On/Off Control versus PID Control: A Comparative Case Study on Condensers of Cooling Systems

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Abstract

The exponential growth of industries makes energy efficiency a key factor to be considered, especially in industries that relies on equipment with a high demand of electrical power. Therefore, an analysis of device efficiency is one of the premises of the evolution of industrial equipment. A condenser is an equipment present in cooling systems that are used in small, medium and large organizations. Research and studies on the efficiency of this type of equipment becomes relevant, especially in countries that experience blackouts that reach cities and states, such as Brazil. In the present work, a case study of a local supermarket that uses industrial refrigeration systems was carried out, in which the performance of a control of an ON-OFF vs PID system was evaluated. After collecting the specific parameters of the fans, it was found that the control via PID became more efficient than the ON-OFF, with a considerably lower power consumption of about 26.35%, resulting in greater use of electrical energy and considerable savings for the organization.

Keywords: Energy Efficiency, Refrigeration, PID, Industrial Automation, On/Off Control.

1. Introduction

Refrigeration is a significant factor in the daily life of human beings, being essential for the conservation of various products, especially food. For the conservation of products, medicines, among others, huge areas of controllable temperature are built, called cold chambers. However, for the conditioning of these areas, huge amounts of money are spent on electricity, thus raising the final cost of these products (Nunes, 2013).

The profit of any company is directly proportional to the way in which it deals with its production costs, with electricity consumption representing an average expense of 15% of its revenue (SEBRAE-MS, 2021). This high cost promotes an incessant search for new technologies that perform the same tasks, but with greater energy efficiency, avoiding production costs, and remaining competitive in the market. In the case of refrigeration, this is no different, since it is a system that remains in uninterrupted operation for the conservation of products, therefore, the way in which electrical energy is used to maintain constant temperature in areas that require a temperature lower than the external environment.

Since refrigeration is fundamental for the conservation of several products, the energy supplied for its operation cannot suffer from interruptions (Nunes, 2013; Silva, 2014). Something similar was seen in the blackout that occurred in the state of Amapá in 2020. After a major storm, three transformers in the largest substation in the state caught fire, leading to a cut in the power supply to most of the regional population (G1, 2020).

The solution taken by the authorities and entrepreneurs to maintain the operation of hospitals and supermarkets was the activation of diesel generators to meet this demand, but this solution has a high cost, making it unfeasible to be used for long periods.

The ventilation condensation systems that the current refrigeration systems have, from the point of view of energy efficiency, are considered outdated, mainly because they are systems that are mostly composed of ON-OFF controllers, which allow the electrical fans to operate only with the logic signals on and off (Batista et al. 2014; Chen & Norford, 2020).

With this premise, two types of drives are implemented in refrigeration equipment: STEP (where the drive is performed by discrete levels of drive signals) or PID (Proportional-Integral-Derivative). Such methods impact the energy efficiency of the equipment.

Thus, the general objective of this work is to perform a critical comparative analysis between the STEP and PID methods in a cooling equipment in operation. The specific objectives are: an assessment of the operating environment and the installed cooling system; a definition of reference metrics with the relevance of the equipment application; and, finally, a comparison between the triggering methods and the possibility of optimization. This project aims to evaluate the energy efficiency when applying the two types of control in condensing fans installed in a refrigeration rack of a traditional chain of large supermarket in Belo Horizonte, Brazil.

2. Material and Methods

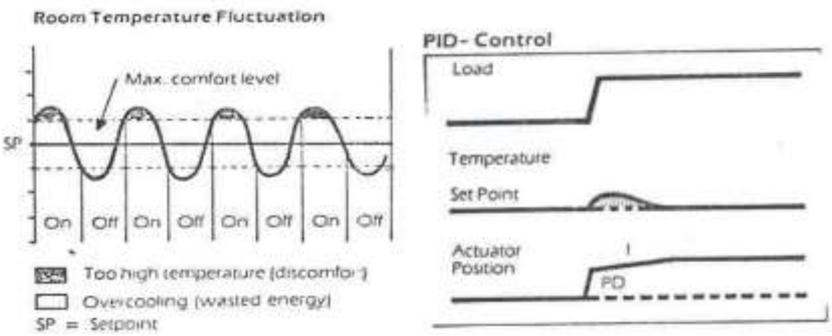
2.1 Theoretical Reference

The main concepts that referenced this research are the air condensing equipment and its types of control. Air-cooled condensers use this same fluid as a cooling medium, where air is forced through a coil, absorbing the heat of the refrigerant gas that passes inside the coil, so that it can change its gaseous state to liquid.

