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Assessment of the Energy Efficiency of Three-Phase Induction Motors Powered by A Photovoltaic System

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ABSTRACT

This study aims to determine the energy efficiency of three-phase induction motors (TIM) powered when operated with photovoltaic systems (PVS). The environmental advantages of photovoltaic systems (PVS) are very well known. However, there are still challenges related to energy quality, electricity generation instability, failure in frequency regulation, instability in reactive power, and harmonics generation. However, the impact of PVS on TIM efficiency has not been thoroughly explored. This research compares a TIM's electromechanical characteristics and efficiency when powered by a conventional electrical grid versus a PVS. Experimental studies revealed that when powered by the PVS, the TIM experienced increased voltage and higher voltage and current harmonics compared to grid power. These electrical difficulties, attributed to the PVS inverter, resulted in a 2.7% decrease in TIM efficiency compared to grid power. Modeling conducted under actual load variation conditions demonstrated a 2.6% increase in energy consumption when powered by the PVS compared to grid power. Based on these findings, PVS installers are advised to consider the energy quality provided by these systems, as it may affect the efficient operation of TIM, leading to increased energy consumption.

Keywords: Three-Phase Induction Motors, Photovoltaic Systems, Energy Efficiency, Electrical Grid, Harmonics, Energy Consumption
JEL Classifications: L8, Q2, Q41.

1. INTRODUCTION

The research arises from the need to verify the effects of integrating PVS in Colombia and their influence on the efficiency of TIM. Globally, PVS are Colombia's fastest growing and most promising renewable energy sources (Eras et al., 2019). Similarly, TIM represents the most significant loads in industrial electricity consumption (Sagastume Gutiérrez et al., 2018).

PVS comprises solar panels, regulators, converters, and batteries and is part of Renewable Energy Sources (RES). Their use has increased worldwide as a decarbonization strategy, in line with the goals of the 2015 Paris Agreement (UNFCCC, 2015). These efforts aim to reduce greenhouse gas emissions to counteract the negative impacts of climate change (Eras et al., 2019; Sagastume Gutiérrez et al., 2018; UNFCCC, 2015; Zerrahn et al., 2018).

Existing studies demonstrate the adverse effects of PVS feeding on the operation of electrical systems, attributable to operational variability generated by electronic devices. These include intermittency in electricity generation, waveform distortions, lack of reactive power, and inconveniences in voltage regulation. However, it is crucial to note that these studies do not evaluate the impact of these PVS on the efficiency of TIM. Considering that TIM represents nearly 68% of the global electricity consumption in the industrial sector, this lack of evaluation is significant.

Critical components of PVS, such as power converters, have been the subject of numerous studies to improve their operation and minimize adverse effects on the electrical system. (Fernandes et al., 2017) propose a control strategy for a PV system connected through a power converter. At the same time (Yu et al., 2015) present a cascaded H-bridge converter applicable for medium voltage and high power. (Hu and Gong, 2015) introduce a power boost converter with parallel input and series output configuration.

PVS plants must meet specific requirements of the electrical grid to which they are connected, especially concerning energy quality issues. Energy quality is affected by electromagnetic phenomena that modify device operation and reduce lifespan (IEEE, 2009). In the case of TIM operating power pumps, fans, compressors, and conveyor belts, losses during electromechanical conversion occur when energy is irreversibly transformed into heat. These devices are designed to operate with balanced voltages close to their nominal value, and any deviation affects their operation and efficiency (Sousa Santos et al., 2019; Al-Badri et al., 2017).

Given the variability of PVS generation and the use of electronic devices, harmonic distortion, and voltage deviation are presents. Although these aspects have been evaluated in various research, the influence of harmonics generated by PVS on the operation of TIM has not been analyzed. Voltage and frequency variation affects the core losses of TIM (Nour and Thirugnanam, 2017), and voltage variation influences the torque/speed characteristic of TIM (Bonnett et al., 2016). Although these aspects have been evaluated, no research has addressed the influence of voltage variation problems generated by PVS on TIM.

In this context, no studies are analyzing the impact of increased PVS generation on the efficiency of TIM. This article aims to evaluate the performance of a TIM powered by a PVS under various load conditions in laboratory and field conditions to analyze the effects of powering from PVS with different configurations on the efficiency of TIM. Additionally, the aim is to provide selection and operation criteria for PVS for electrical systems with TIM, to prevent motors' efficiency impairments due to energy quality issues.

