Induction motors with copper rotor: a new opportunity for increasing motor efficiency

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Article Info

Article history:

Received Jun 1, 2022
Revised Jul 8, 2022
Accepted Aug 18, 2022

Keywords:

Copper rotor induction motor
Economic feasibility
Electric motors
Energy efficiency
High-efficiency motors

ABSTRACT

The copper rotor induction motor (CURIM) was recently introduced because it has lower rotor fusion losses than the aluminum rotor (ALRIM). Furthermore, with CURIM, it is easier to reach IE4 and IE5 efficiency levels. The CURIM is advantageous for compact motors, escalators, and electric vehicle applications. However, CURIMs present slip, power factor, temperature increase, and torque decrease problems that must be analyzed. This study compared the economic feasibility of using CURIM with ALRIM by applying discount techniques. A case study was carried out in a sugar company with a cyclical operation, where 5.5 kW motors will be installed in the intermediate conductors of the mill's feeders. The facility works three shifts between 3 and 6 months. The cost increase (ΔCI) of CURIM over ALRIM was between 1.1 and 1.5 times. With 3,600 h/year and 4,000 h/year of operation, the ΔCI greater than 10%, it was found that the payback is more than four years, and the net present value (NPV) grows linearly.

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1. INTRODUCTION

A significant reduction in rotor losses is achieved using copper rotor induction motors (CURIM) instead of aluminum rotor induction motors (ALRIM). This is mainly because the electrical conductivity of copper is approximately 170% that of aluminum; therefore, the total machine losses also decrease. In a medium power induction motor, from 15% to 25% of the total losses, the efficiency increases from 2% to 5% [1], [2]. However, problems regarding the copper casting process have had to be solved first due to the high melting temperature of copper compared to aluminum (1,083 °C for copper compared to 660 °C for aluminum). The fundamental difficulties that appeared were shortened life of the die, oxidation in the casting process of pure copper, and porosity distributed in the molten copper [2].

As the electric power cost grew, awareness grew that the motor life cycle cost is essential, and consumers realized the convenience of paying a higher initial cost for more efficient motors [3]. Additionally, a driving factor has been government regulations and incentives. So, many companies and associations have worked to eliminate the drawbacks of copper casting and have developed die materials and casting processes for rotor manufacturing, which have made mass production possible and economical [1], [2], [4].

With copper rotors, super-premium (IE4) and ultra-premium (IE5) efficiency induction motors can be made without increasing the frame. As copper's conductivity is higher than aluminum's, the rotor current in CURIM is higher. Then, the power developed is higher for the same induced electromotive force. Smaller materials can also be used for the same power output with efficiency [5]. Thus, the CURIM may have a lower cost, lower weight, and less volume than an aluminum rotor. At the same time, the excellent copper anti-corrosion characteristics can make rotors more reliable. These advantages give designers and manufacturers more excellent maneuverability to obtain greater efficiency, more reliability, lower cost, lower volume, and weight or seek a balance between these factors. Mature copper die-casting technology has provided a simple, reliable, economical, and practical way to improve motor efficiency for manufacturing [6], [7].

Considering the preceding, this paper compares CURIMs with ALRIMs based on construction characteristics and associated costs, operation, losses, electromechanical, energy, and temperature characteristics. The characteristics of CURIMs in applications such as escalators and electric vehicles are presented, where a higher density in the rotor and a higher degree of compaction than with ALRIMs stand out. Finally, an economic feasibility study of replacing a 5.5 kW motor in a sugar factory is conducted by comparing the results of replacing a CURIM with an ALRIM of equal capacity.

2. METHOD

2.1. Structure and principles of CURIM

There were three fundamental obstacles to eliminating or reducing the difficulties in copper rotor casting [1]. Oxidation in the casting process of pure copper should be avoided when copper is melted. It reacts with oxygen in the air, forming copper oxide, which reduces conductivity, affecting efficiency. While it is easy to prevent oxidation in a laboratory, it is more challenging to do it in the factory, in a mass production process. So, a suitable method is necessary to avoid this problem.

Porosity is distributed in molten copper. Molten copper is a very fluid material, and apart from its high melting temperature, it is easy to die cast. However, the high speed at which it enters the die cavity and the shrinking of the metal during solidification generally result in randomly distributed porosity in the molten copper. This difficulty is not only reduced in the case of copper; porosity in the bars and end rings of aluminum rotors has long been a problem. The historically known optimization of the die casting process applied in the case of aluminum rotors has reduced porosity to acceptable levels. Similar optimization is needed in the case of copper rotor melting processes.

