8,23,24,26,33,34].
- In the third stage, the models developed with the NNs are used. The LVCM's energy-saving potential was evaluated by modeling the EM of 1.1 kW in three operating regimes (OR). These ORs were derived from actual applications over a life cycle and modeled with time series.

2.3. Description of the stages

In the first stage were used the experimental facility shown in Fig. 1 and the following equipment shown was used:

- Three-phase EM of 1100 W, 220 V, 3.9 A, power factor of 0.86, 3420 rpm, 60 Hz, nominal mechanical torque of 3.07 Nm, and nominal efficiency of 86 %. Table 1 shows the parameter data of the motor equivalent circuit [35].
- "De Lorenzo (DL 1013)" variable voltage source.
- "De Lorenzo (DL 1054 TT)" brake control unit together with a "De Lorenzo (DL 1019P)" magnetic powder brake to control the load torque.
- Brake control unit (DL 1054 TT) sensors to measure mechanical parameters (i.e., torque and speed).

The dust brake control unit (DL 1054 TT) enables the measurement

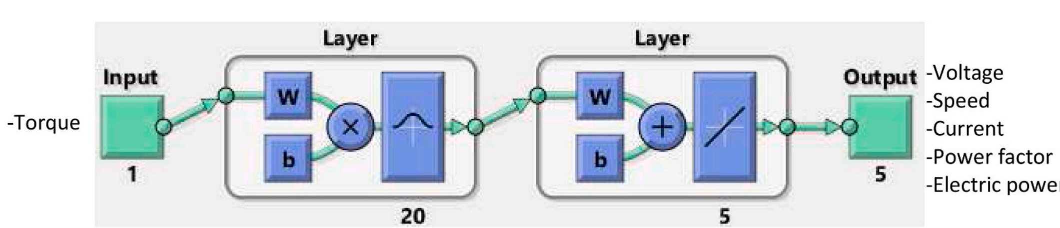


Fig. 3. Diagram of the NN architecture (obtained from MATLAB [41]).

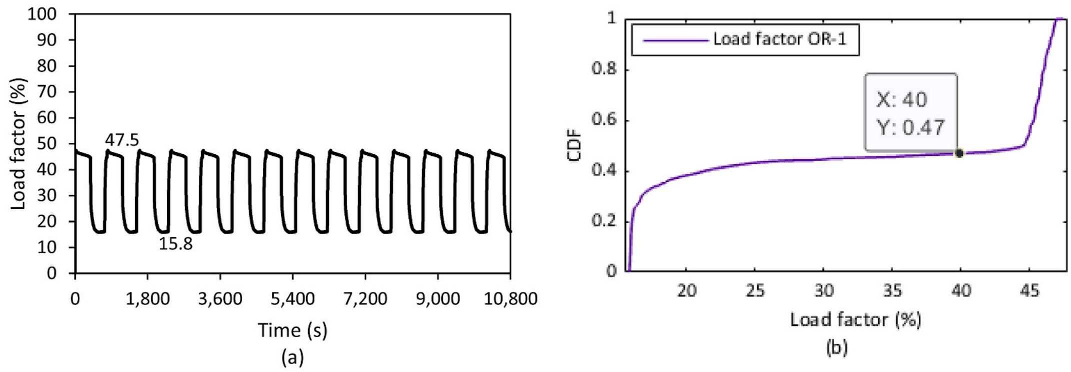


Fig. 4. Characteristics of the OR-1, a) LF for 3 h, b) CDF in one operating cycle.

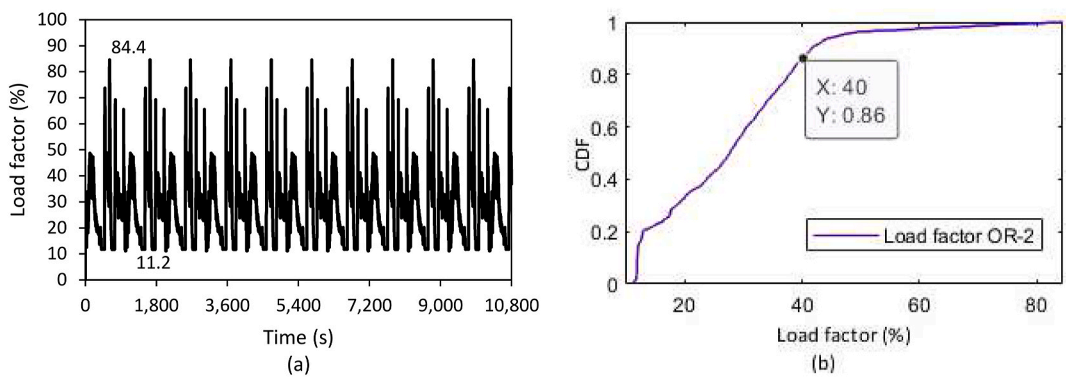


Fig. 5. Characteristics of the OR-2: a) LF for 3 h, b) CDF in one operating cycle.

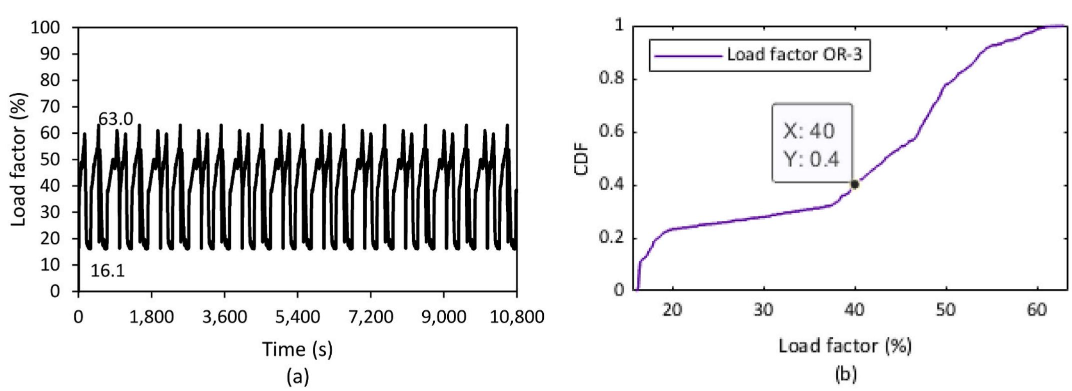


Fig. 6. Characteristics of the OR-3, a) LF for 3 h, b) CDF in one operating cycle. Figs. 4, Fig. 5, and Fig. 6 show that the three ORs have differences, both in the maximum and minimum values of the LF (see Figs. 4(a)–Fig. 5 (a), Fig. 6 (a)), as in the operation time with an LF less than 40 % (see Figs. 4(b)–Fig. 5 (b), Fig. 6 (b)).

of the rotational speed and torque generated by the electric motor. The speed and torque meters have an accuracy class of 1.5 (maximum error of ±1.5 %) and a DC voltage output equivalent to speed measurements (1mV/min^{-1}) and torque measurements (0.1 V/Nm) [36].