This article's main contribution lies in assessing the impact of PVS on the efficiency and other operational parameters of TIM, such as power factor, voltage, electrical power, and current. This article's main purpose is to comprehensively evaluate the performance of a TIM powered by a PVS, considering various load conditions. This analysis is performed by assessing the effects of supplying power from PVS with several configurations, both in laboratory and field conditions, to understand their influence on the efficiency of TIM. Additionally, the aim is to provide recommendations regarding the selection and operation criteria of PVS systems feeding electrical systems with the presence of TIM, to prevent motors' potential efficiency impairments due to energy quality issues.

This article's significant contribution lies in assessing the impact of PVS on efficiency and other essential operational parameters, such as power factor, voltage, electrical power, and current in TIM.

This research aims to contribute to scientific knowledge in the field, providing crucial information for the optimal selection and operation of PVS in environments that coexist with three-phase induction motors.

2. MATERIALS AND METHODS

The methodology implemented for the experimental evaluation and modeling of the TIM under real operating conditions is described below. Figure 1 shows the flowchart of this methodology.

2.1. Description of the Experimental Evaluation Under Laboratory Conditions

The experiment aimed at evaluating the impacts of supplying power from PV systems on the efficiency of TIM was conducted in the electrical machines laboratory of the University of the Coast (CUC). A ten 340 W panels PV system was implemented connected to the three-phase grid via a CHINT POWER three-phase DC/AC inverter, without including batteries. The inverter was positioned near the motor test bench, allowing its connection to the control devices of the TIM. The used TIM bench is shown in Figure 2.

The experiments were conducted under two conditions: In the first, the TIM was powered from the electrical grid; and in the second from the PV system. Under each condition, the load was varied using the brake control from 5% of the total load (55 W) to 100% (1100 W), with increments of 5%. Electrical parameters were measured using a power analyzer, and mechanical parameters were measured using the brake control and a data acquisition card.

Harmonics were analyzed using THDV (Total Harmonic Distortion of Voltage) and the K factor. As seen in equations (1) and (2), THDV was used to assess voltage harmonics, while the K factor was used to evaluate current harmonics (Kalair et al., 2017), (IEEE, 2014).

$$THDV = \frac{\sqrt{\sum_{k=2}^{50} V_k^2}}{V_1} \cdot 100 \tag{1}$$

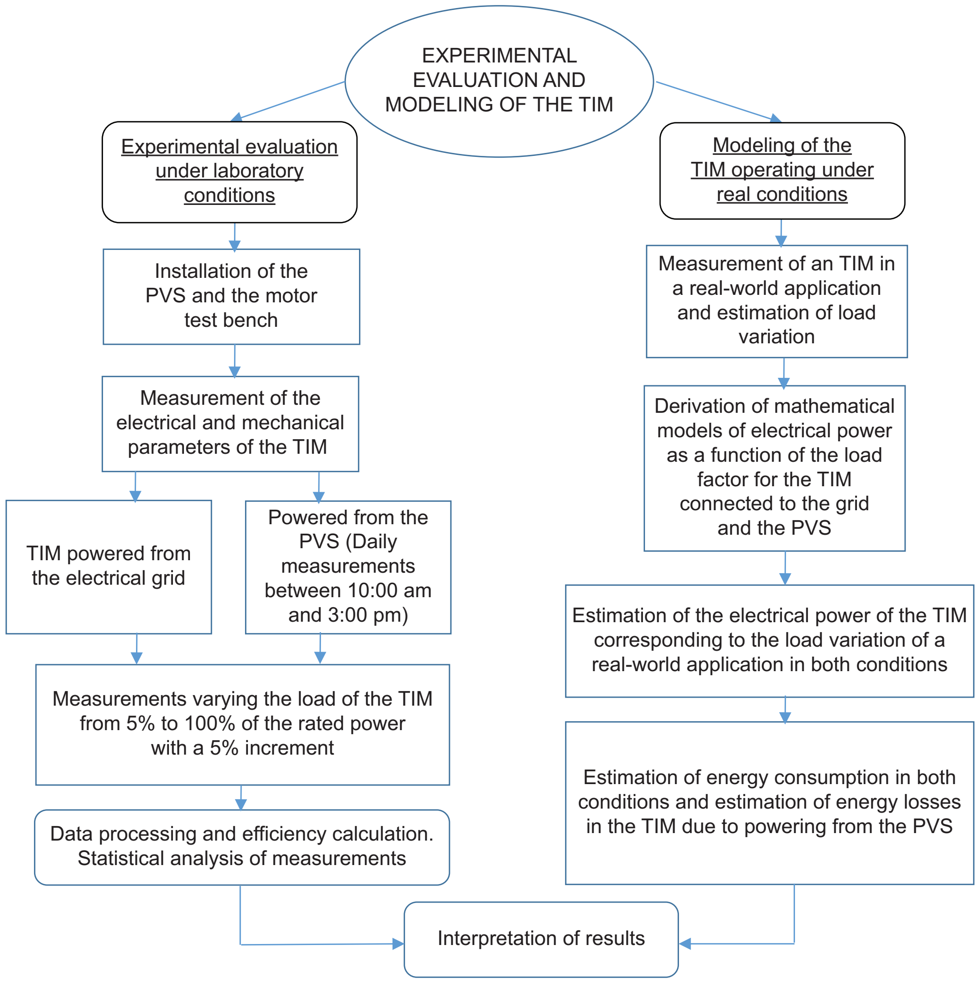
$$Factor\ k = \sum_{k=1}^{\infty} \left(\frac{I_k}{I_{rms}} \right)^2 \cdot k^2 \tag{2}$$