Shortened life of the die. This is the most crucial obstacle of the three. In the case of copper rotors, the life of the die is substantially reduced due to the high melting temperature of copper (the copper rotor must be melted at least 1,200 °C). Due to these high temperatures, the life of a non-optimized copper rotor, using conventional materials and designs, is only 600 cycles, compared to the 50,000 cycles for a similar aluminum die. This places a considerable burden on the life of the die, which, if not avoided, will substantially increase the production cost of the copper rotor.

Currently, copper rotors are mass-produced through the following solutions [1]:

- Use of an antioxidant gaseous protection method. An antioxidant gaseous protection method is employed throughout the copper melting process to prevent copper oxidation during the die-casting process. With this method, the oxygen content is kept in an acceptable range between 300 and 600 ppm.
- Use of software to simulate the copper die casting process. The software has been developed to simulate copper melting to optimize the process and die design. The software simulates the casting process: filling, temperatures, fluid flow, estimation of the filling time, defect prediction such as porosity or poor fill, and die design optimization. The solidification process (during which most defects are formed) predicts where they may appear and suggests how to minimize them. The simulation can also show the effects of designing different melted copper entrant gate positions for the filling process and helps optimize the die runner design.

Extension of the useful life of the die [8] and increasing die life to acceptable levels have required many detailed changes. Among them, the most important have been preheating of the die, optimization of the material, and construction of the die mold:

- Preheating of the die. Longer die lifetimes have been obtained by preheating it to near the melting temperature of copper. If the die is not preheated, the thermal shock experienced during filling will lead to cracks that significantly reduce its life. Careful design of the heating oven is required so that the temperature range of the die remains uniform. If not, the die is deformed. The resulting thermal field simulation for a copper rotor die software has been developed to simulate temperature in the preheated and casting states. The software has also helped optimize the die heating and cooling system design.

- Optimization of the die material. The conventional critical components of the die were changed for hot mold steel based on high-temperature tungsten to prevent early failures. Those components include the injection cylinder and plunger that feeds the molten metal into the die and the mold cavity itself. The reason for the better performance of this new material is considered. Its resistance to abrasion at high temperatures. It was also determined that the surface hardening of the plunger case and the shot sleeve positively improved the performance.
- Optimization of the construction of the mold. Changing the die architecture to include replaceable inserts leads to a 2 to 4-fold increase in die life optimization of mold construction. Changing the die architecture to include replaceable inserts leads to a 2-4 fold increase in die life. In this case, the inserts in the middle of the mold that surround the pack of electromagnetic steel laminations and the end rings of the squirrel cage are designed to be rotated and interchanged, leaving the main mold structure in place. This process enables fast insert change during the casting process.

With the improvements achieved by these methods, die thousands of cycles have increased life, production costs have been reduced, and product quality [8]. Table 1 shows the average loss segregation in seven CURIMs of 11.2 kW, tested by a manufacturer, using the IEEE specification 112 standards test method B [5], [7]–[9].

Table 1. Average loss segregation in seven CURIMs of 11.2 kW [5]

Losses	Aluminum rotor	Copper rotor	Difference (W)	Difference (%)
Stator resistance	507	507	0	0
Iron core	286	286	0	0
Rotor resistance	261	157	-104	-40
Friction and windage	115	72	-43	-37
Stray load losses	137	105	-32	-23
Total	1306	1127	-179	-14

According to Table 1, the rotor resistance losses constitute the critical aspect of using copper instead of aluminum: the reduction is 40% in the measured losses, and they constitute 58% of the losses, which are reduced with the use of copper [5]. Although it seems that friction and windage losses have no relevance concerning the material used, they do. There are no fins for ventilation in copper rotors as in aluminum. Accordingly, they have a smoother surface in the end rings. The projections that constitute the counterweights to achieve balance due to inconsistencies in the rotor bars reduce this advantage, although there is usually no big problem.

Consequently, there are fewer windage losses; less heat must be dissipated so the fans can be of fewer dimensions and, therefore, more minor losses. As shown in Table 1, compared to rotors with aluminum fins, these losses are reduced from 115 to 72 W (i.e., by 37%) even with the same bearing friction. Also, less copper is required since the fins are eliminated. Also, less copper is required as the fins have been removed.

A non-uniform air gap and an unbalanced rotor negatively affect the stray load losses and increase the current component required. Uniformity in the conductivity of the rotor bars is critical. Porosity, or the presence of non-metallic elements in the rotor bars casting, also negatively influences these losses. All of this reduces the overall efficiency. In the copper rotors analyzed, a consistency in favor of CURIM is evident since there is a reduction in stray load losses from 137 to 105 W and, therefore, an increase in motor efficiency. However, the numbers shown in Table 1 cannot usually be wholly achieved in a typical rotor mass casting [5]. Apart from the loss measurements, other aspects of the motor behavior as shown in Table 2. These data show differences between copper and aluminum rotor motors, favoring the copper rotor.

