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Single-Phase Induction Motors and the Challenge of Energy Efficiency in Brazil: A Critical and Proposed Analysis

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Abstract. There is a global effort to optimize energy use and reduce the consumption of fossil fuels, aiming to decrease greenhouse gas emissions as a strategy for mitigating climate change. One way to improve this situation is by addressing the demand side, such as regulating trade and producing energy-consuming equipment. Among the devices that consume the most electricity are electric motors, which use about half the electricity available in industrialized countries. Some countries have already included single-phase electric motors in their Minimum Energy Performance Standards (MEPS). Single-phase motors are commonly used in applications where, three-phase motors are limited and the power demand is typically lower, such as in residential, rural, commercial, and service settings. Despite the significant market presence of this type of motor in Brazil, with approximately 55 million units consumed in 2019, Brazil has not yet implemented MEPS for single-phase motors. Considering this context, this study aims to evaluate the possibility of including MEPS for single-phase motors in Brazil in three stages. Firstly, *i*) a literature review of MEPS for single-phase motors worldwide was conducted. Subsequently, *ii*) an evaluation of 25 single phase motors from 11 different manufacturers that are sold in Brazilian market was done to check how was the efficiency level of these motors. *iii*) a proposal for the adoption of MEPS for single-phase electric motors in Brazil is presented. Additionally, lastly *iv*) an estimate of energy savings from the implementation of MEPS for single-phase motors in three scenarios over a 30-year horizon is presented.

Keywords: Energy Efficiency, Single-phase electric motors, Minimum Energy Performance Standards (MEPS), Environmental Sustainability, Brazilian Energy Policy.

1 Introduction

In accordance with the findings reported by the International Energy Agency (IEA), it was observed that global energy efficiency gains needed to increase by 4% annually

through 2030 for nations to meet the objectives established by the Paris Agreement [1]. One approach to achieve these targets involved striving for energy efficiency. Numerous countries have implemented regulations governing the production and trade of equipment within their jurisdictions, aiming to prevent the commercialization of energy-inefficient devices [2].

Regarding end-uses, electric motors comprised a group of equipment that were identified as the primary consumers of electricity worldwide, accounting for approximately 70% of industrial electrical consumption in developed countries [3], [4]. Consequently, the establishment of Minimum Energy Performance Standards (MEPS) was deemed extremely important [5]. In the context of motors, it was noted that most of the observed MEPS were restricted to Three-Phase Induction Motors with Squirrel Cage Rotors (TPIM) [6]. However, some countries or economic blocs had also established MEPS for Single-Phase Induction Motors (SPIM), including, for instance, the United States of America (USA) and the European Union (EU).

In this study, an analysis was conducted on the energy efficiency of SPIM, covering since from the origins of international regulations to current practices. Section 1.1 addressed the evolution of regulations and the standards established for the classification of electric motors. Section 2 presented the main types of SPIM and their applications. Section 3 focused on presenting key developments in the specific regulatory policies of the USA, EU, and other territories. Sections 4, 5, and 6 were dedicated to the statistical analysis of SPIM available in the Brazilian market and their average efficiency, to the simulation of implementation scenarios for MEPS for SPIM, and to the gains in energy efficiency over a 30-year period.

1.1 Regulations and standards for the energy efficiency of electric motors

The regulation of the production and trade of TPIM was initiated almost concurrently worldwide, beginning in the USA in 1997, with varying paces of implementation during the early decades of the 21st century [7], [8]. This led to the necessity for the standardization of motor classification nomenclature. The International Electrotechnical Commission (IEC) proposed the development of international labeling standards that subsequently influenced various regulations globally. The resulting nomenclature is currently utilized, ranging from IE1 for less efficient motors to IE4 for more efficient ones.

Within Brazilian territory, the entity responsible for defining technical standards is the Brazilian Association of Technical Standards (ABNT), which traditionally bases its standards on those of the IEC. The ABNT standards pertaining to Single Phase Induc-

tion Motors (SPIM) are ABNT 17094-2;2016 and ABNT 17094-4:2016. Although compliance with minimum efficiency indices is not mandatory, ABNT 17094-2 includes tables indicating IE1[1] and IE2 efficiency indices, while ABNT 17094-4 describes test methods [9], [10].