According to Matos (2010), the required size and configuration of a condenser is based on the saturated temperature of the fluid to be condensed. When designing a condenser, some quantities are considered, namely: operating pressures (they vary according to the refrigerant fluid), fluid pressure drops, physical space limitations; environmental characteristics of the condenser location, and manufacturing cost. Among the various types of control of this equipment on the market, two are well spread among companies that design and develop refrigeration equipment.

The ON-OFF control, represented in figure 1-a, is one of the most used due to its lower complexity and low cost. This model uses a pressure measuring instrument (pressure switch) to activate the condensation fans. As the pressure of the environment in which this equipment is installed varies, its electrical terminals switch between two states, on and off, activating the fans or not. As described by Da Silva (2005), forced ventilation condensation systems applied in refrigeration systems that use controllers with only two stages on or off, have low energy efficiency, since this type of control has limited management capacity. This type of control is commonly called Step Control. In addition to ON-OFF control, there are other less common methods that are used in the industry.

Figure 1: Control ON-OFF (Step) versus Control PID



a) Control ON-OFF *b) Control PID*

Source: (Matos, 2010)

Seeking a better efficiency of the fans in addition to a better stability of the variable to be controlled, according to De Lima et al. (2019), controllers that perform PID (Proportional, Integral and Differential) calculation are used, represented in Figure 1.b, together with EC (Electronically Switchable) fans. Through these devices it is possible to automate the process for controlling the speeds of these fan models, avoiding peak currents during on-off operation and providing energy savings.

2.2 Related Works

Several works in the literature and in the market, such as those listed in table 1, have a direct or indirect relationship with the proposal of this article. It can be said then that this research contributes with an experimental case study in practical terms in an updated way.

Table 1: Literature revision

Ref.	Description	Differences
Salvador (1999)	This work presents the energy optimization of refrigeration systems by vapor compression through the operation with variable regime for the refrigeration cycle, specifically through the operation with set-point of variable evaporation temperature.	In this work, the regulation of the refrigeration system by variable set point is discussed with more details, while the present work makes a comparison between the Step and PID systems for controlling the ventilation of the condensers.
Silva (2003)	The work consists of the assembly and instrumentation of a refrigeration prototype for liquid cooling (Chiller) that allows the implementation of conventional control systems (PID and PI) and fuzzy control.	It is an analysis of which method can be used to control the cooling of a liquid, while the present work deals with the cooling of a fluid.
Da Silva (2005)	This book aims to clarify the concepts and components of refrigeration systems, in order to allow the identification of the different opportunities for their optimal use.	This book covers the a general topic related to energy efficiency, not presenting a specific case study.
Lima (2016)	This work looked for energy efficiency opportunities in the refrigeration system of a brewery using ammonia and 20% ethanol as refrigerant.	The author focused on energy efficiency in a brewery, using a different refrigerant fluid, but that is similar to this work.
Brasil (2019)	This work showed the use of different types of chillers for the cooling process and which one is best applied in a given situation.	This study uses only a chiller refrigeration system, while the proposed work has application for different types of refrigeration systems.

Source: (Authors, 2022)

2.3 Methods

This article is a case study and proposes to analyze two very specific types of control used in cooling equipment. In the current scenario, it has been observed that the low investment in new technologies due to their cost, is not reflected in a low production cost, as equipment with low energy efficiency is often used, thus raising the final cost of the product. In general, different types of equipment can be used to perform the same task, but each one can present different results, especially regarding energy efficiency. This case study proposes to numerically analyze the difference between two types of air condenser control applied in refrigeration racks. The first one to be presented uses pressure switches to drive EC (Electronically Switchable) fans applied to an air condenser. The second makes use of a PID controller to command the same fans.