Table 2. Other performance characteristics of the 11.2 kW motor [5]

	Aluminum rotor	Copper rotor	Difference	Difference (%)
Efficiency (%)	89.5	90.7	1.2	1.34
Temperature rise (ºC)	64.0	59.5 ºC	-4.5 ºC	-7.03
Full load speed (rpm)	1760	1775	15	0.85
Slip (p.u)	2.22	1.37	-0.85	-38.29
Power factor (%)	81.5	79.0	-2.50	-3.07

- Efficiency: From the total loss reduction seen in Table 1, Table 2 is shown a significant 1.2 percentage points increase in the efficiency with the copper rotor.
- Temperature rises and life expectancy: The temperature rise above ambient temperature significantly concerns motor life expectancy. A rough rule states that life can be reduced by half for every 10°C

increase in temperature. So, with the CURIM operating near design capacity and working almost 5°C lower, a relative value of a 50% increase in life expectancy can be expected [10].

- Power factor: The power factor is slightly reduced (-2.5%). However, it is only a tiny quantity of the measures that a company must face to avoid a low power factor in the entire installation. A low power factor is usually compensated by installing capacitor banks in the electrical system.

Full load speed, slip, and torque: The slip s is expressed as (1):

$$s = \frac{n_1 - n_2}{n_1} \quad (1)$$

where n_1 (rpm) is the synchronous speed of the magnetic field, and n_2 (rpm) is the rotor speed at full load.

Motors with a low slip are known as "stiff" motors, which do not reduce their speed much when the load increases. This occurs in CURIMs concerning those with an aluminum rotor, as shown in Table 2. This is an advantage when working with variable frequency drives. However, when the motor drives centrifugal loads (pumps and fans), there is a problem: the power varies with this load with the speed cube. Thus, in the case of Table 2, the CURIM full load speed is 1.00852 times greater than that of the ALRIM, so the CURIM power will be 1.02579 times greater. This effect increases consumption, even though the CURIM is more efficient than ALRIM. If this slight increase is significant, it must be analyzed to bring the centrifugal load speed down to its design value.

Table 3 shows that CURIM, which has a lower slip, develops lower torques [2], [5]. As seen in Table 3, the CURIM locked rotor torque value, the static measurement of the starting torque, is very near the ALRIM value. However, the dynamic performance of starting torque, the torque needed to get the load up and running, is reduced by over one-third. This could imply problems with starting high inertia loads. Maximum torque is also comparatively reduced [5]. Table 4 shows the data of other motors studied, comparing the loss reduction and the increase in the CURIM efficiencies concerning the ALRIM. A wide range from 3 to 200 kW is shown. In all cases, the increase in efficiency is more significant than 1% [5].

Table 3. Measured torque values for the 11.2 kW motor [5]

	ALRIM (Nm)	CURIM (Nm)	Difference (Nm)	Difference (%)
Locked rotor torque	69.0	65.0	-4.0	-6.0
Maximum torque	152.0	125.9	-26.1	-17.0
Dynamic starting torque	58.2	37.0	-21.2	-36.0

Table 4. Efficiency increase and total loss reduction in various CURIM compared with ALRIM [5]

Nominal Power (kW)	Poles	Efficiency (%) ALRIM	Efficiency (%) CURIM	Difference (%)	Loss Reduction (%)
3.0	4	83.2	86.4	3.2	19.0
5.5	4	74.0	79.0	5.0	19.2
7.5	4	85.0	86.5	1.5	10.0
11.2	4	89.5	90.7	1.2	11.4
18.8	4	90.9	92.5	1.6	17.6
30.0	4	88.8	90.1	1.3	11.6
90.0	2	91.4	92.8	1.4	16.3
200	4	92.0	93.0	1.0	12.5

2.2. Applications

2.2.1. Compact copper rotor motors

CURIMs can be designed to obtain a smaller motor for applications in gearboxes, pumps, and escalators. In these variants, the power density of the motor is improved [4], [5]. In [2], the results of two compact 75 kW motor prototypes designed to drive two compressors are shown. Table 5 shows that, compared to ALRIMs, CURIMs are shorter, and efficiency is improved from 93.8% to 94.91%. This means that the efficiency category is enhanced from IE2 to IE3, and the steel weight in the stator is reduced from 375-300 kg.

2.2.2. Copper rotor motors for escalators

Another application of CURIM has been in escalator drives. Torque is essential in the case of escalators. Usually, the starting torque is around two times the nominal for general-purpose ALRIM. Nevertheless, the minimum requirements are 2.2 to 2.5 nominal. Table 6 shows technical data of a CURIM of 11 kW, six poles. It achieves an IE3 efficiency, with a locked rotor torque of 2.95 concerning nominal.