2 Types of Single-Phase Induction Motors

Various configurations of single-phase electric motors were identified, each being more suitable for a specific group of applications. Table 1 indicated the types of existing SPIM motors and highlighted some of their main characteristics.

Table 1. Main characteristics, advantages, and applications of single-phase induction motors. Source: [11], [12].

Type	ST x Rated Torque	Rated Power (kW)	Advantage	Applications
(SPSP)	1x	0.12 - 0.75	price and versatility	fans, grinder, dishwasher
(SPCS)	3x	0.18 - 2.2	ST	washing machines, pumps, air compressor
(SPCR)	1x	0.37 - 1.5	PF-efficiency	air compressor
(SPCSR)	3x	>0.75	ST-PF-efficiency	pumps, air compressor
(SSP)	0,5x	0,001 - 0.18	very low price and high versatility	fridge fan, appliances,fans

Abreviation

SPSP - Single phase split phase

SPCS - Single phase capacitor start

SPCR - Single phase capacitor run

SPCSR - Single phase capacitor start and run (also known as 'two capacitors')

PF - Power factor

ST - Start torque

[1] In Brazil, the nomenclature for efficiency ratings was slightly different, being referred to as "Índice de Rendimento" (Performance Index, or IR). IR1 was designated for the least efficient category, while IR4 denoted the most efficient.

3 MEPS for single-phase electric motors

In sections 3.1 to 3.3, the countries (and economic blocs) that implemented MEPS within their territories for Single Phase Induction Motors (SPIM) were sequentially presented.

3.1 United States of America (USA)

In the United States, a movement to implement MEPS to limit the commercialization of inefficient SPIM commenced in 2010 with the publication of energy efficiency parameters defined in DOE 75FR10874. The enforcement of rules for the marketing of motors in accordance with MEPS became effective in 2015. Between 2021 and 2023, a review of the rules established in 2015 was conducted, which essentially did not alter the energy performance parameters previously defined [13]. Currently (2024), the United States requires an energy efficiency of IE2 for SPIM of the types Single Phase Capacitor Start (SPCS) and Single Phase Capacitor Start and Run (SPCSR) ranging between 180 W and 2.2 kW.

3.2 European Union (EU)

Regulation (EU) 2019/1781 established the application of Minimum Energy Performance Standards (MEPS) for SPIM, which also included the use of Variable Speed Drives (VSD). The principal motivation cited for the application of MEPS was that the market volume of this type of electric motor had become significant, reaching 200,000 new units per year [14]. The rules came into effect in July 2023 and require an energy efficiency of IE2 for SPIM with more than 120 W [15].

3.3 Other countries adopting MEPS for SPIM

China has established MEPS for SPIM in 2021, SPCS (0,12kW up to 3,7kW), Single Phase Capacitor Run (SPCR) (0,12kW up to 2,2kW) and SPCSR (0,25kW up to 3,7kW) are included. Besides these types of SPIM the Chinese regulation was pioneer to include SPIM used in domestic air conditioning. The first Chinese standard published was GB (GUOBIAO STANDARD) 25958-2011, setting the IE1 level. It was later revised and renamed to GB 18613-2020, introducing an intermediate level called IE1.5 [16]–[18].

Ecuador implemented IE2 for SPIM through Resolución No. 17.524 of 2017, where IE2 was established for Single Phase Capacitor Start (SPCS) [19]. Fig. 1 presents a timeline highlighting key events related to MEPS for Single Phase Induction Motors (SPIM).