The reason for this proposition is to identify between the two controls which one offers the best relationship between the quality of temperature control and its energy efficiency.

For the development of this study, an air condenser applied in a chiller-type refrigeration rack was used as a test platform, where the expansion of a refrigerant gas is used to cool the water and thus force the passage of this same cold water through the environment that is under the temperature control. A electrical data were collected, such as current (A), voltage (V) and active power (W), of the equipment to be evaluated. The data is directly related to the physical quantities that is controlled by the system, namely: pressure (bar) and temperature (ºC). For a graphical analysis of this relationship, the respective data was collected at ten minute intervals, during a period of seven consecutive days.

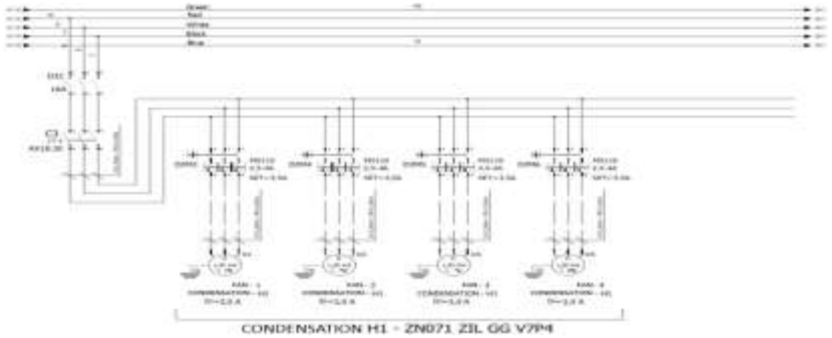
3. Results

3.1 Demand Survey and Planning

The base equipment for the development of the study belongs to a supermarket chain in Belo Horizonte. The refrigeration rack applied for the cooling of environments, has two sides, both consisting of two piston compressors model 4HE-15Y from the BITZER brand. The refrigerant fluid used is R134a, working with an evaporation temperature of approximately 2.0 °C, and a condensing temperature of 39 °C. Interconnected to the refrigeration lines that leave the rack are fan vests that work with temperatures varying between 10°C to 17°C. Figures 2-5 demonstrate the circuits of the equipment used, as well as the points of analysis that were reference for the collection of data that supported the following comparisons. On each side of the forced ventilation unit (condenser) four EC (Electronically Switchable) axial fans of the brand ZIEHL ABEGG model ZN071 ZIL GG V7P4 are used, which are the object of this study. Figures 2 and 3 present in a practical way the electric drive concept applied to each type of control. To collect the consumption data, two meters from the manufacturer CAREL model MT300W3200 were used, which were installed after the fan operation contactor.

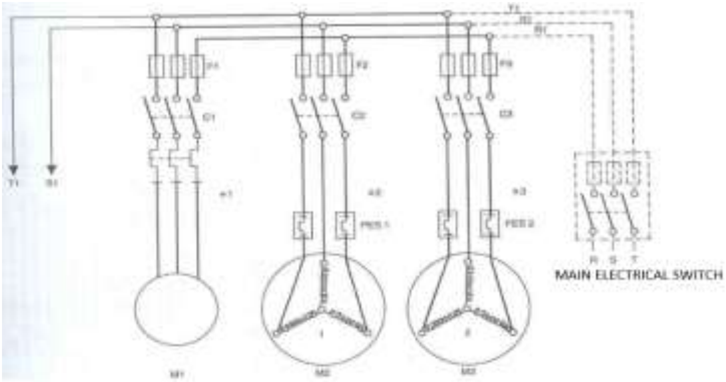
One of the meters was installed on the “H1” side of the equipment, which has a set of fans managed by a PID controller with output varying (AO) from 0 to 10 V. This signal is sent to the EC fans (figure 4), where these vary their speed according to the received signal. The other meter was installed on the “H2” side, using the same type of control on the “H1” side. These monitors, as described previously, can be integrated into other BMS systems using the ModBus®/RS485 communication. Through this interface, it is possible to communicate to the network of controllers connected to the supervisor of the manufacturer CAREL, mod. BOSS (Figure 5), responsible for storing all the information, which can be arranged in graph form for analysis.