- Power quality analyzer "Dranetz," model "PowerVisa" of accuracy class A (maximum error of ±1 %), for the measurement of electrical parameters (i.e., electrical power, voltage, current, and power factor) [37].

The precision class of these measuring instruments ensures errors of less than 5 %, as suggested in engineering applications [18–20].

The LF of the EM is calculated as [38]:

$$LF = \frac{T}{T_n} \bullet 100 \tag{10}$$

The mechanical power of the EM is calculated by equation (11) [32]:

$$P_{out} = T \bullet \omega \tag{11}$$

The experimental program, 20 load states were evaluated, from a 5 % LF (0.15 Nm) to full load (3.07 Nm), with a 5 % increase between each. The measurements were conducted under steady-state conditions characterized by nearly constant temperatures. In this study, transient operating conditions (startup and sudden stops) were excluded, given that the LVCM substantially impacts energy efficiency during the steady-state operation of the EM. Furthermore, transient conditions are characterized by their brief duration (seconds or minutes); hence, they have a negligible effect on the energy consumption of EM throughout their

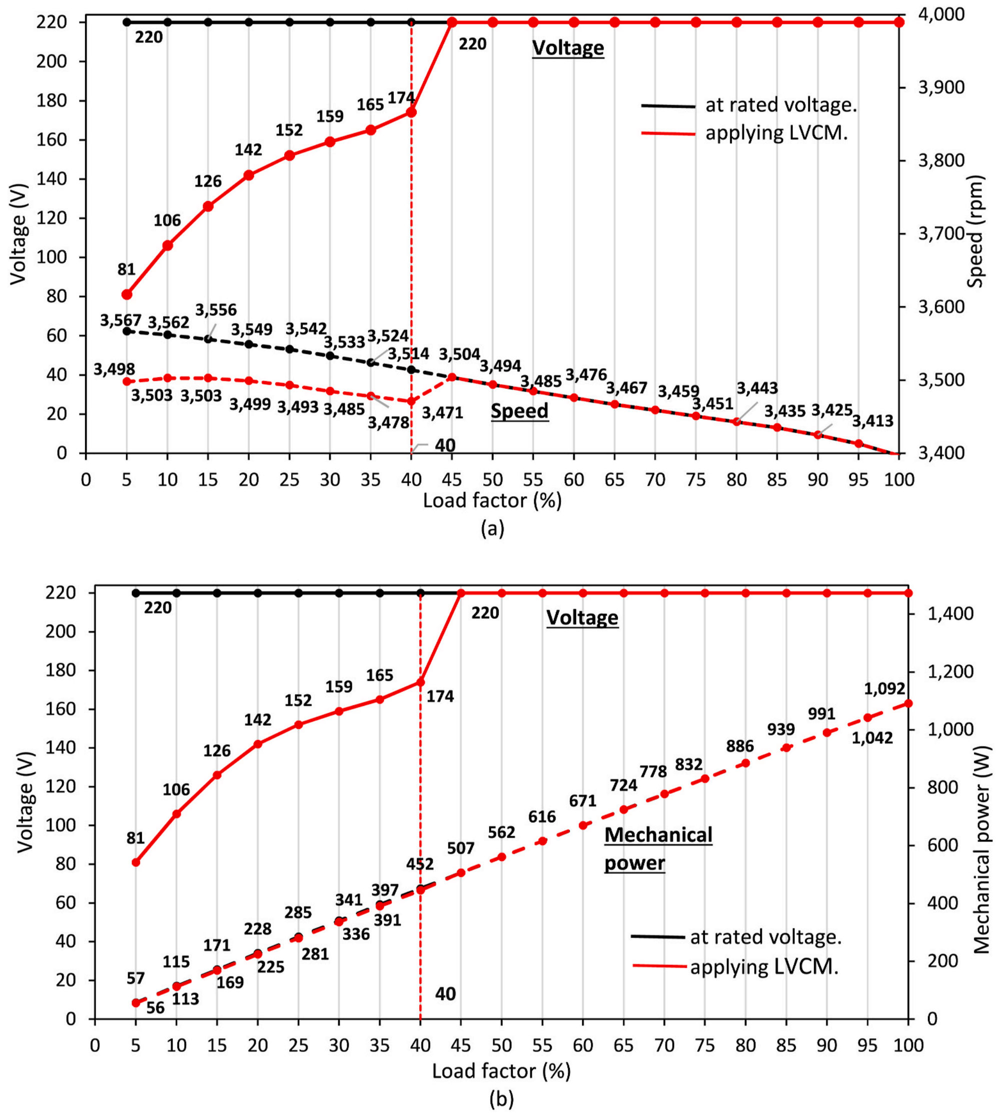


Fig. 7. Mechanical parameters, (a) speed and (b) mechanical power at rated voltage and applying the LVCM.

lifecycle.

For the application of the LVCM in each LF, the voltage was reduced from the rated voltage (i.e., 220 V) to a minimum at which the current began to increase to counteract the weakening of the magnetic flux of the EM core. Fig. 2 shows the voltage and current behavior when the LVCM is applied to the EM at 15 % LF.

As shown in Fig. 2, for a 15 % LF, the voltage could be reduced from 220 V to 126 V, reducing current consumption from 1.86 A to 1.36 A. For voltages below 126 V, the current consumption began to increase to counteract the weakening of the magnetic field.

Electrical power, voltage, current, power factor, torque, and speed were measured for each LF, and the EM efficiency was calculated. The test was replicated 15 times.

The experimental data were analyzed in the Statgraphics Centurion XV software [39], emphasizing the standardized bias and kurtosis to determine if the sample comes from a normal distribution. The standardized bias ranged from −1.69 to 1.61, while the standardized kurtosis ranged from −1.75 to 1.96. Since these values are within the range of −2 and 2, it can be concluded that the data have a normal distribution; therefore, they are valid for any statistical test regarding the standard deviation [40]. The coefficient of variation behaved between 0.013 % and 1.170 %, demonstrating reasonable control in the measurements [40], so the average of the 15 measurements made for each LF was used. Table 2 shows the measured voltage and current data for each LF at rated voltage and applying the LVCM.

According to Table 2, the LVCM can be applied between 5 and 40 % LF. The method is not applicable for higher LFs because the current and losses increase with the voltage reduction [30].