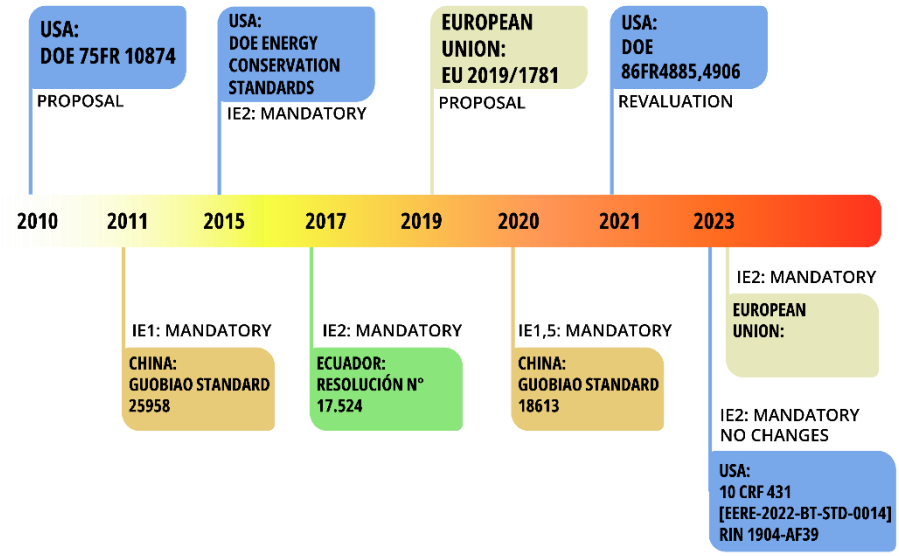

Fig. 1. Main events associated with MEPS.

4 An analysis of the energy efficiency of 25 single-phase electric motors sold on the Brazilian market

Before proposing MEPS, it was necessary to understand the efficiency of equipment available in the market. For this purpose, an analysis of the energy efficiency of SPIM marketed in the Brazilian market was conducted.

The data used in this phase of the study were collected at the Laboratory of Electrical Machines of the Institute of Energy and Environment at the University of Sao Paulo (IEE/USP). The laboratory is accredited and periodically audited by the National Institute of Metrology, Quality and Technology (INMETRO), which is a signatory to international quality treaties. The testing methodology employed was derived from the ABNT NBR 17094-4 standard, which is similar to method 2-1-1B of the IEC 60034-2-1:2014 standard [20]–[22].

A total of 25 Single Phase Induction Motors (SPIM) were tested, all two poles; these motors are available in the Brazilian market and are represented by 11 manu-

facturers, 5 imported and 6 national brands. The results obtained are presented in Fig. 2.

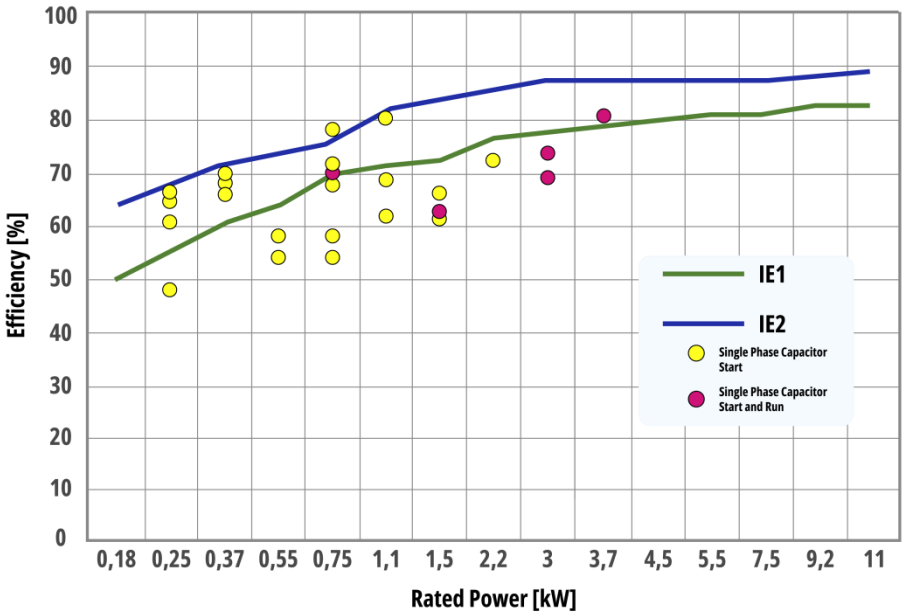

Fig. 2. Main events associated with MEPS.

From the study of MEPS for SPIM already published, it was observed that only a portion of the SPIM universe is covered by the MEPS, as most motors have specific end uses and are typically integrated into other parts that constitute a piece of equipment. Consequently, SPIM that cannot be separated for individual testing fall outside the scope of MEPS. Thus, only those SPIM that compete with Three-Phase Induction Motors (TPIM) in their end uses are subject to MEPS.