Measurements were recorded for 30 s at one-second intervals for each load level. During data processing, the simultaneously measured electrical and mechanical parameters were synchronized. From these measurements, mechanical power, load factor, and efficiency were calculated using equations (3), (4), and (5) following the methodology proposed by (Lu et al., 2006, 2008), (Sousa Santos et al., 2019).

$$P_{mec} = \frac{T \cdot n}{9.549} \tag{3}$$

$$F_c = 100 \cdot \frac{P_{mec}}{P_n} \tag{4}$$

Figure 1: Flow of the experimental description in the laboratory and modeling of the three-phase induction motors under real operating conditions



$$\eta = 100 \cdot \frac{P_{mec}}{P_{elec}} \tag{5}$$

The measurements were conducted daily for a week, and evaluation under condition 2 (i.e., powered by the PV system) was carried out between 10:00 am and 3:00 pm, h during which solar radiation allowed sufficient electrical energy generation to operate the TIM.

Another aspect of the study involved modeling the TIM operating under a regime of constant torque and variable load, which corresponds to a practical application achieved by 5 h of field measurements of a TIM, ensuring that the behavior of mechanical power matched that of the measured electrical power. This phenomenon is characteristic of applications with constant torque and variable load.

Subsequently, the studied TIM was simulated, operating with the load variation obtained from the actual measurement. The energy consumption was compared when the TIM was powered from the electrical grid versus when it was powered from the PV system. This comparison allowed the impact of PV systems on the efficiency of the TIM to be estimated in a real operating scenario.

2.2. Modeling the TIM Operating Under Actual Conditions

The TIM under study was modeled under a load condition representative of a practical application, simulating 5 h of operation. This duration was chosen to reflect the potential for energy generation through PV in a high solar radiation region, such as Barranquilla, Colombia (Noriega-Angarita et al., 2016). Figure 3 illustrates the analyzed load profile, revealing variations ranging from 7.6% to 100% of the nominal power.

The electrical power demanded by the TIM under the conditions of supply from the Electric grid and the PVS was estimated using a mathematical model of linear regression, employing experimental data for both conditions. The linear regression models are presented in Figure 4.

Based on this behavior of the electrical power demand, the energy consumption in both conditions was calculated, as well as the energy losses when the TIM was powered by the PVS, applying equations (6), (7), and (8) as proposed by (Angarita et al., 2019).

$$E_{grid} = \int_0^5 P_{elec(grid)} \cdot dt \tag{6}$$

$$E_{pvs} = \int_0^5 P_{elec(pvs)} \cdot dt \quad (7)$$

$$DE = 100\left(1 - \frac{E_{grid}}{E_{pvs}}\right) \quad (8)$$

Egrid represents the energy consumed by the TIM when powered by the electric grid, expressed in watts (W). Similarly, E_{pvs} denotes the energy consumed by the TIM when powered by the PVS, also measured in watts (W). The variable DE is defined as the difference in energy consumption, expressed as a percentage. This set of parameters is crucial for evaluating and comparing the energy performance of the TIM under different power sources.

Figure 2: Motor test bench (a) three-phase induction motors - Powder brake (b) Brake controller

