Energy Diagnosis for the Recovery of Furnace 3 at the Nickel Mechanical Company in Moa

Diagnóstico energético para la recuperación del horno 3 de la Empresa Mecánica del Níquel en Moa

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Abstract: An energy diagnosis was applied to furnace 3 of Nickel Mechanical Company in Moa, Cuba, with the objective of restoring its efficiency as an industrial-frequency resonant electromagnetic induction furnace. Electrical voltages, active power, power factor, and capacitor bank capacity were measured. This equipment productivity under current conditions and the monthly electricity consumption bills over two years were reviewed. Its correction mechanism for power factor and frequent breakdowns´ causes—mainly in its magnetic contactors, which prevented operation in electrical resonance—were analyzed. The power factor systematic measurement allowed to identification of low energy efficiency causes. Six solution proposals were evaluated: the variant involving the replacement of magnetic contactors by semiconductor devices proved to be the most technologically and economically viable solution.

Keywords: industrial economy, furnaces, electromagnetic induction

Resumen: Se realizó un diagnóstico energético al horno 3 de la Empresa Mecánica del Níquel en Moa, Cuba, con el objetivo de devolverle la eficiencia como horno de inducción electromagnética resonante a frecuencia industrial. Se realizaron mediciones de tensiones eléctricas, potencia activa, factor de potencia y capacidad de los bancos de condensadores.

How to cite: Silva-Aguilera, E., Guardiola-Romero, R.L., & Guerrero-Rojas, Y. (2026). Energy Diagnosis for the Recovery of Furnace 3 at the Nickel Mechanical Company in Moa. *Ciencia & Futuro, 16.* https://revista.ismm.edu.cu/index.php/revistacyf/article/view/2921

Se revisó la productividad del equipo en las condiciones actuales y las facturas del consumo de energía eléctrica mensual de dos años. Se analizó su mecanismo para la corrección del factor de potencia y causas de las frecuentes averías, principalmente en sus contactores magnéticos, que provocaban el no funcionamiento en resonancia eléctrica. La medición sistemática del factor de potencia, permitió conocer las causas de la baja eficiencia energética. Se evaluaron seis propuestas de soluciones, la variante que trató la sustitución de contactores magnéticos por dispositivos semiconductores resultó ser la solución tecnológica y económica más viable.

Palabras clave: economía industrial, hornos, inducción electromagnética

1. Introduction

In the 21st century's technological world, low-frequency induction furnaces are no longer manufactured. Hence, acquiring new parts requires seeking for innovative solutions to keep them operating. In Cuba, there are entities using induction furnaces, one of them is the Nickel Mechanical Company (Empresa Mecánica del Níquel, EMNI) in Moa, Holguín province.

Three electromagnetic induction furnaces are used for metals and alloys casting. Furnaces 1 and 2 operate at medium frequency (up to 1310 Hz), while furnace 3 operates at industrial frequency (60 Hz) (Álvarez *et al*., 2016).

In the last ten years, Furnace 3 has experienced continuous breakdowns, affecting production targets and leading to high energy consumption. This, combined with technological obsolescence, hinders its operation at the unity power factor for which it was designed, causing production delays and incurring in high electricity consumption (Torres *et al*., 2020). It was verified that more than 90 % of these breakdowns are caused by the high deterioration of magnetic contactors, as they are burned by the electric arc resulting from the capacitor banks energized at 1 kV switching (Acosta, 2019; Cabello, 2023; López *et al*., 2023).

Consequently, it is necessary to carry out an energy diagnosis (Calla & Maldonado, 2021; Martínez & Gassinski, 2022; Ruano, 2023; Hernández *et al.*, 2024; Martínez, 2025) to identify fundamental cause of breakdowns in Furnace 3 and its high energy consumption. This would help eliminate the electric arc generated by switching capacitor banks, minimizing failures and allowing for the switching of a greater number of capacitor banks.

By correcting the power factor, it is possible to reduce the high energy demand. To this end, a study was conducted on induction heating, starting from analyzing the operating principle of a low-frequency induction furnace (Acosta, 2019). Subsequently, an energy diagnosis is carried out on Furnace 3 based on an evaluation of its current technical condition, the identification and implementation of technical procedures aimed at increasing energy efficiency, coupled with the development of a pre-feasibility study that uses the identified procedures, in order to rank the proposals according to their economic and technological viability.