The CURIM allows reducing, for the same frame, the length of the machine (higher power density) to adapt it to the space requirements in the stairs (another variant would be to reduce the frame by one level, keeping the nominal power and efficiency the same). The table also shows vibration and noise data [2].

Table 5. Comparison between Al and Cu compact rotors 75 kW motors [2]

Motor type	Efficiency (%)	Frame size	Steel in the stator (kg)
Copper rotor motor	94.91	225	300
Aluminum rotor motor	93.80	280	375

Table 6. Parameters for 11 kW, six pole escalator copper rotor motor [2]

Parameter	Value
Efficiency (%)	89.86
Power factor (p.u.)	0.78
Locked rotor torque (p.u.)	2.95
Vibration (m/s)	0.61
Noise (dB)	54.4
Temperature rise (^{0}C)	65.1

2.2.3. Copper rotor motors for electric vehicles

The growing market for electric vehicles is a great potential for the use of CURIM. With CURIMs, motors can be designed with high efficiency, high speed, high-power density, and outstanding behavior under overload. This machine has an advantage when operating at high speed and has a higher speed range. Although a permanent magnet motor has better starting behavior, the CURIM surpasses it in general performance characteristics at high speeds. Table 7 gives the fundamental parameters of a CURIM for an electric vehicle [2], [11]–[13].

Table 7. Parameters for a 160 kW electric vehicle [2]

Parameters	Values
Rated power (kW)	160
Rated speed (rpm)	3,000
Rated voltage (V)	380
Frequency (Hz)	50
Maximum efficiency (%)	96.2
Maximum speed (rpm)	7,000
Nominal torque (Nm)	511@1 h
Peak power (kW)	300
Peak torque (Nm)	1,700@0.5 min
Cooling type	water
Weight (kg)	280
Temperature rise (^{o}C)	65.1

2.3. Increasing CURIM efficiency

2.3.1. General considerations

The demand for higher efficiency motors increased globally [14]–[17]. The copper rotor technology is one of the easiest and most economical solutions for satisfying this demand, reaching the efficiency standard IE4 and even ultra-premium efficiency (IE5) [2]. In [18] there are several types of motors for improving motor efficiency to meet higher efficiency standards: Permanent magnet synchronous motors [19], synchronous reluctance motors [19], permanent magnet assisted reluctance synchronous motors [20], and specific variants such as the direct online start permanent magnet assisted synchronous reluctance motors with ferrite magnets for driving constant loads [21] and CURIM. Each solution has its advantages and disadvantages. However, a copper rotor is the most economical and straightforward solution to increasing motor efficiency. With CURIM, losses can be reduced without increasing the motor frame size as in ALRIM.

They have a significant advantage compared with motors using high-quality electromagnetic steel [14] or super-conductor materials as rear earth permanent magnets [20]. They also can be manufactured without changing too much the production lines. On the other hand, as the CURIM has lower resistivity than ALRIM, the rotor current will be bigger than its peer ALRIM. That means fewer materials can be used to manufacture motors with the same power and efficiency. This reduction conduces to lower materials cost, less weight, and smaller volume [22], [23]. The excellent anti-corrosion features of copper make the CURIM more reliable and have better environmental tolerance [5], [6].

2.3.2. Meeting IE4 and IE5 efficiency standards in CURIM

To meet IE4 and IE5 efficiency standards, losses have been reduced as:

- Stator copper losses: To reduce this loss, what is generally done is to enlarge the stator slot and reduce the air gap. This is easier in the case of motors having a large outer diameter. Furthermore, improving the stator winding design contributes to this task [4].
- Rotor bar losses: Moving to cast copper grade rotor bars has been the first step toward increasing motor efficiency to IE4 at a reasonable cost. However, working in the optimum rotor bar shape is also necessary [3], [24].
- Iron losses: The approaches to reduce the iron loss include reducing the silicon steel sheet thickness (from the conventional 50 mm thickness to 0.35 mm thickness) and using low loss, cold-rolled silicon steel. An additional loss reduction measure is anaerobic annealing to reduce the internal stress generated during the lamination punching process. The annealing process can repair the deformed grain, the distorted lattice, and the poorly arranged magnetic domains produced by the presence of shearing at the lamination edges. This results in an essential reduction of the hysteresis loss in the silicon steel sheet. On developing an IE4 motor, a manufacturer reports a decrease of 30% in iron loss using a post-punching annealing process [4].
- Mechanical losses: It has been found that using backward style fans and accompanying conical fan cover increases the airflow and reduces mechanical losses [18].