In the second stage, two NNs were developed in MATLAB [41] using the "nntool" graphical interface from the experimental data. These NNs allow for the modeling of the operation of the EM under study in real scenarios and the evaluation of the energy impact of the LVCM. The first NN was constructed using the data collected at rated voltage, as presented in Table 3. The second NN was trained with data acquired from LVCM tests, as outlined in Table 4. Each NN utilized six parameters (torque, voltage, speed, current, power factor, and electrical power), with 20 data points corresponding to each load factor, resulting in a total dataset of 120 data points for each NN.

Fig. 3 shows the architecture of NN obtained from the MATLAB "nntool" graphical interface [41]. The architecture comprises an input variable (torque) and five output variables (voltage, speed, current, power factor, and electrical power). The torque was selected as the input variable because this is the base parameter for the LVCM application; that is, when the torque is reduced, the LF is diminished, and the voltage can be reduced [8]. In addition, torque variation determines the behavior of the speed, current, power factor, and electrical power of the

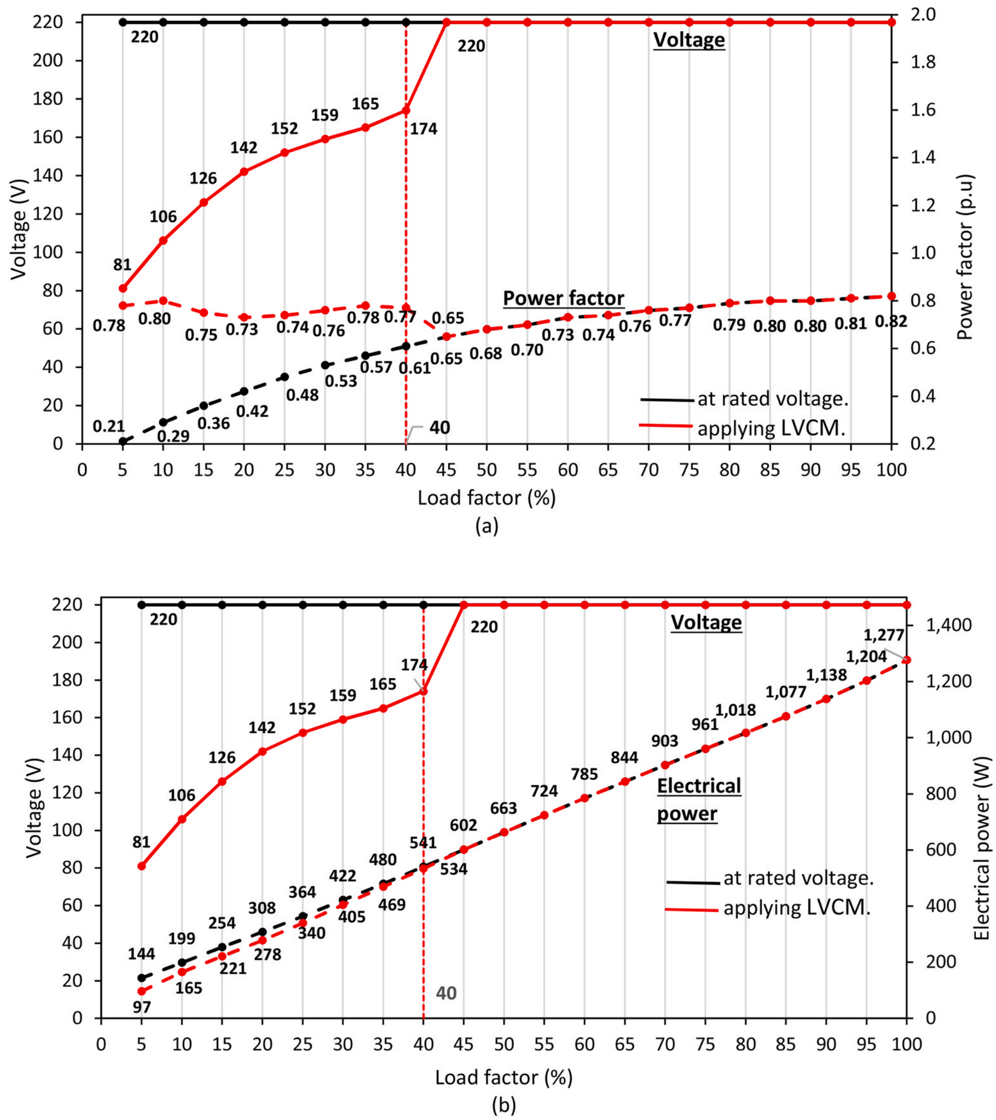


Fig. 8. Electrical parameters, (a) power factor and (b) electrical power at rated voltage and applying the LVCM.

EM [14].

The NNs were developed with supervised training using the radial basis transfer function (exact fit). This type of network is recommended for experimental data and allows the simplification of mathematical manipulation [42]. The radial basis function is an integral component of algorithms used in supervised learning. This function aims to approximate the target function by employing a linear combination of radial kernels, such as the Gaussian combination. The radial basis function has gained widespread acceptance within the machine learning community due to its robust performance and strong theoretical properties [42,43]. It has demonstrated favorable results in Refs. [43–45],Haga clic o pulse aquí para escribir texto. and [46] when applied to model various steady-state operational characteristics of electric motors.

In [44], a radial basis function is implemented to design and model an adaptive neural controller integrated into an electric drive with an induction motor (IM). In Ref. [45], this function is employed to develop a novel torque control scheme for a permanent magnet synchronous motor. In Ref. [43], the radial basis function models, controls, and drives reluctance and permanent magnet motor systems. Meanwhile, in Ref. [46], axial flux and an artificial neural network with a radial basis transfer function are employed to diagnose the stator winding condition in induction motors.

The architecture of the NNs is composed of two layers: a hidden layer with 20 neurons that use the “Radial basis” activation function and an output layer with five neurons that use the “pure line” activation function. The number of neurons in the two layers was automatically defined during the design of the NN. The number of neurons in the first layer matches the LF evaluated (20), while the number of neurons in the second layer equals the output parameters (5). The neural networks developed are valid using 20 different measurement data than those used in training. Compared to the models developed by Refs. [8,23,24,26,33,34], the developed NN-based model does not need internal EM data such as resistance and reactance that are difficult to access under industrial conditions.

