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TEMPERATURE CONTROL OF HOUSEHOLD REFRIGERATORS BASED ON THE ELECTRIC CURRENT OF ON/OFF COMPRESSORS

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Abstract. *Over the years, household refrigerators have undergone several control systems upgrades. The main change was the migration of electromechanics bulb thermostats to thermistor-type temperature sensors, connected to an electronic board. However, such an update implies a high cost of manufacturing and maintenance. This study was aimed at developing an alternative low-cost control strategy capable of regulating the internal temperature of a domestic refrigerator using only the electric current of the compressor as the process variable, which is sensitive to the variation of thermal load in refrigeration systems. To this end, an electronic board capable of measuring the compressor current with good accuracy and controlling the refrigerator was developed. Such a technique and electronic board were applied to a single-door refrigerator using a single-speed compressor. The device was tested at two different ambient temperature levels (16 and 25°C) based on the IEC62552 norm. Also, three different types of tests were performed: pulldown, defrost recovery and ambient temperature transitions. All experiments were performed in a climate chamber that controls temperature, humidity and air speed according to the current standards. The control algorithm consisted of a dynamic reference modification for a PI controller, together with a set of empirical conjectures. The electric current control technique was able to maintain the refrigerator temperature within acceptable tolerance levels, around $\pm 1^\circ\text{C}$, figures quite like those obtained from the baseline temperature control, albeit costing twice as lower.*

Keywords: *current control, single speed compressor, household refrigerators*

1. INTRODUCTION

It is estimated that there are currently more than one billion domestic refrigerators in operation around the world. Given such market demand, manufacturers operate in a continuous process to reduce cost and maintain product quality. The evolution of these home appliances led to some changes in the control system, such as the replacement of electromechanical thermostats for thermistors connected to an electronic board, which brought advantages and disadvantages to the product. The advantages are related to the flexibility of adjusting the control by the user and the ease of incorporating new control logics by the manufacturer. However, among the disadvantages we can mention the sensor positioning and the manufacturing and maintenance costs, problems that can be circumvented through control strategies based on variable estimations.

Such strategies, also known as sensorless techniques, are quite widespread in the position and rotation control of Brushless DC motors. The study by Johnson et al. (1999), for example, contemplates the main control methods to act on DC motors, highlighting the implementation of a Kalman filter to estimate the process variable. Over the years, control techniques previously applied to DC motors began to be used in variable speed induction motors. However, to control this type of motor, an internal actuation loop is required, as proposed by Cho (2003), who developed and patented a controller capable of regulating current levels and keeping the actuator speed at the desired levels. Along the same lines, Shiga et al. (2020) obtained satisfactory results when designing an estimator for the rotational speed of the compressor using only the electric current of the motor as a process variable.

Applications and studies of sensorless techniques in refrigeration systems with fixed speed compressors are scarce in the literature. However, there are works that present alternatives to regulate the temperature of a refrigerated environment

The outputs for the actuators were designed using mechanical relays with 5 VDC coil rating and contact rating of 10 A at 250 VCA. To protect the microcontroller the coil driver uses an optocoupler with 5 kV isolation and a flyback diode. To measure the two thermistors with the microcontroller's ADC inputs, two low-pass resistive capacitive filters with voltage dividers were implemented, conditioning the signal and filtering high frequency noises and to simplify the board power system design, a commercial 5 W power module was selected, this module is responsible by converting AC inputs of 90 to 245 VAC to 5 VDC 1A.

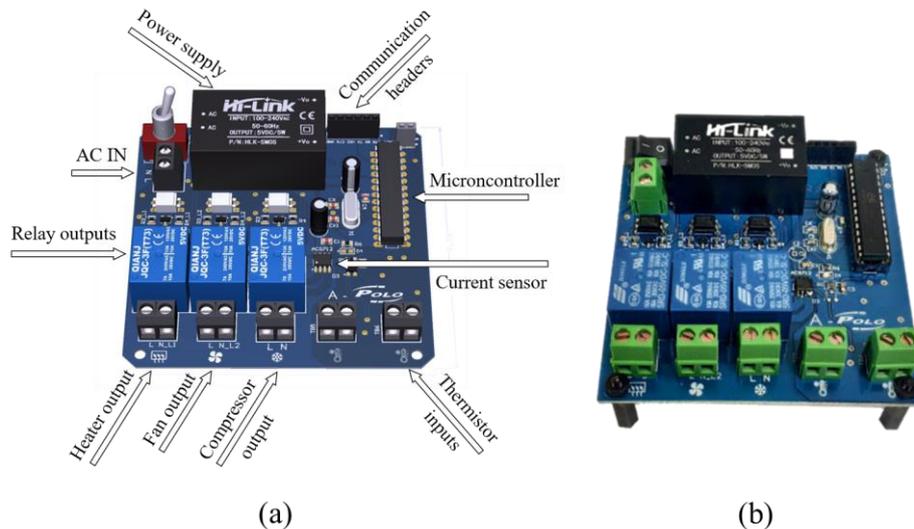


Figure 2. ECAD model (a) and Real model (b).