3. RESULTS AND DISCUSSION

3.1. Increasing CURIM efficiency

One aspect that must be considered when analyzing the economic feasibility of installing a CURIM instead of an ALRIM is that the initial cost of the CURIM is higher due to the following reasons [22], [23]: i) the cost per kg of raw copper is higher than that of aluminum; ii) copper melting requires a significantly longer cycle time (nearly 2) than that aluminum; and iii) the machining that is necessary to melt copper requires more sophisticated equipment than in the case of aluminum. The higher initial cost of the CURIM tends to be compensated by the lower energy cost (because it is more efficient than the ALRIM). However, this lower cost must be calculated precisely. A simplistic valuation leads to errors, which can even determine an investment that is not considered feasible. It is crucial to evaluate the electricity tariff [25] applied to the installation where the motor is located, with all the elements that make it up. In the tariff, it is necessary to evaluate, among others: tariff type, periods of the day for tariff application, the adjustment factor for variation in the fuel prices used in the tariffs, motor working hours, maximum demand cost, motor power factor, and system losses.

Another determining issue in the economic feasibility analysis is the investment payback period. It is not enough that the investment is recovered before the end of the useful life of the motor. The payback must be achieved at an attractive time to the investor. Therefore, other aspects should be considered using discount techniques [26], [27].

3.2. Economic analysis: a case study

The study carried out on the copper casting process at CURIM indicates that the cost of designing, casting, and installing a copper rotor motor of a specific type (that is, rated power, number of poles, voltage) built by a manufacturer, may differ from the cost of another manufacturer. Similarly, building other motor parts for similar reasons may have different costs. Analyzing the economic and operational feasibility of a specific manufacturer can lead to erroneous conclusions when installing a CURIM from other manufacturers, even if it is the same type of machine [7], [8], [21]. Thus, the analysis should be done by varying the list prices in a specific interval. Of course, it must be permanently based on a higher cost of the CURIM compared with the ALRIM.

The case study was carried out in a Cuban sugar company to install the motors in the intermediate conductors of the mill feeders. The economic analysis was carried out in a case study using the criterion of the differential net present value (Differential NPV) [27] so that the equal or almost equal costs are eliminated (for example, those related to the cost of the stator, those of installation, maintenance). According to the Ministry of Finance and Prices [25], the electricity rate applied to the company is the MID (medium voltage for 34.5 kV services, close to 110 and 220 kV substations). Following this resolution, a fuel factor is considered in the cost of energy consumption, usually identified as the K factor, whose value reflects the proportion according to which the weighted average value of the prices of all the fuels used in electricity generation varies. In the Differential NPV, the annual variation of K. The differential list price between the CURIM and the ALRIM varies between 1.1 and 1.5 times [28].

The payback period was calculated and was considered adequate for values less than four years. The useful life was set low for this type of motor (10 years) [29], [30] due to the environmental conditions in which the motor works. The following were considered: the cost of the maximum demand kW, the load factor, efficiency factor, the operating time, the discount rate, and the income tax rate. The annual operating time is determined considering that the motors work three shifts for 3 to 6 months because it is a cyclical industry whose production depends on the rainy season.

Table 8 shows the parameters for the economic analysis with the differential net present value (NPV) method [27]. The motor to be evaluated is 5.5 kW. The CURIM and ALRIM variants are 440 V, four poles, and service factor 1. The data in Table 8 are for the first year, 4,000 h/year, and a 10% cost increase rate of CURIM concerning the ALRIM. With the data of Table 8, differential NPV: 114 USD, Payback period: 4 years.

In Figure 1, the difference in cost can be observed on the investment's profitability indicators. It is inferred that increases in the initial cost above 10% do not purchase a CURIM attractive, while, if there were an increase of only 5%, it would be recovered in 2 years. If this sugar company operates continuously (8,000 h/year), the purchase of CURIM can be considered, even with a higher initial price. The results are shown in Figure 2, which shows that it is possible, under identical other conditions, to pay up to 20% more to recover the difference in 4 years.

Table 8. Parameters for economic analysis using the differential NPV method for a 5.5 kW motor [27]

Parameters	Value	Parameters	Value
Maximum Demand (MD) cost/kW	5.33 USD	CURIM cost increase rate	1.1
Load factor (LF)	0.85	CURIM initial cost	711.15 USD
CURIM rated efficiency	92.7%	Differential cost	64.65 USD
ALRIM rated efficiency	91.7%	Discount rate	15%
CURIM efficiency at LF	92.5%	Income tax	35%
ALRIM efficiency at LF	91.3%	Lifespan	Ten years
CURIM annual operational time	4,000 h	Annual depreciation	6.47 USD
ALRIM annual operational time	4,000 h	Cash flow	22.52 USD
Differential energy saving	26.92 USD	Real discount rate	0.15
MD energy saving	4.25 USD	Discount factor	0.87
Total differential saving	31.17 USD	K factor initial value	1.041
Income	31.17 USD	Annual K factor increase	18.96%
Expenses	0.0 USD	Energy average cost	0.10 USD/kWh
ALRIM initial cost	646.50 USD	Differential input power	0.07 kW