In the third stage, the LVCM was evaluated by modeling the EM under study in three operating regimes (OR). The three ORs correspond to an industrial refrigeration compressor, an industrial air compressor, and an industrial stone cutter with constant torque and variable load characteristics. In this type of load, the relationship of electrical power over nominal electrical power is like the behavior of the LF [30,47]. Based on these characteristics and the difficulty of measuring with a torque meter under industrial conditions, the relationship between electrical power and the nominal electrical power of the EM in the three real applications was used to estimate the behavior of torque and LF [47]. These three torque and LF behaviors were used to simulate, with the NN models obtained, the EM under study in three different ORs and

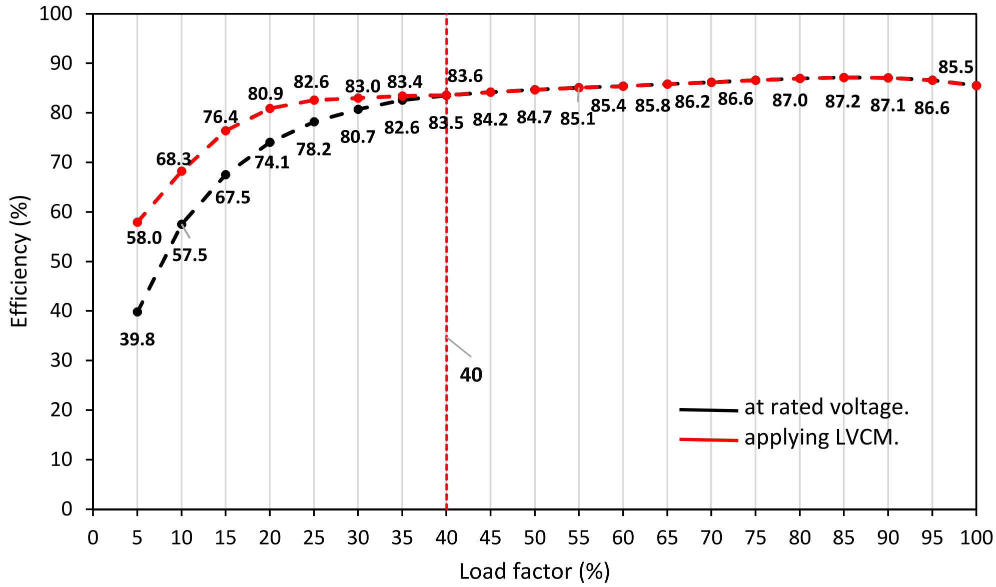


Fig. 9. Efficiency at rated voltage and applying the LVCM.

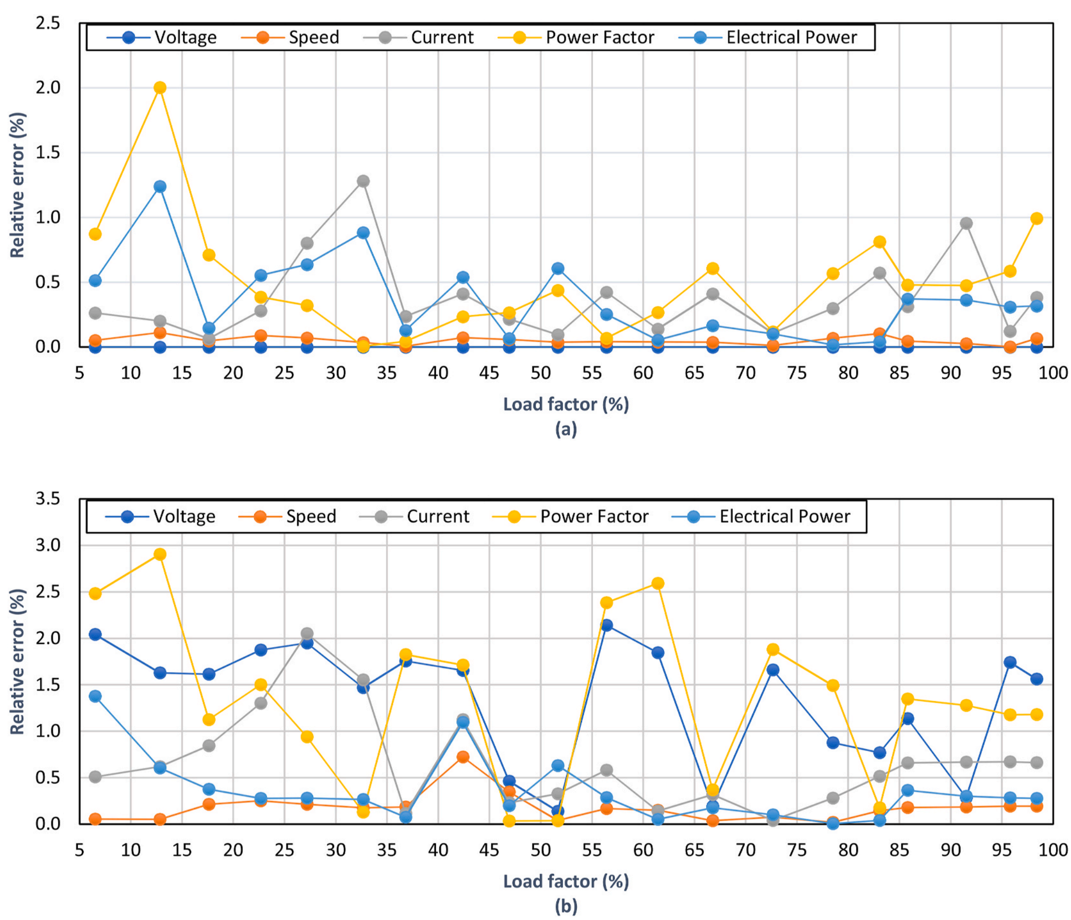


Fig. 10. Relative error between the parameters estimated using the NN and the measured values (a) at rated voltage, (b) applying the LVCM.

compare the power supply with the nominal voltage of the LVCM application. Electrical power measurements were performed using a Fluke 435-II three-phase power quality analyzer with recordings taken every 1 s. Torque and LF can also be estimated under industrial conditions using the estimation methods presented in Refs. [21,22], or [29], which ensure an error of less than 5 %, as suggested in engineering applications [18–20].

The measured data were simulated during a cycle of an EM with 5840 h/year of operation and 20 years of useful life, as is usual in EMs classified as S1 (i.e., continuous operation) [28]. A time series generator was used to generate the data during the life cycle of the EM in the three ORs. This method is used in many studies for parameter forecasts in the