2. Materials and Methods

The experimental study consisted of measuring electrical variables: voltages, active power, operating power factor, as well as the time required to reach the melting temperature, considering the volume of the load to be melted and the alloy, each capacitor capacity in the banks, and the possibility of achieving a unity power factor with the existing banks (Villafaña *et al.*, 2015).

2.1. Technical Data of Furnace 3

The Russian 26-ton H4T-2,5/1-C4 TB4 furnace was manufactured in 1980. It has a capacity to cast up to 2.5 tons of iron, a power of 950kW, and operates at a 60-Hz industrial frequency. It uses a 1020 V nominal electrical voltage supplied by a single-phase transformer with a 6300-kVA apparent power, which has 10 kV on the primary winding and 1 kV on the secondary one. It is water-cooled, has 1 phase, and a power factor ranging between 0.5 and 1 (Pérez *et al.*, 2019).

2.2. Measuring Instruments Used

Measuring instruments were used according to the defined electrical variables. Measurements were taken depending on each casted alloy, at 2-minute intervals. The maximum, minimum, and average voltages, power, and power factor values were calculated. The power factor and active power were measured for each alloy to be casted. Voltages in the inductor coil, melting time for each load-depending on its mass and alloy, as well as each capacitor bank's capacitance, in microfarads, were measured (Kazlauskas *et al.,* 2023).

3. Results

Measurements results are shown in Tables 1-4. Figures 1-4 show the power factor behavior for HK-40, X28H2, Ac 35, and Ac 45 alloys, respectively.

Table 1. Measurements results for a HK-40 steel alloy during its first casting.

Data	cos ϕ	Power	Voltage
Initial reading 600465	cosϕ maximum 0.391	Pmax 310kW	Umax 1020 V
Final reading 600556	cosϕ minimum 0.034	Pmin 310kW	Umin 1020 V
Consumption index 16.3	cosϕ avg 0.26	Pavg 310kW	Uavg 1020 V
Consumption in kW/h 483.3			
Duration 6:00 a 8:05			

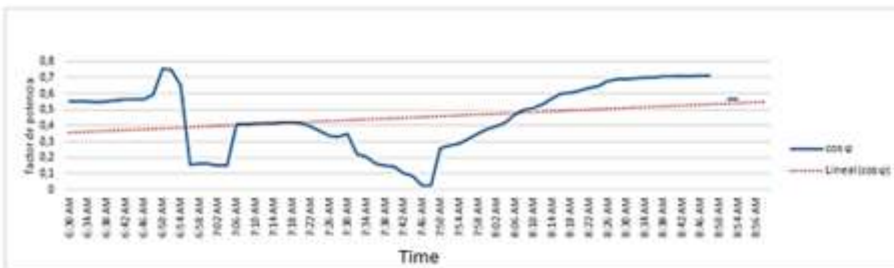

Figure 1. Power factor behavior for a HK-40 alloy. First casting.

Table 2. Results of measurements for a X28H2 alloy (high-carbon steel) during its first casting

Data	cos ϕ	Power	Voltage
Initial reading 601373	cosϕ maximum 0.665	Pmax 320kW	Umax 1020 V
Final reading 601522	cosϕ minumum 0.043	Pmin 120kW	Umin 510 V
Consumption index16.3	cosϕ average 0.423	Pavg 231kW	Uavg 874 V

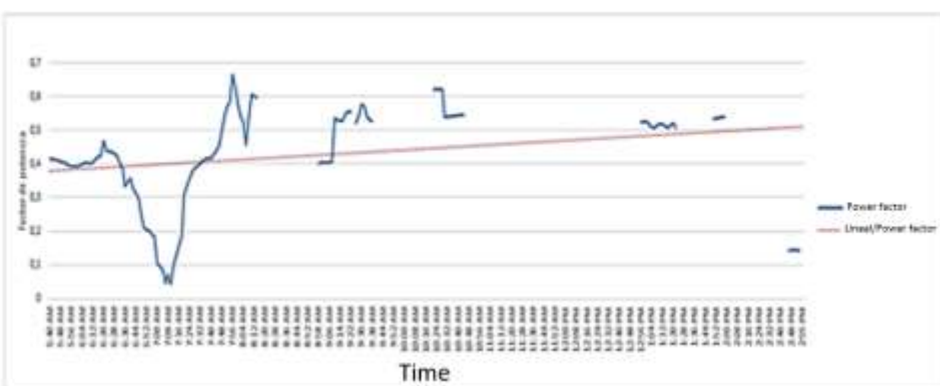

Figure 2. Power factor behavior for a X28H2 alloy. First Casting.