Figure 2: Electrical diagram of the EC fans power supply managed by a PID controller



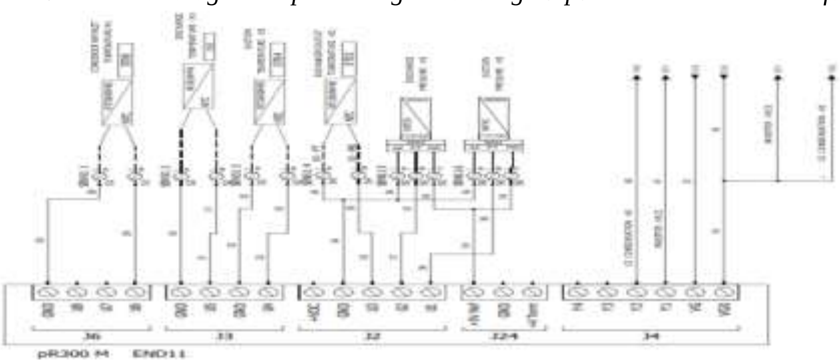
Source: (Authors, 2022 - Data Provided by The Company)

Figure 3: Electrical diagram of the AC fan supply Managed by pressure switches.



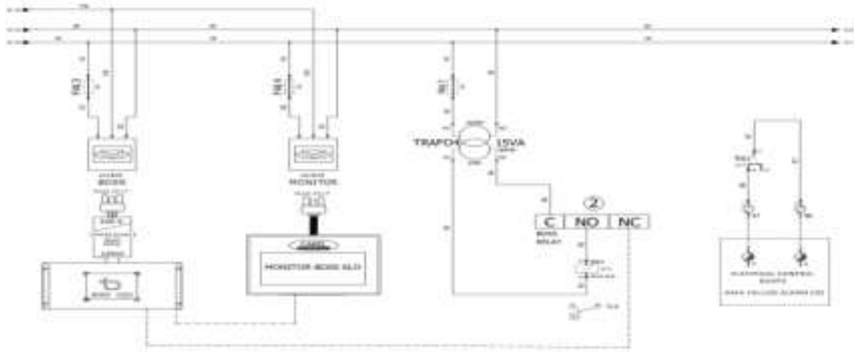
Source: (Matos,2010)

Figure 4: Electrical diagram representing the analog output that connects to EC fans.



Source: (Authors, 2022 - Data Provided by The Company)

Figure 5: Electrical diagram representing the supervisor installed in the equipment.



Source: (Authors, 2022 - Data Provided by The Company)

3.2 Comparative Analysis

Analyzing the two types of control, it is possible to find relevant differences. The ON-OFF control for its simplicity of operation and consequently its low maintenance cost, attracts buyers who see these advantages as a decision factor for its acquisition. On the other hand, for the implementation of PID control, greater technical knowledge is necessary, and this equipment has high added value because it is an electronic component, requiring a more qualified workforce to operate it. However, its control is much more accurate, thus ensuring greater linearity of the quantities to be controlled.