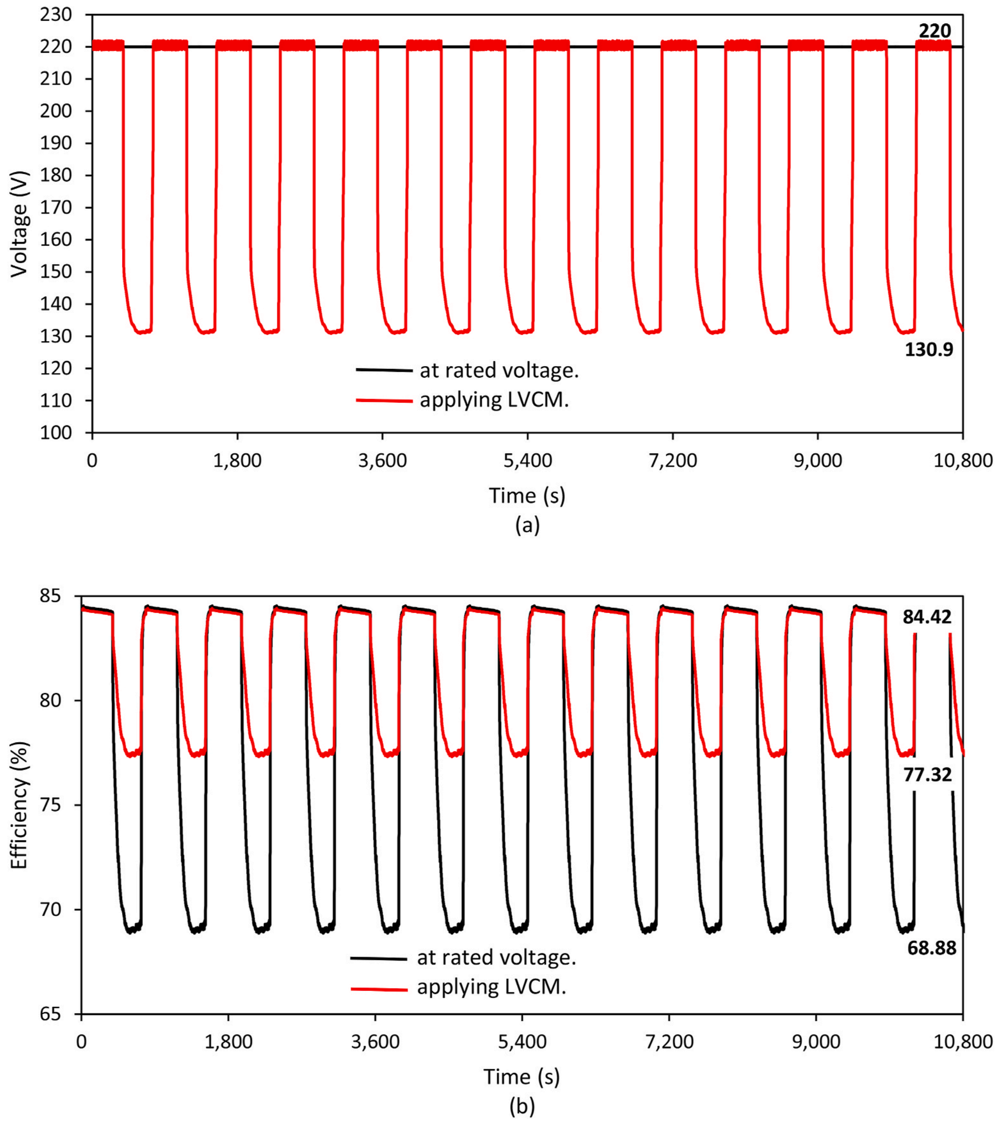


Fig. 11. Behavior of voltage (a) and efficiency (b) for OR-1 at rated voltage and applying LVCM.

short, medium, or long term [48]. The time series was generated in MATLAB software [41] using a resolution that allowed continuous monitoring of the actual data without outliers. The resolution of OR-1 was 789; for OR-2, it was 1025; and for OR-3, it was 1007.

Time series were used because it is impossible to test EMs and record their entire lifespan, especially under highly variable LFs such as those analyzed in the study. This high variability of LFs required high precision in data processing with a data resolution per second. The data generated with the time series fed to the NN allowed the EM under study to be modeled with good precision and high resolution for the different ORs.

Fig. 4, Fig. 5, and Fig. 6 show the behavior of the LF for 3 h (i.e., 10,800 s) and the cumulative distribution function (CDF) of a load cycle of the three ORs. The maximum and minimum LF s values, as depicted in Figs. 4(a)–Fig. 5 (a), and Fig. 6 (a), along with the CDFs presented in Figs. 4(b)–Fig. 5 (b), and Fig. 6 (b), were employed to establish the relationship between the energy-saving potential when implementing the LVCM and the operational regime of the EM. Particular emphasis was placed on LFs below 40 %, as experimental evidence demonstrated the feasibility of applying the LVCM to the EM under study within this range.

In the OR-1, the LF is less than 47.5 % (see Fig. 4 (a)), with 47 % of the time where the LF is less than 40 % (see Fig. 4 (b)). In the OR-2, although the highest LF is reached at 84.4 % (see Fig. 5 (a)), the minimum LF (i.e., 11.2 %) and the most extended period of operation (i.e., 86 % of the period) with an LF of less than 40 % are also obtained (see Fig. 5 (b)). In OR-3, the LF reaches 63 % (see Fig. 6 (a)), and 40 % of the time, the LF is less than 40 % (see Fig. 6 (b)). In all cases, the LF has values below 40 %, so there is potential for energy savings by applying LVCM.

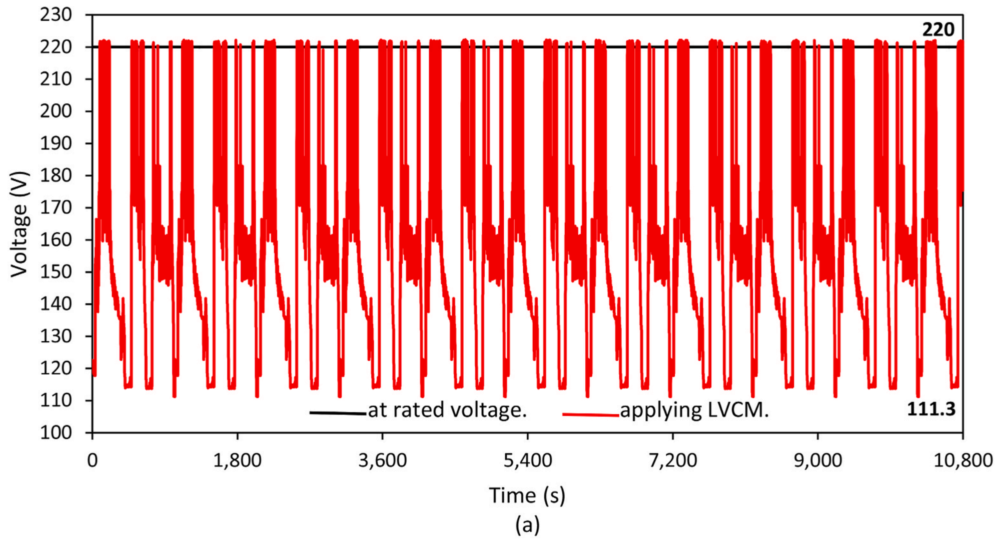
3. Results and discussion

3.1. Experimental evaluation of the LVCM

Fig. 7 shows the behavior of the mechanical parameters (i.e., speed (a) and mechanical power (b)), as well as the rated voltage and voltage when the LVCM is applied. The black curve represents the results at rated voltage, while the red curves correspond to the results for the LVCM application.