An important detail is that Single Phase Shaded Pole (SSP) are not covered by any regulation. Regarding Single Phase Split Phase (SPSP), the American standard does not include them in its regulation, while the European standard does not specify electric motors by type. Single Phase Split Phase (SPSP) have a low starting torque and their application is limited to domestic uses. They are commonly integrated into other parts in a way that they cannot be tested separately, as in refrigerator compressors.

Based on the international pratices the MEPS for Single Phase Induction Motors (SPIM) in Brazil should include:

- Single Phase Capacitor Start (SPCS) and Single Phase Capacitor Start and Run SPCSR, with the possibility of extending to Single Phase Capacitor Run (SPCR) and Single Phase Split Phase (SPSP), provided they can be tested separately.
- To align with the regulation of Three-Phase Induction Motors, motors with power starting from 120 W could be covered by the regulation.
- SPIM operating under S1 (continuous) duty and that are not for special applications (explosive atmospheres, submerged operation, operation at extreme temperatures, etc.).

5 An estimate of the energy gains obtained by MEPS for SPIM in Brazil

To estimate the energy impact of MEPS for SPIM, the methodology proposed by Bortoni et al. (2013) [23] was used. This methodology involves presenting three distinct scenarios to simulate the savings achieved. The first scenario, called the base scenario, consists of a fleet of SPIM installed over 30 years without regulation. The second scenario, termed the intermediate scenario, involves regulation for motor trade requiring that the efficiency levels of SPIM be IE1, while the third scenario, called the ideal scenario, assumes that all SPIM marketed in the Brazilian territory are of IE2 level. A standard motor represents the entire motor population. Figure 3 shows the 5 steps of the methodology used.

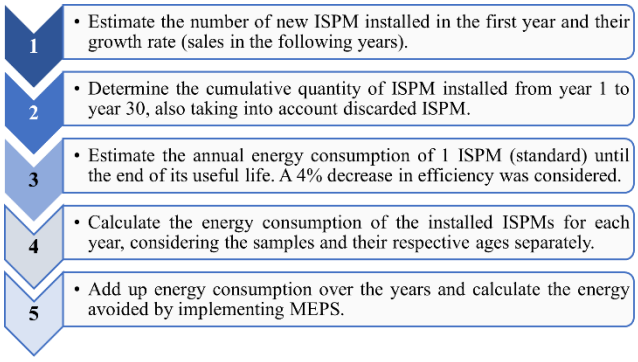

Fig. 3. Flow of steps to simulate the energy impact of MEPS for SPIM in Brazil.

Initially, the simple average of annual sales of Single Phase Induction Motors (SPIM) covered by the proposed MEPS was considered, based on annual sales data provided by the National Association of Brazilian Electrical Equipment Producers. The sales growth rate used was estimated at 1%, according to scenarios from the Brazilian Energy Plan Horizon 2050. To estimate the number of SPIM installed in a given year, equation (1) was used.

$$M_j = \left(\sum_{i=j-n}^{j} Si\right) - D_j \quad (1)$$

Where (M) represents the quantity of motors installed in a year (j), (n) is the average life expectancy of the SPIM, (Si) is the quantity of SPIM sold in year (i), and (Dj) is a disposal function describing a number of SPIM discarded over the lifespan of an SPIM. For simplicity, it was assumed that at the end of its useful life, the SPIM was discarded, not rewound and used again.

In the second step for SPIM, a lifespan of 11 years [24] was considered. In the third step, the annual energy consumption of 1 standard SPIM until the end of its lifespan was estimated, with a decrease in efficiency of 4% over its life [25]. The parameters presented in Table 2 were used in this study.

Table 2. Parameters of standard sample of induction single phase motor.

Rated Power kW-HP	0,55-0,75
Load Factor	55%
Hours Use/ Year (h)	800
$f_{LF\_55\%}$[2]	0,975

The calculation of energy consumed by an SPIM is given by equation (2). Where (EC) represents the annual energy consumption (kWh), (P) is the nominal power of the SPIM in (HP), (LF) is the load factor, (T) is the annual operating time of the motor, (EFF) is the efficiency reported by the manufacturer, (f_{age}) is the age factor of the motor, and (f_{LF}) is the load efficiency factor.