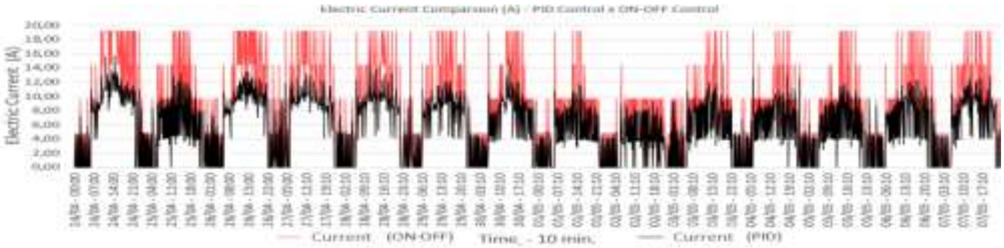
Another positive point of this equipment relies on its form of control, that allows a precise control of the equipment connected to its analog outputs, thus resulting in a greater energy efficiency. For comparison purposes, it can be seen in Figure 6 that it is possible to identify the voltage (V) remaining stable within a range throughout the sampling period, with small variations that corresponds to maximum of 3% of the nominal voltage supplied by the energy concessionaire.

Figure 6: Average voltage (V) during sampling period - PID Control x ON-OFF Control

Source: (Authors, 2022)

Figure 7 shows a higher current consumption when using the ON-OFF control compared to the PID control.

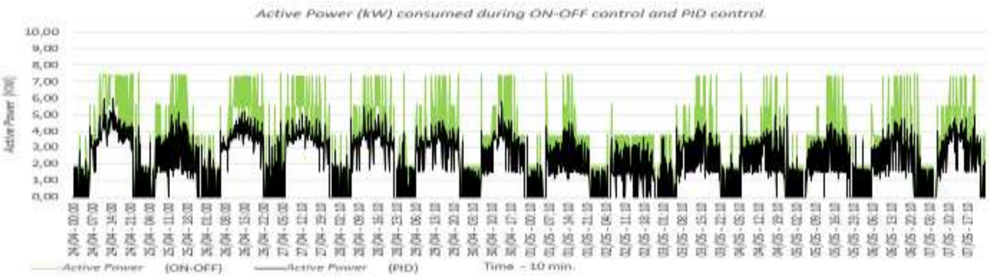
Figure 7 – Comparative graph between the Current (A) consumed during ON-OFF control and PID control.



Source: (Authors, 2022)

Based on the data collected, the maximum and average current of the ON-OFF control were 19.20A and 7.74A respectively, while the same currents using the PID control were 15.74A and 5.70A respectively. The current consumed by the PID control was 26.31% lower than the current consumed when using the ON-OFF control. In figure 8, as well as in figure 9, it is possible to observe a higher value when using the ON-OFF control compared to the PID control. The maximum and average active power (kW) when using ON-OFF control were 7.60 kW and 2.99kW, while the same active power measured when using PID control was 6.03kW and 2.20kW respectively.

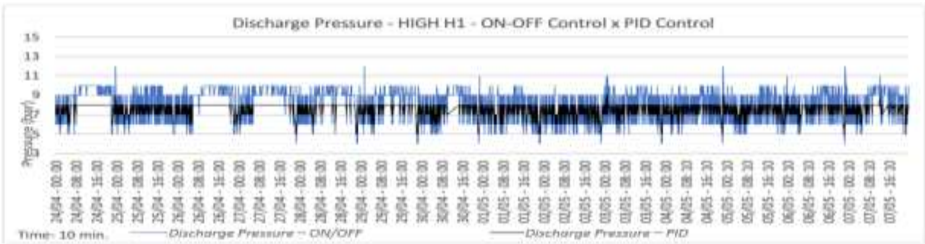
Figure 8: Comparative graph between the Active Power (kW) consumed during ON-OFF control and PID control.



Source: (Authors, 2022)

Figures 9, 10 and 11 represent respectively discharge pressure (bar), discharge temperature (ºC) and condensation temperature (ºC) referring to the ALTA H1 side of the refrigeration rack. Both have higher values when using ON-OFF control in relation to PID control.