In Fig. 7, the speed and mechanical power were very little affected by the reduction in voltage. The most significant difference between these parameters at rated and reduced voltage was 1.9 %, which occurred for the lowest LF (i.e., 5 %).

Fig. 8 shows the behavior of the electrical parameters (i.e., power factor (a) and electrical power (b)), as well as the rated voltage and



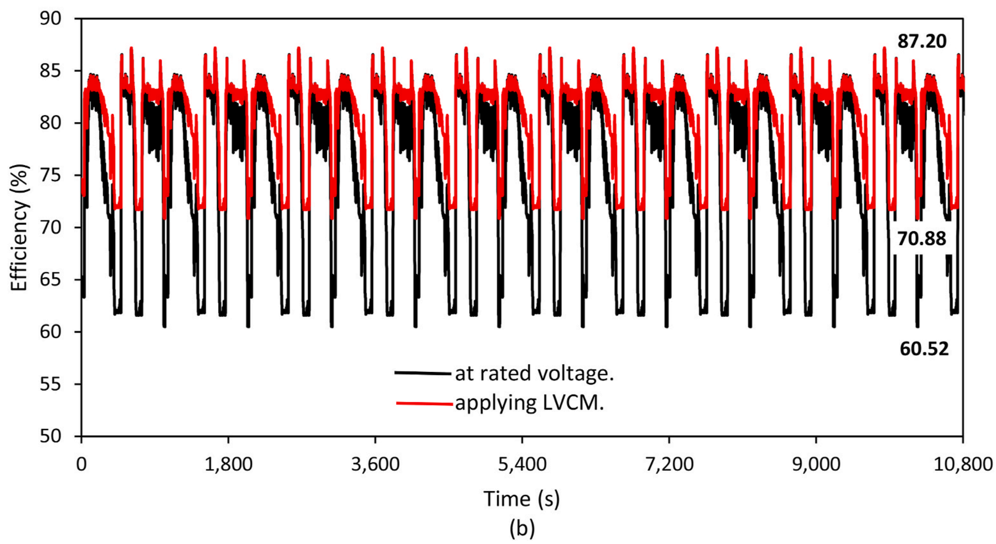


Fig. 12. Behavior of (a) voltage and (b) efficiency corresponding to OR-2 at rated voltage and applying the LVCM.

voltage when the LVCM is applied.

Fig. 8 shows that the power factor and the electrical power varied significantly with the voltage reduction. Fig. 8 (a) shows that the power factor remained practically constant at the reduced voltage points. In addition, the power factor improved by 20.8 % for the 40 % LF and 73.1 % for the minimum LF compared to the rated voltage conditions. These results demonstrate that LVCM can mitigate the power factor reduction problem in EMs operating at low LF s.

Fig. 8 (b) shows that the electrical power was reduced between 1.3 % for the LF of 40 % and 32.6 % for the LF of 5 %, concerning the rated voltage conditions. These results show that the lower the LF, the more significant the reduction in electrical power consumption.

Fig. 9 shows the efficiency behavior in the two conditions (i.e., at rated voltage and applying the LVCM) and the rated voltage and voltage when the LVCM is applied.

Fig. 9 illustrates that the difference in efficiency when applying the LVCM, compared to operating the EM at its rated voltage, varies from 0.06 % for an LF of 40 %–18.1 % for the minimum LF (i.e., 5 %). This implies that when employing the LVCM, the improvement in the efficiency of the EM becomes more pronounced as the LF decreases compared to the operation at the rated voltage. These results arise because mechanical power remains almost constant because of the application of the LVCM. However, electrical energy is significantly reduced, especially at low voltage.

3.2. Validation of NN

To validate the NNs, the measured parameters of the EM (voltage, speed, current, power factor, and electric power) were compared with the values obtained through the NN. Different LFs were employed for validation, distinct from those utilized during the NNs' training. Fig. 10 presents the results of the relative error analysis between the measured parameters and those predicted by the NNs.

Fig. 10 (a) shows that the results obtained by the NN for rated voltage are satisfactory since the maximum error in estimating the power factor was 2.0 %. Fig. 10 (b) shows that the results obtained by the NN for the reduced voltage are accurate enough since the maximum error obtained was 2.91 % in estimating the power factor, too.

The relative errors in the two NN models were less than 5 %, which is an accepted error limit in engineering applications [18–20]. These results suggest that the NN models can be used as a forecasting tool for the energy behavior of the EM under study in various operating regimes.

Under industrial conditions, NN can be trained to assess the impact of energy savings on electric motors using LVCM or any other energy-saving measure. Considering the challenges of directly measuring with a torque wrench under these conditions, any of the methods evaluated in

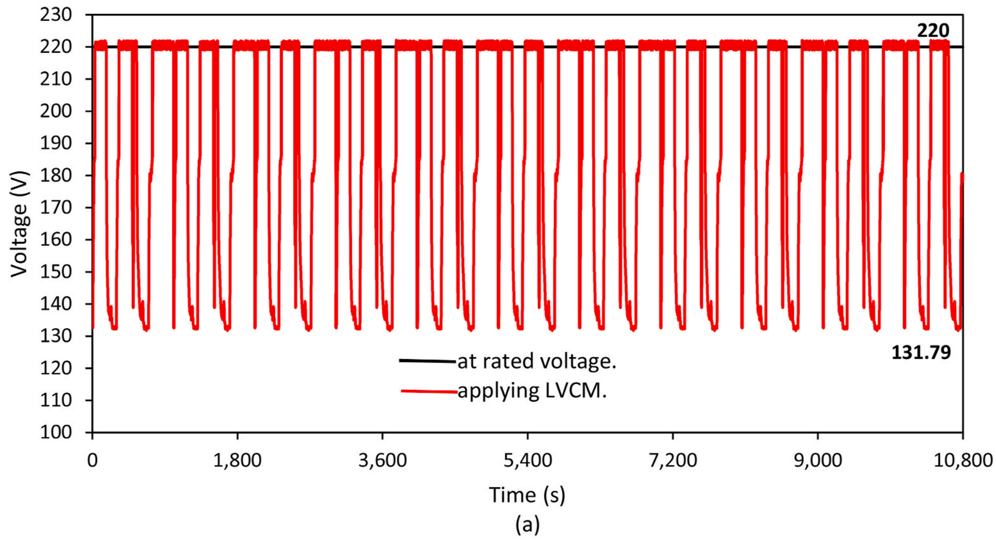


Fig. 13. Behavior of (a) voltage and (b) efficiency corresponding to OR-3 at rated voltage and applying the LVCM.