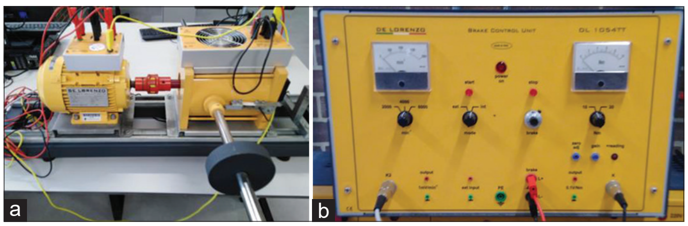


Figure 3: Load factor modeled in the studied three-phase induction motors

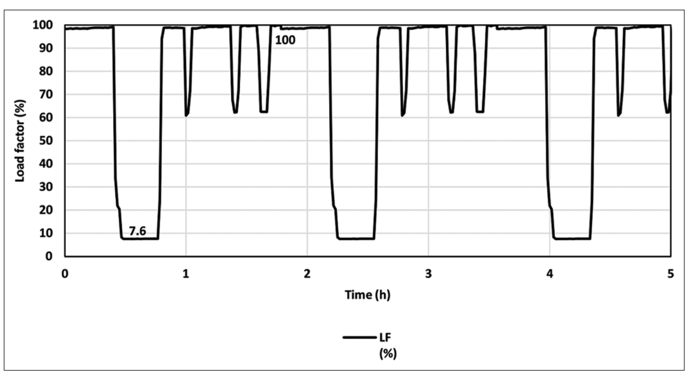
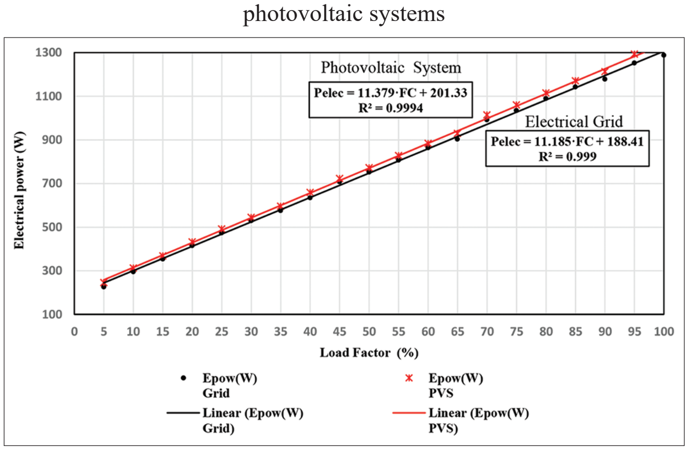


Figure 4: Linear regression models of the electrical power of the three-phase induction motors supplied from the electrical grid and the photovoltaic systems



3. RESULTS AND DISCUSSION

3.1. Results of the Experimental Evaluation under Laboratory Conditions

The measurements taken on the TIM, operating both from the conventional grid and the PVS, underwent statistical analysis. An average was computed considering the slight variation in the measured parameters. The results of these measurements are presented in detail in Table 1 for the TIM powered by the grid and Table 2 for the TIM powered by the PVS. These tables provide a comparative view of the operational characteristics of the TIM under different power sources, highlighting the obtained average values and supporting the statistical analysis conducted.

The Tables 1 and 2 show that, at each load level, the mechanical parameters remain constant for both feeding conditions. In contrast, the electrical parameters exhibit significant variations, attributable to differences in the electrical supply conditions.

Figure 5 illustrates the behavior of the voltage in both conditions, while Figure 6 represents the behavior of the power factor when the TIM is powered from the electric grid and from the PVS.

Figure 5 shows that the voltage in the PVS is higher than that from the Electric Grid. The average voltage in the PVS is 1.2% higher, increasing by 2.8 V, attributed to the presence of capacitors in the DC/AC (direct current/alternating current) inverters (Hu and Gong, 2015). An unregulated increase in voltage can result in the deterioration of control and automation systems powering the motors, as well as an increase in core losses and reactive power consumption (Chuang et al., 2019).

In Figure 6, it is observed that the power factor of the TIM powered by the PVS is lower compared to the supply from the Electric Grid, caused by the increase in the supply voltage induced by the inverter. In industrial environments with multiple TIMs, this effect can affect the system's total power factor and lead to billing penalties.

Figures 7 and 8 present the behavior of total harmonic distortion (THD) of voltage, which characterizes voltage harmonics, and the k-factor, which represents current harmonics, respectively.

Figure 7 shows that the total harmonic distortion of voltage (THDV) with the PVS supply is significantly higher than the supply from the Electric Grid. While the THDV with the Electric grid supply does not exceed 1%, the PVS supply is higher, ranging from 2.9% to 3.4%. According to a study presented by (Sousa Santos et al., 2019), these values suggest a reduction in efficiency of more than 1.5% in a TIM.