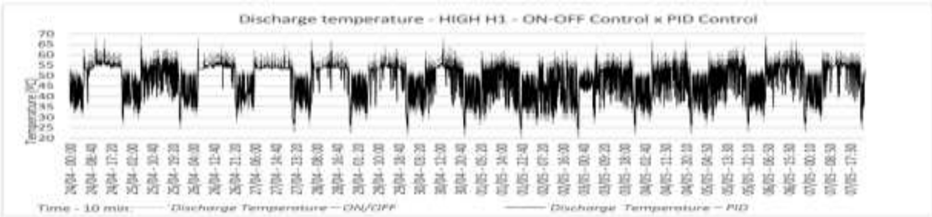
Figure 9: Comparative graph between the discharge pressures (bar) during the sampling time between the ON-OFF control and the PID control on the HIGH H1 side.



Source: (Authors, 2022)

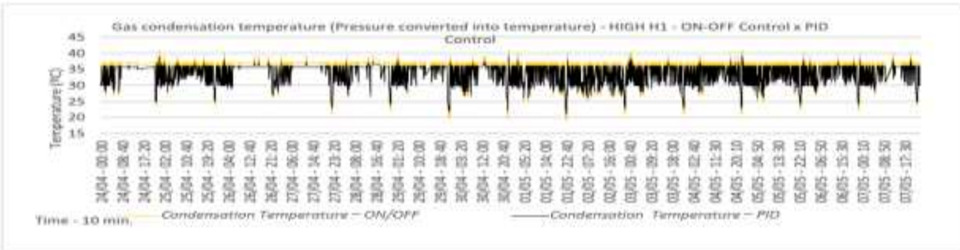
In figure 9, the maximum and average pressure values when using ON-OFF control were 12.00 bar and 7.94 bar, respectively. The same figure shows the same discharge pressure when using PID control. In this situation the maximum and average pressures were 9.00 bar and 7.53 bar, respectively.

Figure 10: Comparative graph between the discharge temperatures (ºC) during the sampling time between the ON-OFF control and the PID control on the HIGH H1 side.



Source: (Authors, 2022)

Figure 11: Comparative graph between the condensing temperatures (ºC) during the sampling time between the ON-OFF control and the PID control on the HIGH H1 side.

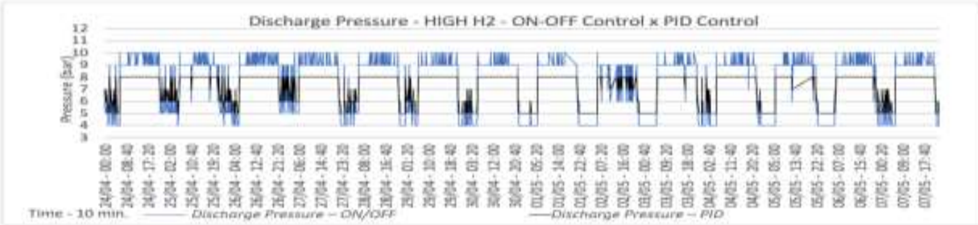


Source: (Authors, 2022)

In Figure 10, the maximum and average discharge temperature values when using ON-OFF control were 69.00ºC and 49.31ºC, respectively. The same figure shows the same discharge temperature when using PID control. For this case the maximum and average temperature values were 64.00ºC and 47.39ºC, respectively. Figure 11 shows the condensation temperature values during the data collection period. The condensing temperature is the discharge pressure converted to temperature using the pressure versus temperature conversion factor of the refrigerant fluid. Its maximum and average values when using ON-OFF control were 41.00ºC and 34.37ºC, respectively. The same figure shows the same discharge temperature when using PID control. For this situation the maximum and average condensing temperature values were 39.00ºC and 33.76ºC, respectively.

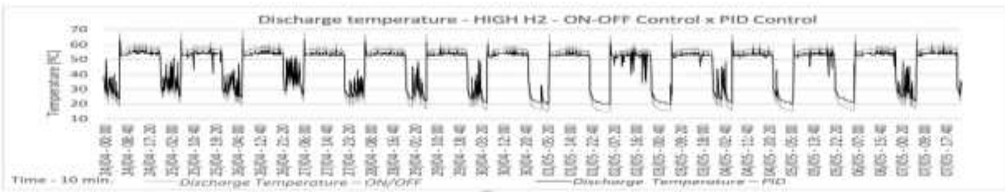
Figures 12, 13 and 14 represent respectively discharge pressure (bar), discharge temperature (ºC) and condensation temperature (ºC) referring to the ALTA H2 side of the refrigeration rack. Both have higher values when using ON-OFF control in relation to PID control. In figure 12, the maximum and average pressure values when using ON-OFF control were 10.00 bar and 7.68 bar, respectively.