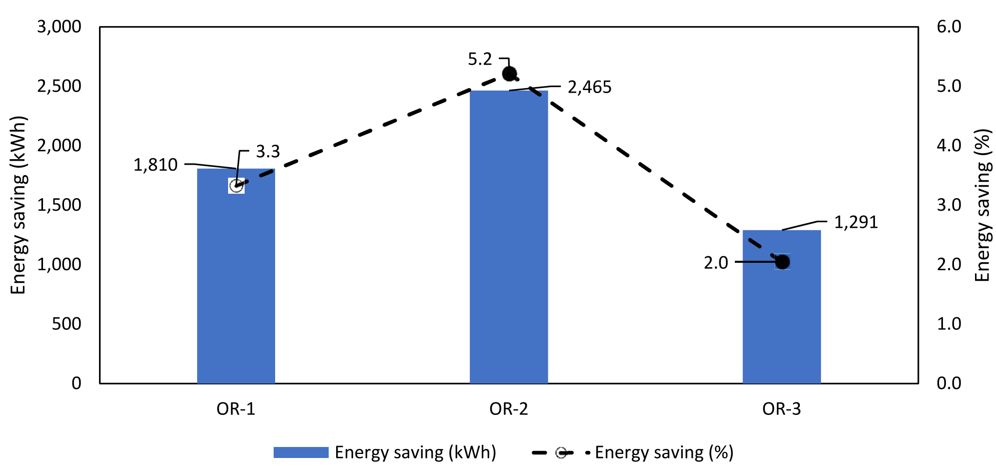


Fig. 14. Estimating energy savings with the LVCM during 20 years of operation for OR-1, OR-2, and OR-3.

Table 5
Energy consumption and estimated annual energy savings in reference motors.

Motor	Energy savings (%)	Energy consumption (kWh/year)	Energy savings (kWh/year)
Motor (OR-1)	3.3	187,817	6198
Motor (OR-2)	5.2	94,041	4890
Motor (OR-3)	2	245,402	4908

Table 6
Costs for energy consumption and energy savings in reference motors.

Motor	Costs for energy consumption ($USD/year)	Costs for energy savings ($USD/year)
Motor (OR-1)	46,954	1549
Motor (OR-2)	23,510	1223
Motor (OR-3)	61,351	1227

Table 7
Costs of components to develop a system to implement the LVCM.

Components of the LVCM System	Price ($USD)
Force washer-type sensor	913
PLC System	764
Arduino System	943
Three-phase power regulator with (SCR)	645
Current sensor	157
Total	**3421**

Ref. [21], the one proposed in Ref. [22], or the one utilized in Ref. [29] can be employed.

3.3. LVCM evaluation results under simulated operating conditions

Fig. 11 shows the results of the voltage (a) and efficiency (b) obtained from the NNs corresponding to OR-1 when the motor is operating at a rated voltage and applying the LVCM. A sample of 3 h of operation (i.e., 10,800 s) is represented in the figure.

In Fig. 11 (a), it is evidenced that with the LVCM, a minimum of 130.9 V is reached for the lowest LF (i.e., 15.8 %), representing a voltage reduction of 40.5 % concerning the rated voltage. Fig. 11 (b) shows that with the LVCM, the operational efficiency of the EM improves significantly concerning the supply with rated voltage. As can be seen at the point of least LF, the efficiency with rated voltage is 68.88 %, while with the application of the LVCM, it is 77.32 %, indicating an improvement of 8.4 %. In OR-1, the maximum efficiency reaches 84.42 %. This value is lower than the nominal efficiency of the EM (i.e., 88 %) since the maximum LF is only 47.5 % of the nominal power of the EM. Fig. 12 shows the results of the voltage and efficiency obtained from the NNs corresponding to OR-2 when the motor is operating at rated voltage and applying the LVCM.

Fig. 12 (a) shows that with the LVCM, a minimum of 111.3 V is reached for the lowest LF (11.2 %), representing a voltage reduction of 49.4 % about the operating at rated voltage. According to Fig. 12 (b), at the point of the lowest LF, the efficiency at rated voltage is 60.52 %, while with the application of the LVCM, it is 70.88 %, indicating an improvement of 10.4 %. In the OR-2, the maximum efficiency is 87.2 %, a value very close to the nominal efficiency of the EM (i.e., 88 %) since the LF is high, with a maximum that reaches 88.2 %.

Fig. 13 shows the voltage and efficiency results obtained from the NNs corresponding to OR-3 when the motor operates at rated voltage and applies the LVCM.

Fig. 13 (a) shows that with the LVCM, a minimum voltage of 131.8 V is reached for the lowest LF (16.1 %), representing a voltage reduction of 40.1 % about the rated voltage. In Fig. 13 (b), at the point of the lowest LF, the efficiency at rated voltage is 69.26 %, while with the LVCM, the efficiency rises to 77.59 %, increasing by 8.3 % at this point. In the OR-3, the maximum efficiency is 85.67 %, a value lower than the nominal efficiency of the EM because the maximum LF in this OR only reaches a maximum of 63 %.

The three ORs evaluated show that with LVCM, energy efficiency improves in the low LF area of operation (i.e., less than 40 %). The results differed in the three applications because the OR varied in each case. In OR-2, the most significant increase in efficiency was observed at the point with the lowest LF. The LF was the minimum in this OR, and the most considerable voltage reduction was obtained.

The energy impact of LVCM was evaluated by estimating the energy consumption and energy savings in the life cycle of the EMs for 20 years in the three operation regimes. Fig. 14 shows the estimated energy savings by applying LVCM in the three cases.

Fig. 14 shows that the energy-saving potential with the LVCM ranged between 2 % and 5.2 %, representing savings between 1.3 MWh and 2.5 MWh. The most significant energy saving (i.e., 5.2 %) was obtained in OR-2, where the EM worked with the minimum LF (i.e., 11.2 %) and the longest time (i.e., 86 % of the time) with an LF lower than 40 %. In turn, the lowest savings potential (i.e., 2 %)) was obtained in OR-3, where the minimum LF (i.e., 16.1 %) was highest and the operating time below the 40 % LF was also lower (i.e., 40 %). These results show that the savings potential obtained with the implementation of LVCM is related to the minimum LF and the operation time with a low LF of the EM.