Table 3. Power factor measurements results for an Ac 35 alloy.

Data	**cos ϕ**	**Power**	**Voltage**
Initial reading 602443	cosϕ maximum 0.987	Pmax 290 kW	Umax 1020 V
Final reading 602537	cosϕ minimum 0.421	Pmin 125 kW	Umin 692 V
Consumption index 16.3	cosϕ average 0.848	Pavg 236 kW	Uavg 948 V

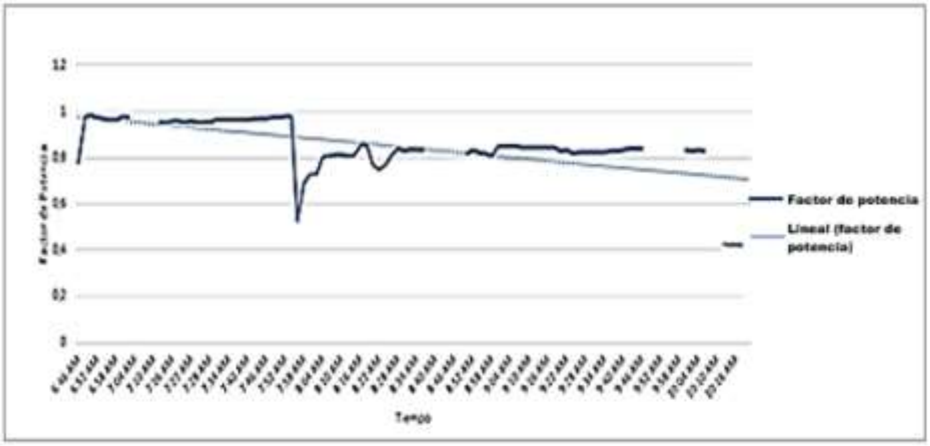

Figure 3. Power factor behavior graph for an Ac 35 alloy.

Table 4. Results of measurements for an Ac 45 alloy in its first casting

Data	**cos ϕ**	**Power**	Voltage
Initial reading 602927	cosϕ maximum 0.983	Pmax285 kW	Umax 1020 V
Final reading 603093	cosϕ minimum 0.006	Pmin145 kW	Umin 692 V
Consumption index 16.3	cosϕ average 0.664	Pavg 239 kW	Uavg 968.4 V

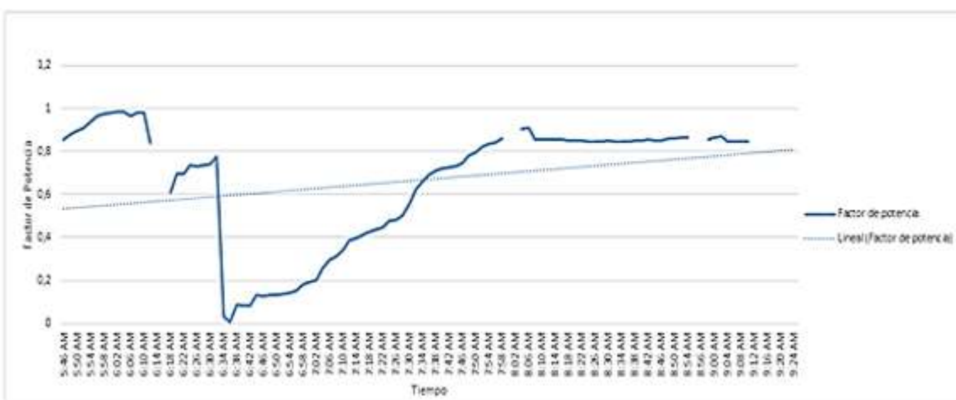

Figure 4. Power factor behavior graph for an Ac 45 alloy. First casting.