In Figure 8, it is evident that the k-factor generated by the PVS is also higher than that of the Electric Grid. While on the Grid, that value does not exceed 0.2%, with the PVS supply, it is more significant than 1.3% and reaches up to 1.5%. Studies indicate that when the k factor exceeds 1, losses occur in copper and magnetic components due to harmonics (Gómez et al., 2016). The voltage

Table 1: Measurements of the TIM connected to the Electrical grid

LF (%)	Moment (Nm)	Speed (rpm)	Mpow (W)	V (V) Grid	I (A) Grid	Epow (W) Grid	PF (pu) Grid	THDV (%) Grid	KFactor (%) Grid	Efic (%) Grid
5	0.15	3564	57	219	2.3	226	0.26	0.88	0.14	25.4
10	0.31	3560	114	219	2.3	295	0.33	0.88	0.13	38.8
15	0.46	3555	171	219	2.4	354	0.39	0.89	0.12	48.5
20	0.61	3551	228	219	2.4	415	0.46	0.89	0.11	55.0
25	0.77	3546	285	219	2.5	474	0.51	0.91	0.11	60.1
30	0.92	3540	341	219	2.5	530	0.56	0.91	0.10	64.5
35	1.07	3534	398	219	2.5	576	0.62	0.91	0.09	69.1
40	1.23	3528	454	219	2.6	634	0.65	0.91	0.08	71.6
45	1.38	3521	509	219	2.7	708	0.70	0.93	0.08	72.0
50	1.54	3514	565	219	2.8	752	0.72	0.93	0.07	75.1
55	1.69	3507	620	219	2.8	807	0.76	0.93	0.07	76.8
60	1.84	3499	675	218	2.9	863	0.78	0.92	0.06	78.2
65	2.00	3491	730	218	3	903	0.80	0.94	0.06	80.8
70	2.15	3483	784	218	3.2	992	0.82	0.92	0.06	79.0
75	2.30	3474	838	218	3.3	1035	0.82	0.95	0.06	81.0
80	2.46	3464	891	218	3.4	1089	0.84	0.95	0.06	81.8
85	2.61	3455	944	218	3.6	1142	0.83	0.94	0.07	82.6
90	2.76	3445	997	218	3.7	1178	0.84	0.94	0.08	84.6
95	2.92	3434	1049	218	4.1	1252	0.81	0.95	0.08	83.8
100	3.07	3423	1101	218	4.2	1288	0.81	0.95	0.10	85.4

TIM: Three-phase induction motors

Table 2: Measurements of the TIM connected to the PVS

LF (%)	Moment (Nm)	Speed (rpm)	Mpow (W)	V (V) PVS	I (A) PVS	Epow (W) PVS	PF (pu) PVS	THDV (%) PVS	KFactor (%) PVS	Efic (%) PVS
5	0.15	3564	57	222	2.6	246	0.24	2.87	1.52	23.3
10	0.31	3560	114	222	2.6	312	0.32	2.90	1.44	26.6
15	0.46	3555	171	222	2.5	369	0.38	2.98	1.44	46.5
20	0.61	3551	228	222	2.5	432	0.44	2.89	1.53	52.8
25	0.77	3546	285	222	2.6	491	0.49	2.98	1.38	58.0
30	0.92	3540	341	222	2.6	544	0.54	3.01	1.40	62.7
35	1.07	3534	398	221	2.7	596	0.58	2.94	1.42	66.7
40	1.23	3528	454	221	2.7	659	0.63	3.06	1.37	68.8
45	1.38	3521	509	221	2.8	723	0.67	3.12	1.39	70.5
50	1.54	3514	565	221	2.9	772	0.70	3.18	1.40	73.2
55	1.69	3507	620	221	3	828	0.72	3.14	1.39	74.9
60	1.84	3499	675	221	3.1	884	0.76	3.20	1.40	76.4
65	2.00	3491	730	221	3.2	930	0.77	3.20	1.36	78.5
70	2.15	3483	784	221	3.3	1015	0.80	3.26	1.34	77.2
75	2.30	3474	838	221	3.4	1060	0.81	3.25	1.39	79.0
80	2.46	3464	891	221	3.6	1115	0.82	3.28	1.35	79.9
85	2.61	3455	944	221	3.8	1170	0.81	3.27	1.33	80.7
90	2.76	3445	997	221	3.9	1213	0.81	3.29	1.35	82.2
95	2.92	3434	1049	221	4.2	1293	0.81	3.35	1.30	81.1
100	3.07	3423	1101	221	4.4	1321	0.79	3.35	1.25	83.3

TIM: Three-phase induction motors, PVS: Photovoltaic systems

and current harmonics measured in the PVS supply are due to the process of converting direct current to alternating current, which involves the use of nonlinear devices such as transistors and thyristors, which distort the waveform (Akin et al., 2008).

Figures 9 and 10 present the TIM's current consumption and electrical power respectively when powered directly from the Electric grid and from the PVS.