To increase component density, resistors, capacitors, LED's and diodes used are Surface Mounted. Screw terminal blocks were used to connect the external components, to program and communicate with the microcontroller headers connected to the necessary pins allows the use of an external USB to Serial converter. With all components selected and the design of the sub-circuits, the Electronic Computer-Aided Design (ECAD) was developed and is presented on Fig. 2 (a) with the main parts highlighted. Also, in Fig. 2 (b), a picture of the real model is presented.

3. CURRENT MEASUREMENT

The main innovation on the electronic board developed is the integration of a current sensor, which is responsible for measuring the compressor electric current, that is used as process variable for the control logic. The current sensor for this purpose should be compatible with the electrical data of the compressor, that are listed on Tab. 1.

Table 1. Compressor electrical data.

Locked Rotor Current [A]	Power [W]	Voltage [V]	Frequency [Hz]
4	123	198-242	50 - 60

With these values, the sensor must have a nominal current up to 4 A, peak current up to 50 A due to the start behavior of the current on the compressor, bidirectional current compatible on at least 60 Hz bandwidth, output signal readable by the microcontroller without any amplification or active component and voltage isolation up to 240 VAC. The sensor model selected is the Allegro ACS 712ELCTR-05B-T, a fully integrated Hall effect based current sensor, that measures the current by an indirect way. The sensor measures the current flowing through a cooper path inside the package by sensing the magnetic field generated above it with a hall sensor, that is attached to an integrated circuit that converts the measuring to a proportional voltage on the output of the component. This allows the sensor to provide isolation between the current terminals and the signal pins on voltage rates up to 2.1 kV. On Tab. 2 the most relevant ratings of the selected current sensor.

Table 2. Allegro ACS712ELCTR-05B-T main characteristics

Current Range [A]	Peak Current [A]	Bandwidth [kHz]	Sensitivity [mV/A]	Isolation [kV]
±5	±100	80	185	2.1

Therefore, with the sensor selected and embedded on the electronic board developed, the product was tested under normal conditions, while the electric current of the compressor was measured simultaneously by a current transducer and the electronic board developed. Figure 3 (a) presents the compressor electric current behavior during refrigeration cycles,

where can be seen that the measurement by the electronic board is similar to the reference equipment, where more than 95% of the data points are in between an $\pm 10\%$ error band as seen on Fig. 3 (b). Also, in Fig. 3 is possible to notice that the points that are outside the error band are related to the current spike on the compressor start, which relates to a bigger response time of the ACS, although, this aspect will not interfere with the control logic operation that will be described on Section 4.