Tables 1-4 present the results of the electrical measurements taken on Furnace 3 circuit, which demonstrate a marked energy inefficiency, as it is unable to operate in electrical resonance or at maximum power (950 kW), even operating at maximum voltage of 1020

Volts. This installation is designed to cast 2.5 tons of iron in 48 minutes. The tables show the excessive time consumed, reflected in high energy costs (Grupo Elecond, 2015).

Figures 1 to 4 show that Furnace 3 does not reach electrical resonance in any casting due to several causes: melting alloys with low iron content, incomplete or short-circuited capacitor banks, and magnetic contactors burned out when switching banks energized at 1 kV. Sharp drops in power factor values indicate capacitor bank switching without observing the power factor behavior as a phasemeter is lacked (Risoul, 2021).

Blank spaces in the power factor line indicate that, at that moment, Furnace 3 was shut down, reasons negatively influencing this equipment's productivity and efficiency. Trend lines, which in most cases are upward, indicate that, with the passing of time, the furnace tends to increase the power factor. As the metal is casted, it forms a body that, although liquid, behaves as a solid, which is beneficial for the electromagnetic process for as the body mass (without internal spaces) increases, the Foucault's currents increase in value, as well as the losses due to the Joule effect, allowing better utilization of the energy consumed in the form of work, which in the case of induction furnaces, is to generate heat within the piece being casted (González *et al.,* 2013).

4. Discussion

As a result of the diagnosis, a marked energy inefficiency during Furnace 3 operation became evident, a phenomenon attributed to technological obsolescence and breakdowns, mainly in the magnetic contactors and capacitor banks. An additional cause is melting low-iron-content alloys, such as HK-40 and X28H2 alloys, when Furnace 3 is designed for high-iron-content alloys.

Wrongdoings identified during the diagnostic stage were observed, such as preheating (or turning on) the furnace while still unloaded. This practice is mistakenly performed to facilitate metal casting. To avoid this, it would be favorable to load the furnace with larger volume pieces in its first casting.

It is necessary to ensure operation with the upper safety lid as provided in the manufacturer's manuals. The cooling water used must be distilled to prevent internal corrosion in the inductor coil.

The installation should be used to cast metals with good ferromagnetic characteristics. Introducing wet or fuel/paint-contaminated pieces into Furnace 3 should be avoided.

It is necessary to ensure the operation of the leakage protection system. The furnace lid must remain closed. If it is not installed, it is recommended to carry out the necessary actions for its correct installation. It is advisable to study the possibility of installing capacitor banks to correct the power factor by using artificial neural networks (GUASCH S.A., 2021).

4.1. Proposals for furnace 3 recovery at Nickel Mechanical Company in Moa

To achieve the furnace's energy efficiency, increase productivity, and reduce energy costs, six solution proposals with their corresponding advantages, disadvantages, and their economic evaluation were generated (Monar, 2023; Ramos *et al.,* 2024).

4.1.1 Proposal 1. Reconstruction (refilling) of the magnetic contactors' electrical contacts, using electrodes made of an alloy with a silver content greater than 5%.

Advantages
-Offers an immediate solution to Furnace 3 magnetic contactors breakdowns.
- Refilling, milling, and sanding operations are relatively fast (8 to 10 contacts in a workday).
- Competent personnel for contact refilling and milling operations.
- The furnace's electrical circuit and the operating principle are not modified.

Disadvantages
- Lack (or difficult acquisition) of silver-alloy electrodes with a concentration greater than 5 %.
- Persistence of the electric arc.
- Need for shorter maintenance and repair cycles.
- More frequent production interruptions.
- Energy inefficiency due to furnace operation at low frequency (60 Hz) and not in electrical resonance.
- It is estimated a 30-days period to refill the furnace's electrical contacts.

Economic assessment: the development of this proposal confirms the existence of silver rods (electrodes). Specialists from the company's purchasing group were consulted, information on potential suppliers of this and other products with higher silver concentration was sought, and current prices were studied. For this solution, 192.53 USD and 1200.16 CUP are needed each month, and 2,310.36 USD and 14,401.92 CUP annually. Using 15 % silver alloy rods would entail an expenditure of 2,948.92 CUP and 279.11 USD, so annually, 35,387.04 CUP and 3,349.32 USD would be needed.