Figure 12: Comparative graph between the discharge pressures (bar) during the sampling time between the ON-OFF control and the PID control on the HIGH H2 side.



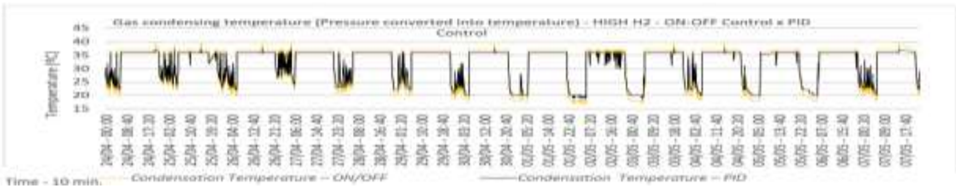
Source: (Authors, 2022)

Figure 13: Comparative graph between the discharge temperatures (ºC) during the sampling time between the ON-OFF control and the PID control on the HIGH H2 side.



Source: (Authors, 2022)

Figure 14: Comparative graph between the condensation temperatures (ºC) during the sampling time between the ON-OFF control and the PID control on the HIGH H2 side.



Source: (Authors, 2022)

The same figure shows the same discharge pressure when using PID control, which resulted in a maximum and average pressures of 8.00 bar and 7.21 bar, respectively. In Figure 13, the maximum and average discharge temperature values when using ON-OFF control were 69.00ºC and 45.76ºC, respectively. The same figure shows the same discharge temperature when using PID control, which resulted in a maximum and average temperature values of 64.00ºC and 45.03ºC, respectively. Figure 14 shows the condensation temperature values during the data collection period. When using ON-OFF control, the maximum and average temperatures were 39.00ºC and 32.36ºC, respectively. The same figure shows the same discharge temperature when using PID control, which resulted in a maximum and average condensing temperature values of 37.00ºC and 32.14ºC, respectively.

4. Conclusion

Refrigeration is an extremely important sector, and the cost to maintain it directly affects the final product. Thus, techniques to reduce production and conservation costs are advantageous for consumers and producers, as they increase profit and can decrease the value of the final product. The unit value of energy consumption given by KWh according to the local energy supplier (Minas Gerais Energy Company - Companhia Energética de Minas Gerais (CEMIG)) is 0.65803 BRL. Considering this unit consumption cost constant throughout the year and considering a workload of 24 hours, it is possible to estimate that the refrigeration unit working with the ON-OFF control would generate a monthly cost of approximately 1,399.32 BRL, while the system working with the PID controller would cost 1,029.60 BRL.

In this way, the project proves to be economically viable, since the energy costs for the condensation of the refrigerant fluid could be reduced by 26% (such savings verified by the maximum and average measurements of the ON-OFF control were 19.20A and 7.74A, while the same currents using the PID control were 15.74A and 5.70A respectively - current consumed by the PID control was 26.31%) using PID control compared to the ON-OFF, reducing the electronic stress of the equipment that would need to operate at maximum load unnecessarily. Furthermore, the PID control will increase the durability of the equipment, which indirectly will reduce unscheduled downtime in the long term, with a reduction in maintenance costs in general.

As future studies, it is considered that in a refrigeration system there are several points to be observed regarding the energy efficiency requirement. One of the points not addressed in this technical analysis was the thermal efficiency of the condenser. Considering the application of a frequency inverter it would be possible to achieve a more stable condensing pressure curve than in the system with ON-OFF control. Thus, a comparative study of analysis of the cooling capacity of the system with the changes made shows potential.

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