[2] f_{LF} - is related to motor alignment.

$$EC_j = \frac{0{,}745 * P * LF * T}{EFF * fage * fLF} \quad (2)$$

In the third step, the annual consumption of the installed fleet of Single Phase Induction Motors (SPIM) was calculated, taking into account the active SPIM, their age, and the annual disposal of units over eleven years old. The overall average energy consumption of a group of motors OECj (MWh) was determined by considering the annual average energy consumption of a given motor ECj and the installed quantity of motors (M) in that particular year (j), as described in equation (3).

$$OECj = Mj * AECj \quad (3)$$

To perform the calculations, a standard motor of 0.75 HP, two-pole, single-phase with one start capacitor was considered as representative of the entire motor fleet. The results considered a base scenario composed of 75% SPIM IE1 and 25% SPIM with an efficiency level of 91% of IE2. Fig. 4 displays the consumption over 30 years of the three proposed scenarios, and Table 3 indicates the energy consumption provided in each situation. The estimated savings are the differences between the scenarios.

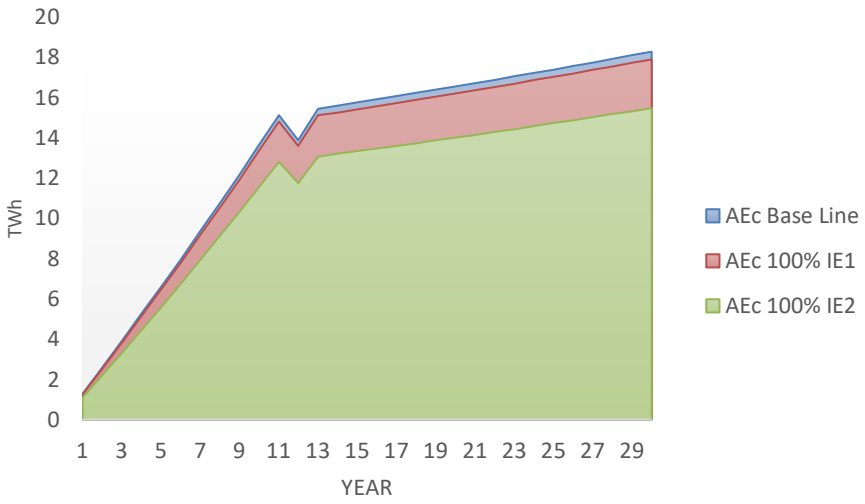

Fig. 4. Energy consumption over 30 years in the 3 scenarios.

Table 3. Parameters of standard sample of induction single phase motor.

Total Consumption Over 30 Years (TWh)	
Base line	404,8
100% - IR1	396,2
100% - IR2	342,7

It was observed that the implementation of MEPS for Single Phase Induction Motors (SPIM) with a minimum index of IE1 resulted in a gain of 8.6 TWh of energy over 30 years. And the shift to IE2 has the potential for a gain of 53.5 TWh in the same period. The IE2 gains represent approximately 10% of the energy consumed by Brazil in the year 2011.

6 Conclusions

It was observed that the first MEPS for Single Phase Induction Motors (SPIM) were applied to those that are direct competitors of Three-Phase Induction Motors, being SPIM for general uses, part of specific electrical equipment can be included as long as they can be tested separately..

The MEPS in China for SPIM in fans and air-conditioning are fractional motors. This indicated the potential for inclusion of SPIM within the scope of upcoming MEPS, which would require an additional study for the Brazilian market.

The tests conducted on 25 motors from 11 different manufacturers indicated that the SPIM marketed in the Brazilian market mostly have efficiency indices below IE2, and 60% of them are below IE1, which could be referred to as IE0.

The study showed that over 30 years, the energy gains would be 10% of the energy consumed by the country in the year 2011.

A possible path for the use of MEPS for SPIM would be: first regulate IE1 for Single Phase Capacitor Start (SPCS) and IE2 for Single Phase Capacitor Start and Run (SPCSR) and after a while of adaptation for stakeholders, replace all SPCS motors with SPCSR leaving only IE2 motors on the Brazilian market. Additional benefits of this path would be improve the power factor of the electric system and reduce energetic losses due to the Joule effect in the same system.

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