4.1.2. Proposal 2. Replacement of damaged electrical contacts with platinum-coated contacts by using the contact welding method

Advantages
- Platinum contact lifespan is superior to that of the silver contact (2 to 5 years).
- Maintenance cycles extension.
- Breakdown reduction in magnetic contactors.
- Longer production cycles in Furnace 3.
- The magnetic contactor and the electrical circuit of Furnace 3 are not modified.
- The operating principle of Furnace 3 is not modified.

Disadvantages
-The electric arc persists a one of the breakdowns' causes.
- Requires a reasonable amount of time to carry out repairs.
- Difficulties in acquiring platinum contacts, depending on suppliers and their prices, as well as the mechanisms for acquiring these products.
- Requires the construction of a contact welding machine, or its purchase on the market.

Economic assessment: constructing a contact welding machine, purchasing platinum contacts and sheet-type foot electrodes requires consulting several suppliers.

4.1.3 Proposal 3. Acquisition of new magnetic contactors

Advantages
- Reduction of Furnace 3 stoppages.
- Maintenance cycles are extended.
- Counts on magnetic contactors with modern technology including electric arc reduction systems.
Greater energy efficiency of the furnace by switching more capacitor banks.
- Increased productivity in this facility.

Disadvantages
- High investment cost.
- Difficulty in acquiring magnetic contactors.

- Need to adapt the new contactors to the existing electrical circuit in Furnace 3 (technological incompatibility).
- The electric arc —fundamental cause of breakdowns— is not eliminated.

Economic assessment: Furnace 3 requires 12 magnetic contactors to operate. 700-A magnetic contactors would cost 30,075.84 euros. Acquiring twelve 1000-A contactors requires an investment of 64,725 euros.

4.1.4. Proposal 4. Replacement of magnetic contactors with semiconductor devices (SCR or IGBT)

Advantages
- Elimination of the electric arc — the fundamental cause of breakdowns.
- Replacement of electromechanical control with electronic control.
- Manual and automatic (precise) control of the power factor.
- Longer maintenance cycles.
- Magnetic contactors are no longer needed.
- Greater power control range.
- Devices can be found in the national market (other companies).
- Presence of qualified personnel for the construction of the control circuit and the installation of semiconductor devices.
- Better power factor adjustment.
- Smaller size, allowing for more compact and automatable elements.
- Lower working voltage, activated at 1.5 V.
- Completely silent operation.
- SCRs operate at higher speed compared to a magnetic contactor.
- Longer lifespan, even if switched many times, as there are no mechanical parts to wear out or contacts to deteriorate at high currents.
- Clean connection, contact switching is bounce-free
- Less sensitive to storage and operating environment such as shocks, vibrations, humidity, and external magnetic fields.
- Do not produce electromagnetic waves that cause interference in other equipment.
- Allows Furnace 3 to operate with the best possible energy efficiency.
- Automatic and precise power factor control (eliminates human factor).
- Furnace operation in electrical resonance.

- Requires the acquisition of a single controller relay.
- Allows reusing the existing capacitor banks in Furnace 3.
- Only requires the acquisition of capacitors to complete the missing amount in each bank according to the power factor value set by the alloy to be melted.

Disadvantages
- Requires a reasonable amount of time for constructing the control circuit, the SCR gate trigger circuits, and for installing the semiconductor devices in the power stage.
- Generation of harmonic frequencies.
- Difficulty in immediate acquisition of SCR power semiconductor devices, dispositivos semiconductores SCR de potencias well as the power factor controller relay (varmetric relay).
- Energy inefficiency when operating at low frequency (60 Hz), compared to medium and high-frequency furnaces.

Economic assessment: the furnace uses 12 two-pole magnetic contactors. Each one must be replaced by 4 thyristors. The replacement requires 48 thyristors at prices ranging from 49.60 to 470 USD per unit. The total amount ranges between 2380.80 and 22,560 USD. A relay is required to control the furnace's power factor (Gallardo, 2017; Flores, 2019). The financial cost for its acquisition ranges between 16.50 and 35 USD.