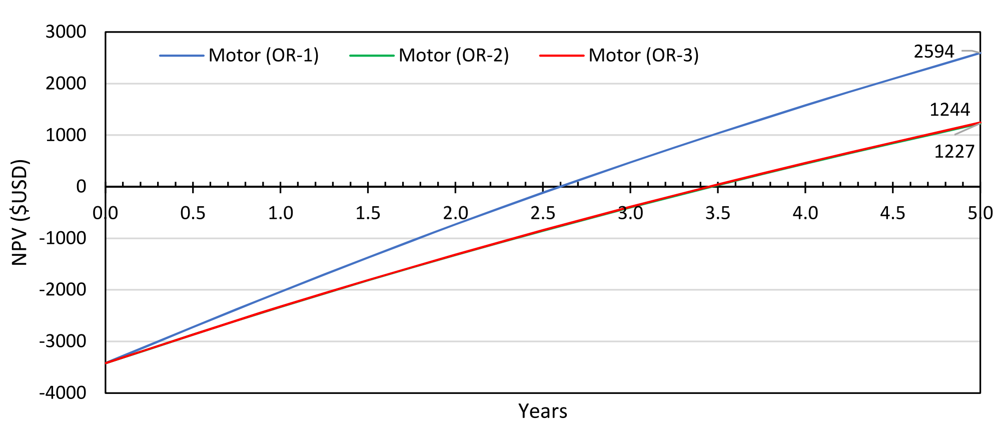


Fig. 15. NPV of the three reference EMs projected over five years.

3.4. Economic feasibility analysis of the LVCM

The economic viability of LVCM was evaluated in the three EMs that presented the OR used as a reference to assess the energy-saving potential of LVCM in the 1.1 kW EM under study. The economic viability of LVCM was assessed in these three EMs because the 1.1 kW motor is tiny, and energy consumption and energy-saving costs are low. Additionally, the reference EMs have the characteristics of EMs commonly used in industries [3]. The three EMs used as a reference present the following data:

- Motor (OR-1): 93 kW, 230 V, 278 A, 1780 rpm.
- Motor (OR-2): 56 kW, 440 V, 100 A, 1770 rpm.
- Motor (OR-3): 100 kW, 440 V, 152.8 A, 1119 rpm.

Table 5 shows the energy consumption and estimated annual energy savings of each EM used as a reference. Energy savings were calculated considering the same percentage obtained with the 1.1 kW EM in each operating regime. This consideration assumes that the energy-saving potential in the 1.1 kW EM was estimated using the same load factor behavior as the three references EM. Therefore, the relative voltage and electrical power variation are considered approximately equal.

Table 6 shows the annual costs for energy consumption and energy savings considering the energy cost at USD 0.25/kWh [49].

The LVCM can be implemented in industrial conditions by measuring the voltage, current, and motor load torque estimation in a closed loop. This is achieved using a current transformer (CT) and a torque estimation sensor. From these signals, the effective voltage is controlled by adjusting the phase angle of the voltage using a power regulator with SCR controlled by a trigger signal with an Arduino board and a PLC. If the phase angle of the voltage spikes before half a cycle, the practical value of the output voltage increases. In contrast, if the trigger time is delayed, only a portion of the voltage waveform passes through the system, thus decreasing its practical value.

Voltage, current, speed, and torque estimation sensors must be high-resolution (bandwidth between 20 and 50 kHz). The control system receives the signal and acts at intervals less than a full wave (16.67 ms). This allows real-time measurement and control with instant energy-saving effects.

Voltage regulation for a load factor less than 40 % can be done by reducing the voltage while measuring the current. The voltage remains constant once the current begins to increase due to the weakening of the magnetic field. Otherwise, the current starts to increase due to the increase in load, and the voltage increases until the current stabilizes. Table 7 shows the prices of the components required to develop a system to implement the LVCM [50].

The economic feasibility assessment of the system to implement the LVCM was conducted using the Net Present Value method, with equation (12) [2].

$$\mathrm{NPV} = \text{-}k_0 + \sum_{i=1}^{n} \frac{Cf_i}{(1+D)^i} \tag{12}$$

The cash flow is calculated with equation (13) as:

$$Cf_i = In_i \text{-} E_i \tag{13}$$

The initial investment cost comprises the system cost to implement the LVCM; the income is based on the energy savings from the implementation of the LVCM, while the expenses may include system maintenance costs. A discount rate of 12 % was applied [51], and the project duration was assessed to be 20 years in alignment with the lifespan of EMs [2]. Fig. 15 depicts the NPV of the three reference EMs projected for the first five years of the investment project. The zero crossing indicates the payback period of the investment [2].

Fig. 15 shows that the system to implement the LVCM is economically feasible in all three reference cases because the investment is recovered in less than three and a half years. This period is less than one-third of the EM lifespan (i.e., 20 years), a suggested limit for approving an energy-saving investment project in electric motors feasible [52].

The shortest payback period (i.e., two years, seven months) and the highest NPV over five years (i.e., USD 2594) are achieved with Motor (OR-1). In Table 5, it can be observed that Motor (OR-1) does not have the highest energy savings percentage (i.e., 3.3 %); however, it exhibits the highest energy savings (i.e., 6198 kWh/year). On the other hand, Motor (OR-2) and Motor (OR-3) both have the same payback period (i.e., three years, five months) and NPV over five years (i.e., USD 1227 and USD 1,244, respectively). This is because, as shown in Table 5. However, Motor (OR-2) and Motor (OR-3) have the highest and lowest energy savings percentages, respectively (i.e., 5.2 % and 2 % respectively), they also have the lowest and highest energy consumption, respectively (i.e., 94,041 kWh/year and 245,402 kWh/year respectively), resulting in similar energy savings (i.e., approximately 4900 kWh/year).

4. Conclusions

The study showed that the LVCM is an excellent alternative to save energy in EMs with low LF s. In evaluating the method in three ORs of an EM of 1.1 kW, a 2–5 % energy-saving potential in the motor life cycle was estimated. The most significant energy-saving potential was obtained in the OR with the lowest LF and the longest operating time with a low LF.

The study results allow us to conclude that LVCM can significantly impact energy savings in industries since EMs with powers greater than 5 kW predominate in this sector, operating more than 5000 h/year and with an LF of less than 40 %. To evaluate LVCM in industries, actual operating conditions must be considered during the life cycle of the EM and not only assess the cost of the initial investment and the operation in nominal conditions. To this end, NNs and time series generators are practical evaluation tools during the EM life cycle and do not require EM design data.

The advantage of LVCM over other EM energy-saving measures, such as high-efficiency EM substitution, SRM, power regeneration, and power quality improvement, is that it can be applied in all load types without high investment costs. In the economic feasibility assessment of a system to implement the LVCM in three industrial EMs with varying ORs, it was demonstrated that this method could yield savings ranging between $1227 and USD 1549 per year and achieve investment payback in less than three and a half years.

CRediT authorship contribution statement

Vladimir Sousa Santos: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Juan J. Cabello Eras:** Writing – review & editing, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Mario J. Cabello Ulloa:** Validation, Software, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Engineering Faculty.

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