Figure 9 shows the increase in the current consumption of the TIM in the range of 0.1 A to 0.4 A when powered from the PVS compared to the Electric grid supply. This increase in current consumption translates to a rise in electrical power, ranging from 14.9 W to 40.8 W, as illustrated in Figure 10. The increase in current and electrical power in the TIM powered by the PVS is attributed to the effect of voltage and current harmonics, resulting in higher losses in the TIM. Consequently, when powering the same load, the TIM requires a higher demand for current and electrical power than direct supply from the Electric grid (Sousa et al., 2017).

The efficiency behavior of the TIM, when powered from the PVS and the Electric Grid, is presented in Figure 11.

It is evident from Figure 11 and Tables 1 and 2 that the TIM powered by the PVS exhibits lower operational efficiency compared to direct

Figure 5: Supply voltage of the three-phase induction motors connected to the electric grid and photovoltaic systems

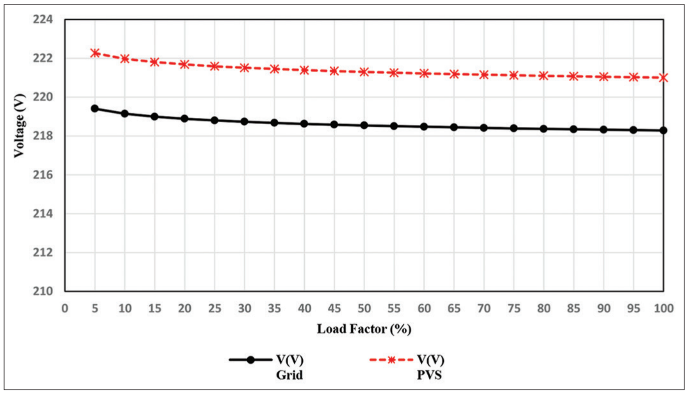


Figure 6: Power factor measured in the three-phase induction motors connected to the electric grid and photovoltaic systems

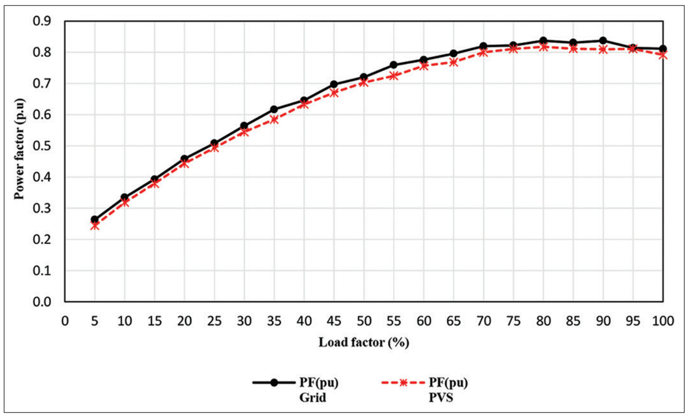
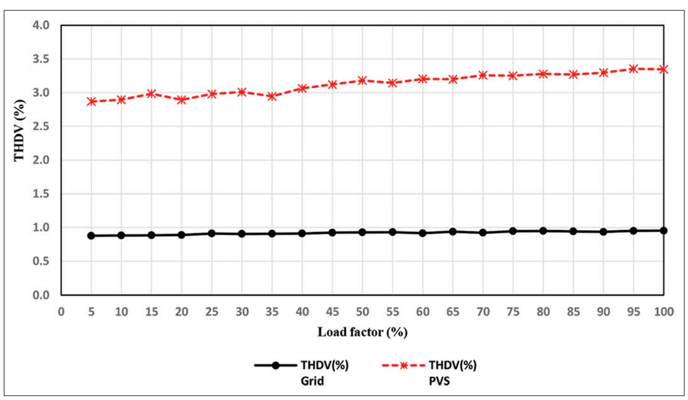


Figure 7: Voltage total harmonic distortion in the three-phase induction motors connected to the grid and to the photovoltaic systems



supply from the Electric Grid. This decrease in efficiency ranges between 1.5% and 2.7%, attributable to the effect of voltage and current harmonics generated by the PVS. This finding is consistent with previous studies, such as those reported by (Sousa et al., 2016), where the impact of harmonics on TIM efficiency was evaluated.

3.2. Results of Real-time Motor Operation Modeling

Figure 12 presents the behavior of the electrical power demand corresponding to the load factor in Figure 4, obtained through linear regression models shown in Figure 5, as a results of the real-time motor operation modeling.