4.1.5 Proposal 5. Acquisition and installation of automatic capacitor banks

Advantages
- Precise power factor control.
- Automatic operation of Furnace 3 (human factor excluded).
- Operation of Furnace 3 in electrical resonance.
- Elimination of the electric arc.
- Longer maintenance cycles.
- The Mechanical Company has qualified personnel to install the automatic capacitor banks.

Disadvantages
- Requires a reasonable amount of time for fixed and switchable banks removal and the installation of the automatic capacitor banks.
- Difficulty in acquiring automatic capacitor banks.
- It requires dismantling technology that is still usable.

Economic assessment: acquiring automatic capacitor banks depends on product imports. Twenty banks are required to reach the furnace's 6,000 kVAr. The cost amounts to 942,622.95 USD.

4.1.6. Proposal 6. Acquisition of a new, medium-frequency (1 to 5 kHz) induction furnace with a 3-t capacity

Advantages
-Definitive solution to the problems caused by the furnace's technological obsolescence.
-Automatic power factor adjustment.
-Higher efficiency compared to low-frequency furnaces.
- Control system adjusted to melting control needs.
- Modern protection system that stop furnace operation upon detecting incorrect operating parameters.
-Modern electronic control (Morfin-Garduño, 2021).

Disadvantages
- Lack of or difficulty in acquiring an industrial induction furnace.
- A reasonable amount of time is needed to remove the old furnace and install the new one.
- The inductor coil has no technological use in Cuba.

Economic asssessment: based on the feasibility study conducted by the Nickel Industry Project Center for the purchase of a 3-ton induction furnace, the total cost is 1,644,070.50 pesos, distributed as follows: 1,462,301.70 USD and 181,768.80 CUP.

4.2. Pre-feasibility Study

A pre-feasibility study was conducted to determine the economic and technological possibilities corresponding to each proposal (Burneo *et al.*, 2016; Fernández *et al*., 2022). A logical order is proposed considering the Nickel Mechanical Company's current technical production circumstances and production needs.

Table 5. Proposed order based on the economic and technological viability resulting from the pre-feasibility study

No.	Proposal	Economic viability	Thecnologic viability	Solution immediacy
1	Refilling of the magnetic contactors' electrical contacts with electrodes made of an alloy with a silver content greater than 5%.	1	6	1
2	Replacement (grafting) of damaged electrical contacts with platinum-coated electrical contacts, using the contact welding method	2	5	2
3	Acquisition of new magnetic contactors	3	4	3
4	Replacement of magnetic contactors with semiconductor devices (SCR or IGBT)	4	3	4
5	Acquisition and installation of automatic capacitor banks	5	2	5
6	Acquisition of a new induction furnace, preferably a medium-frequency one with a three-ton capacity	6	1	6

4.3. NPV and IRR calculation for each solution proposal

The net present value (NPV) and internal rate of return (IRR) calculation corresponding to each solution proposal is shown in Table 6.

Table 6. NPV and IRR results for each proposal

	NPV	IRR	RP (years)
Proposal 1	2,298,114.06	51.1%	1.00
Proposal 2	No commercial offer available		
Proposal 3	2,401,260.79	62.4%	1.00
Proposal 4	2,505,447.74	116.7%	1.00
Proposal 5	1,694,153.87	30.2%	2.00
Proposal 6	1,084,199.48	22.4%	3.00

5. Conclusions

An energy diagnosis was applied to Furnace 3 based on power factor measurement, which enabled the identification of the equipment' s low energy efficiency causes. Technological and human errors were detected in operations, leading to high consumption and reduced useful life of this installation.

Six proposals were evaluated to ensure Furnace 3 energy efficiency. Three solution variants eradicate the fundamental cause of breakdowns: the electric arc. These variants possess the capacity for technical operation and economic feasibility in restoring the furnace's energy efficiency.

Variant 4, addressing the replacement of magnetic contactors with semiconductor devices, proved to be the most technologically and economically viable solution.

With this proposed variant, Furnace 3 can perform three melts in the morning and three more in the rest of a workday, reduce this installation's energy consumption by 30 to 50 %, operate under the electrical resonance phenomenon for which it was designed, eliminate the electric arc (fundamental cause of breakdowns), and double the furnace's daily productivity.

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Conflict of Interest: The authors declare that there are no conflicts of interest.

Author's Contribution according to CRediT Taxonomy

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