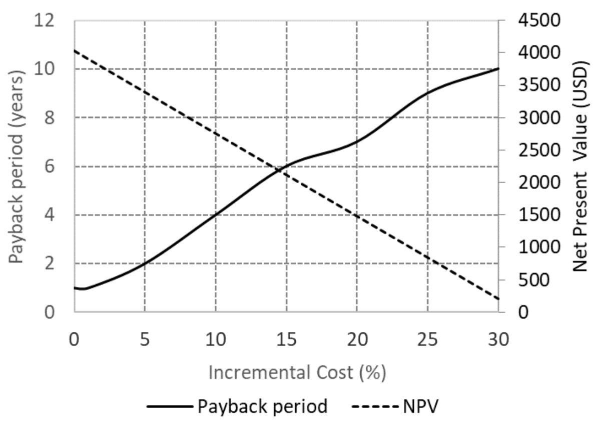

Figure 1. NPV and Payback period function as the initial incremental cost for 4,000 h of operation

As the Cuban sugar industry is cyclical, the harvest goes on only part of the year then the factory operating time can vary from three to six months. For this reason, a sensitivity analysis is made, considering the variable operation time in that range. For example, Figure 3 shows the results for an incremental cost of 10%. The payback period is around four years from five months (3,600 h/year), and the NPV grows linearly with working time.

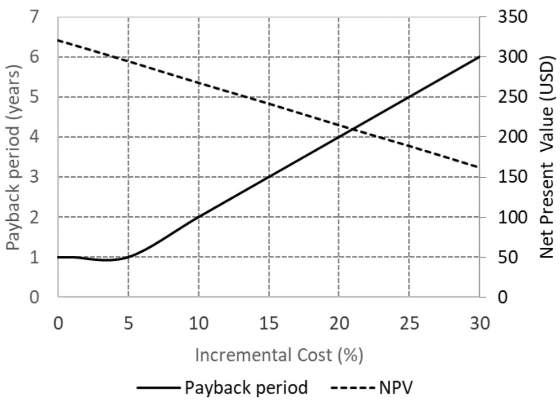

Figure 2. Payback period and NPV as a function of initial differential cost and 8,000 hours of operation

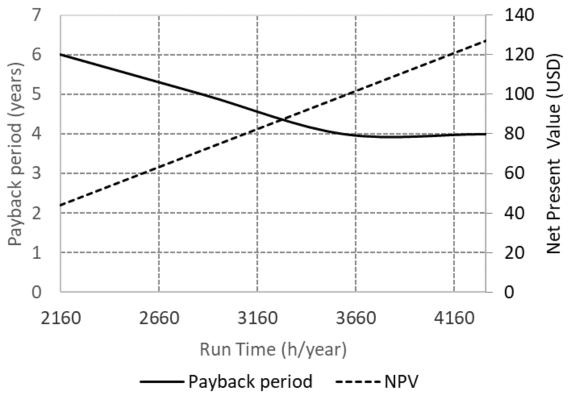

Figure. 3. NPV and payback period as a function of initial incremental cost and variable operating time

4. CONCLUSION

The study evaluated the advantages and disadvantages of CURIMs, as one of the new technological improvements of induction motors to increase energy efficiency. As a result, it was possible to show that the copper losses of the rotor, friction, and beating, and the additional losses are lower in the CURIM than in the ALRIM, and therefore the efficiency is higher. This is due to the characteristics of the molten copper and the design and manufacturing factors of the rotor. It is also shown that increasing the efficiency level of CURIM up to IE4 and IE5 is possible with cheap and relatively simple solutions, without the need to increase the size of the frame as in ALRIM or increase costs through superconducting materials. On the other hand, the CURIM has disadvantages to the ALRIM in terms of the greater complexity and costs associated with the copper smelting process, the increase in temperature, the slip, and the decrease in the power factor. Locked rotor torque, starting dynamics, and peak torque also decrease according to load characteristics.

In a case study in a Cuban sugar company with a cyclical operation, an economic analysis was carried out using the differential NPV to determine the economic feasibility of using CURIMs. The study evaluated the replacement of motors of 5.5 kW, 440 V, four poles, service factor 1, and helpful life of 10 years. An increase in the cost of CURIM over ALRIM between 1.1 and 1.5 times. With 4,000 h/year of operation and increases in the initial cost more significant than 10%, the payback is greater than four years, and the investment is not attractive. A sensitivity analysis found that, from 3,600 h/year, the payback is maintained at four years and that the NPV grows linearly with time. The study demonstrated the multiple variables that must be considered in evaluating the feasibility of using CURIMs to ALRIMs. Therefore, it is imperative to continue delving into these factors.