Figure 8: Factor K measured in the three-phase induction motors connected to the grid and to the photovoltaic systems

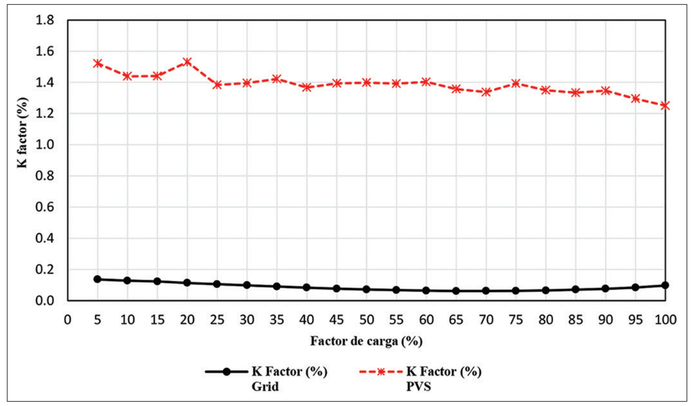


Figure 9: Current consumption of the three-phase induction motors connected to the electrical grid and to the photovoltaic systems

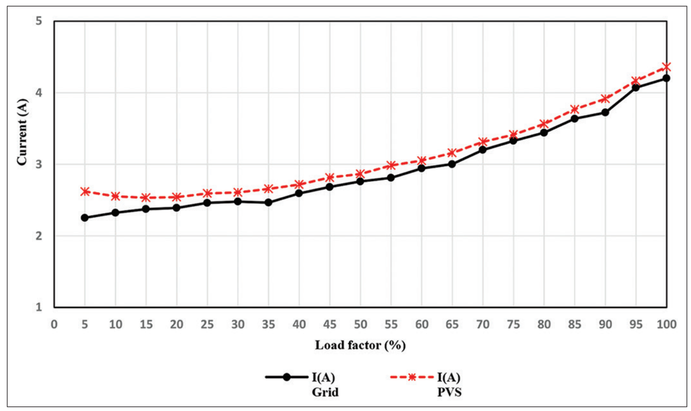


Figure 10: Electrical power demand of the three-phase induction motors connected to the electrical grid and to the photovoltaic systems

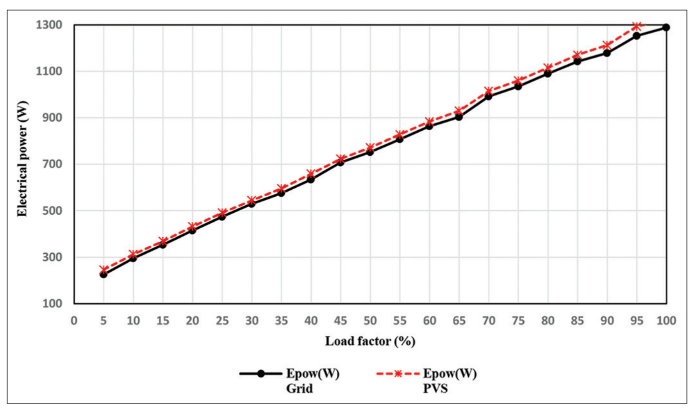


Figure 12 shows that the electrical power demanded by the TIM was higher when powered by the PVS compared to the supply from the Electric Grid. In the case of the Electric grid supply, the electrical power ranged between 273 W and 1306 W, while when powered by the PVS, the variation was from 288 W to 1338 W.

Figure 13 presents the energy consumption over 5 h of operation, both when the Electric grid powered the TIM and when it was powered by the PVS.

Table 3: Energy losses incurred when the PVS powers the TIM

Condition	Energy (kWh/day)	Energy (kWh/year)	Difference (%)	Difference (kWh/year)
Electrical Grid	5,1	1543	2,6	41
PVS	5,3	1584		

TIM: Three-phase induction motors, PVS: Photovoltaic systems

Figure 11: Efficiency of the three-phase induction motors connected to the electrical grid and to the photovoltaic systems

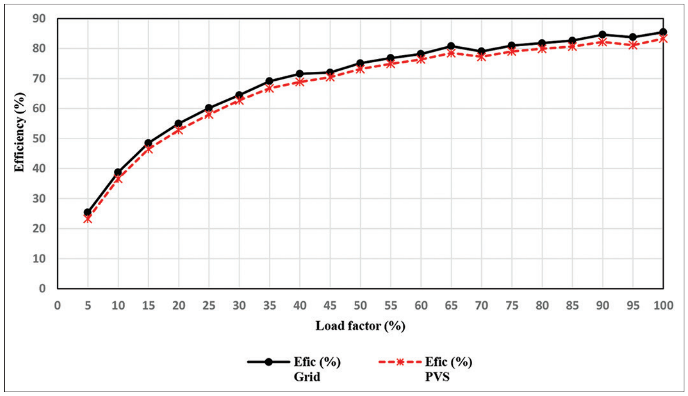


Figure 12: Electrical power demand of the three-phase induction motors connected to the electrical grid and to the photovoltaic systems during 5 h of operation