REFERENCES

[1] D. Liang, J. Yu, X. Yang, and V. Zhou, "Copper rotor motors in China," in *2013 International Conference on Electrical Machines and Systems (ICEMS)*, Oct. 2013, pp. 2031–2034, doi: 10.1109/ICEMS.2013.6713191.

[2] D. Liang, L. Gao, and V. Zhou, "Recent trend development for high performance copper rotor motors in China," in *2018 21st International Conference on Electrical Machines and Systems (ICEMS)*, Oct. 2018, pp. 2571–2575, doi: 10.23919/ICEMS.2018.8549253.

[3] S. Lie and C. Di Pietro, "Copper die-cast rotor efficiency improvement and economic consideration," *IEEE Transactions on Energy Conversion*, vol. 10, no. 3, pp. 419–424, 1995, doi: 10.1109/60.464863.

[4] D. Liang, X. Yang, J. Yu, and V. Zhou, "Experience in China on the die-casting of copper rotors for induction motors," in *2012 XXth International Conference on Electrical Machines*, Sep. 2012, pp. 256–260, doi: 10.1109/ICElMach.2012.6349874.

[5] D. T. Peters, J. G. Cowie, E. F. Brush, and D. J. Van Son, "Copper in the squirrel cage for improved motor performance," in *IEEE International Electric Machines and Drives Conference* 2003, *IEMDC'03*, vol. 2, 2002, pp. 1265–1271, doi: 10.1109/IEMDC.2003.1210402.

[6] S. Yamamoto, "Overview of the latest research and development for copper die-cast squirrel-cage rotors," in *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, May 2018, pp. 1949–1954, doi: 10.23919/IPEC.2018.8507971.

[7] D. Liang and V. Zhou, "Recent market and technical trends in copper rotors for high-efficiency induction motors," in *2018 International Power Electronics Conference (IPEC-Niigata 2018 -ECCE Asia)*, May 2018, pp. 1943–1948, doi: 10.23919/IPEC.2018.8507879.

[8] M. Thieman, R. Kamm, and J. Jorstad, "Copper motor rotors: Energy saving efficiency, now also economic feasibility," in *2007 Electrical Insulation Conference and Electrical Manufacturing Expo*, Oct. 2007, pp. 328–333, doi: 10.1109/EEIC.2007.4562637.

[9] R. Yabiku, R. Fialho, L. Teran, A. Santos, E. Rangel, and D. Dutra, "A comparative study between copper and aluminum induction squirrel cage constructions," in *2010 Record of Conference Papers Industry Applications Society 57th Annual Petroleum and Chemical Industry Conference (PCIC)*, Sep. 2010, pp. 1–9, doi: 10.1109/PCIC.2010.5666832.