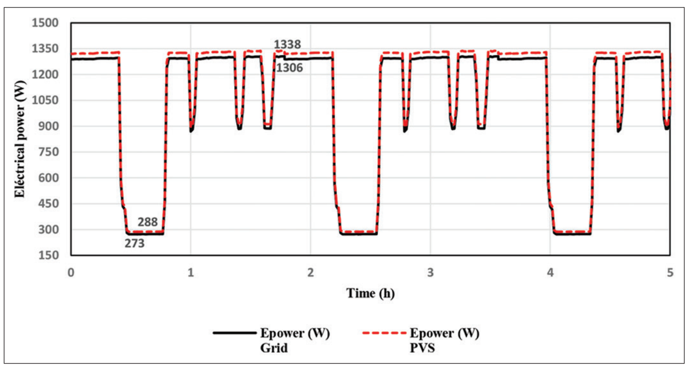


Figure 13: Energy consumption by the three-phase induction motors connected to the grid and the photovoltaic systems during 5 h of operation

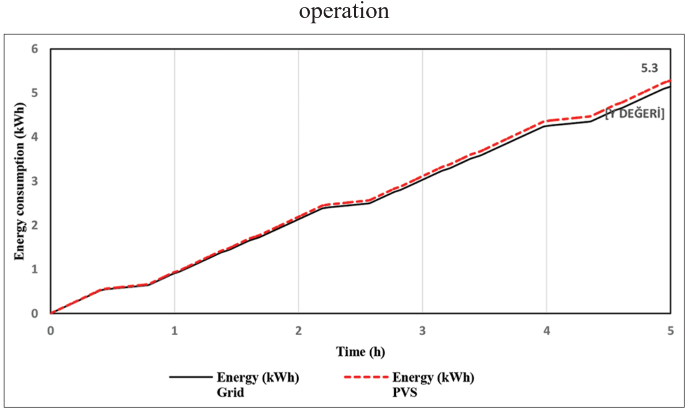


Table 3 presents the annual energy consumption over 5 h, considering 300 days of operation per year and the percentage of energy loss when powered by the PVS.

Table 3 demonstrates a 2.6% increase in energy consumption when powered from the PVS. This rise is notable, particularly considering that in TIMs, achieving a reduction in consumption equal to or >1% is deemed significant according to (Waide and Brunner, 2011). This phenomenon is attributed to the intensive use of TIMs in the industrial sector, where operation exceeds 6000 h per year according to (Hasanuzzaman et al., 2011).

Based on the results obtained, which demonstrated increases exceeding 2% in TIM consumption when powered by a power supply (PVS), the following technical criteria are recommended, especially in electrical systems where TIMs prevail:

- Use of voltage regulators at the output of the converter to ensure that the supply voltage is close to the nominal voltage of the TIMs. This measure prevents excess voltage, which can increase core losses or damage automatic control devices (Adekitan et al., 2018).
- Implementation of harmonic filters or the use of inverters with more than six pulses; this measure aims to avoid supplying TIMs with levels of voltage and current harmonics that may increase losses, overheating, energy consumption, and reduce efficiency and the lifespan of TIMs (Sousa Santos et al., 2019).

4. CONCLUSION

The review of the state of the art regarding renewable energy sources (RES) and PVS revealed that, while the use of alternative energies brings benefits in reducing greenhouse gas emissions associated with coal-based energy sources, it also presents challenges for the operation of electrical systems.

Studies highlight the repercussions that PVS have had on the operation of distribution circuits, mainly due to issues of instability in energy generation, frequency regulation, harmonic generation, and reactive power instability. However, these studies do not directly analyze the influence that PVS may have on the operation of TIMs, which motivated the present research.

In the conducted study, where the behavior of electromechanical parameters and energy efficiency of a 1.1 kW TIM powered from the grid and a PVS was compared, it was demonstrated that with power supply from the PVS, problems of voltage regulation and increased voltage and current harmonics arose. These issues, originating from capacitors and nonlinear elements of the inverter, resulted in a decrease in power factor, an increase in current and electrical power demand, as well as a reduction in the operational efficiency of the TIM by up to 2.7%, compared to power supply from the grid. Under real load variation conditions, the same TIM consumed 2.6% more energy when powered from the PVS than the electrical grid.

Considering these results, this research seeks to draw the attention of entities involved in installing and operating PVS, urging them to consider the quality of the energy that these systems supply in circuits where TIMs predominate, as energy consumption could increase considerably.

5. ACKNOWLEDGMENTS

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