[10] ANSI, "Motors and generators," NEMA, 2016, Accessed Feb. 02, 2022. [Online]. Available: https://www.nema.org/docs/default-source/standards-document-library/ansi_nema-mg-1-2016-contents-and-foreword.pdf?sfvrsn=f27547b8_1
[11] D. T. Peters, E. F. Brush, and J. L. Kirtley, "Die-cast copper rotors as strategy for improving induction motor efficiency," in *2007 Electrical Insulation Conference and Electrical Manufacturing Expo*, Oct. 2007, pp. 322–327, doi: 10.1109/EEIC.2007.4562636.
[12] Q. Zhang, H. Liu, Z. Zhang, and T. Song, "A cast copper rotor induction motor for small commercial EV traction: Electromagnetic design, analysis, and experimental tests," *CES Transactions on Electrical Machines and Systems*, vol. 2, no. 4, pp. 417–424, Dec. 2018, doi: 10.30941/CESTEMS.2018.00053.
[13] M. Popescu, N. Riviere, G. Volpe, M. Villani, G. Fabri, and L. di Leonardo, "A copper rotor induction motor solution for electrical vehicles traction system," in *2019 IEEE Energy Conversion Congress and Exposition (ECCE)*, Sep. 2019, pp. 3924–3930, doi: 10.1109/ECCE.2019.8912248.
[14] V. Mallard, G. Parent, C. Demian, J.-F. Brudny, and A. Delamotte, "Increasing the energy efficiency of induction machines by the use of grain-oriented magnetic materials and die casting copper squirrel cage in the rotor," *IEEE Transactions on Industry Applications*, vol. 55, no. 2, pp. 1280–1289, Mar. 2019, doi: 10.1109/TIA.2018.2873532.
[15] A. Marfoli, M. Di Nardo, M. Degano, C. Gerada, and W. Chen, "Rotor design optimization of squirrel cage induction motor-part I: problem statement," *IEEE Transactions on Energy Conversion*, vol. 36, no. 2, pp. 1271–1279, Jun. 2021, doi: 10.1109/TEC.2020.3019934.
[16] M. Di Nardo, A. Marfoli, M. Degano, C. Gerada, and W. Chen, "Rotor design optimization of squirrel cage induction motor-part II: results discussion," *IEEE Transactions on Energy Conversion*, vol. 36, no. 2, pp. 1280–1288, Jun. 2021, doi: 10.1109/TEC.2020.3020263.
[17] D. Fodorean, C.-V. Pop, and D.-C. Popa, "Electromagnetic and structural analysis of an induction motor with copper rotor bars used in automotive applications," in *2021 IEEE 6th International Forum on Research and Technology for Society and Industry (RTSI)*, Sep. 2021, pp. 340–345, doi: 10.1109/RTSI50628.2021.9597235.
[18] A. T. De Almeida, F. J. T. E. Ferreira, and A. Q. Duarte, "Technical and economical considerations on super high-efficiency three-phase motors," *IEEE Transactions on Industry Applications*, vol. 50, no. 2, pp. 1274–1285, Mar. 2014, doi: 10.1109/TIA.2013.2272548.
[19] P. R. Viego, J. R. Gómez, and E. A. Padrón, "New syncronous high-efficiency motors," *Universidad y Sociedad*, vol. 12, no. 2, pp. 205–211, 2020. Accessed Jan. 21, 2022. [Online]. Available: http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S2218-36202020000200205&lng=es&tlng=es
[20] P. R. Viego-Felipe, J. R. Gómez-Sarduy, V. Sousa-Santos, and E. C. Quispe-Oqueña, "Permanent magnet assisted synchronous reluctance motors: A new advance in electric motors development," (in Spanish), *Ingeniería, investigación y tecnología*, vol. 19, no. 3, pp. 269–279, Jul. 2018, doi: 10.22201/fi.25940732e.2018.19n3.023.
[21] P. R. Viego, V. Sousa, J. R. Gómez, and E. C. Quispe, "Direct-on-line-start permanent-magnet-assisted synchronous reluctance motors with ferrite magnets for driving constant loads," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 1, pp. 651–659, Feb. 2020, doi: 10.11591/ijece.v10i1.pp651-659.
[22] G. C. Mechler, "Manufacturing and cost analysis for aluminum and copper die cast induction motors for GM's powertrain and R&D Divisions," Thesis, Massachusetts Institute of Technology, 2010.
[23] A. Marfoli, M. DiNardo, M. Degano, C. Gerada, and W. Jara, "Squirrel cage induction motor: a design-based comparison between aluminium and copper cages," *IEEE Open Journal of Industry Applications*, vol. 2, pp. 110–120, 2021, doi: 10.1109/OJIA.2021.3073820.
[24] H.-R. Noh, H.-S. Shin, C.-M. Kim, and K.-C. Kim, "A study on the effect of rotor bars of induction motor for electric vehicle," in *2021 24th International Conference on Electrical Machines and Systems (ICEMS)*, Oct. 2021, pp. 1415–1418, doi: 10.23919/ICEMS52562.2021.9634599.
[25] Ministerio de Justicia, "System for the formation of electricity rates for the collection of electricity service: Gaceta Oficial No. 26," (in Spanish) Gaceta Oficial No. 26 (Extraordinaria), La Habana, Cuba, 2021. Accessed: Apr. 13, 2021. [Online]. Available: https://www.gacetaoficial.gob.cu/sites/default/files/goc-2021-ex26_0_0.pdf.
[26] J. C. Andreas, *Energy-efficient electric motors: selection and application*. United States: Marcel Dekker, Inc.,New York, NY, 1982.
[27] M. J. Landt and A. D. Reed, "Project evaluation," in *Archaeological Data Recovery in the Piceance and Wyoming Basins of Northwestern Colorado and Southwestern Wyoming*, Archaeopress Publishing Ltd, 2018, pp. 333–336.
[28] Siemens Industry, "General purpose low voltage cast iron frame motors," Siemens Industry, USA, 2011. Accessed Dec. 13, 2021. [Online]. Available: https://assets.new.siemens.com/siemens/assets/api/uuid:ff39a5d9-875a-4f16-bf17-79beae7a11c7/nema-general-purpose-motors-cast-iron-gp100-brochure.pdf
[29] R. Saidur and T. M. I. Mahlia, "Energy, economic and environmental benefits of using high-efficiency motors to replace standard motors for the Malaysian industries," *Energy Policy*, vol. 38, no. 8, pp. 4617–4625, Aug. 2010, doi: 10.1016/j.enpol.2010.04.017.
[30] B. Cassoret, J. Manata, V. Mallard, and D. Roger, "Comparative life cycle assessment of induction machines made with copper-cage or aluminium-cage rotors," *IET Electric Power Applications*, vol. 13, no. 6, pp. 712–719, Jun. 2019, doi: 10.1049/iet-epa.2018.5401.

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