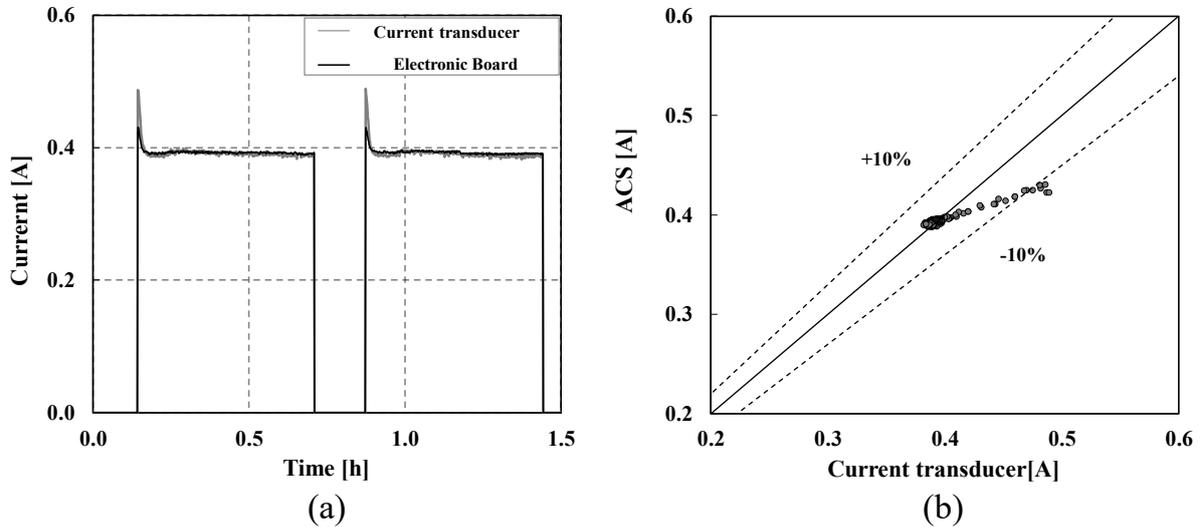


Figure 3. Current measurement: (a) comparative and (b) error evaluation.

4. CONTROL LOGIC DEVELOPED

The developed control logic can be understood through the block diagram of Fig. 5. Once the compressor current reaches the Setup block, two average current values are calculated. Initially, the algorithm waits for the compressor to turn off and then calculate the average of all current values read so far, called OAC (ON Average Current). The second variable is only calculated at the end of the compressor's complete cycle, thus indicating the average of all compressor's current readings during the on and off periods, called TAC (Total Average Current).

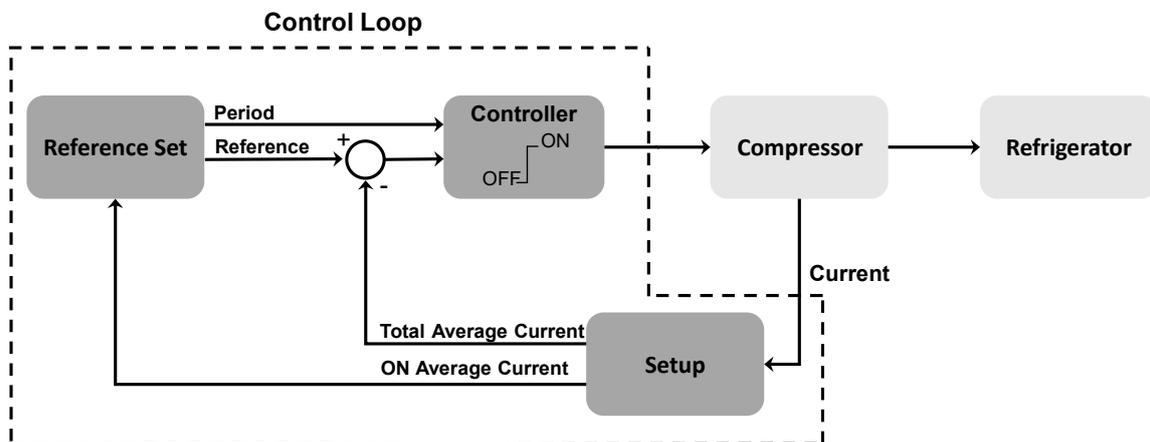


Figure 4. Block diagram of the control system.

With the OAC properly calculated in the Setup block and the data in Tab. 3 - obtained through product identification tests, in steady state, for different ambient temperatures - the Reference Set block chooses which TAC will be used as a reference to calculate the next control action, in this case, the compressor runtime ratio (RTR). In addition to the RTR, it is necessary to estimate the duration of the next cycle, in minutes, which is also done by the Reference Set block based on the data in Tab. 3.

Table 3. Reference values extracted from baseline tests.

Temperature [°C]	ON Average Current [A]	Total Average Current Reference [A]	Period [min]
16	0,34	0,12	15
25	0,36	0,21	19
32	0,38	0,28	23

The developed controller was implemented in a modular way, as shown in Fig. 5. After receiving the current and reference value from the TAC, the controller calculates the error associated with this variable, which is used as input for the first block represented in Fig. 5, where a PI controller with an anti-windup action was implemented, which estimates the RTR of the next cycle through the following expressions:

$$u(i) = u(i - 1) + k_p e(i) + k_p \left(-1 + \frac{T_s}{T_i} \right) e(i - 1) - \frac{T_s}{T_i} e_{aw}(i - 1) \quad (1)$$

$$\begin{cases} e(i) = y_m(i) - r(i) \\ e_{aw}(i) = u(i) - u_s(i) \end{cases} \quad (2)$$

where, u represents the RTR of the next cycle, which is the control action calculated by the PI, k_p and T_i the proportional and integral gains of the PI controller $e(i)$ the difference between the reference and the process variable, e_{aw} the error associated with the saturation of the control action used by the anti-windup logic and T_s the sampling rate used in the experiments.

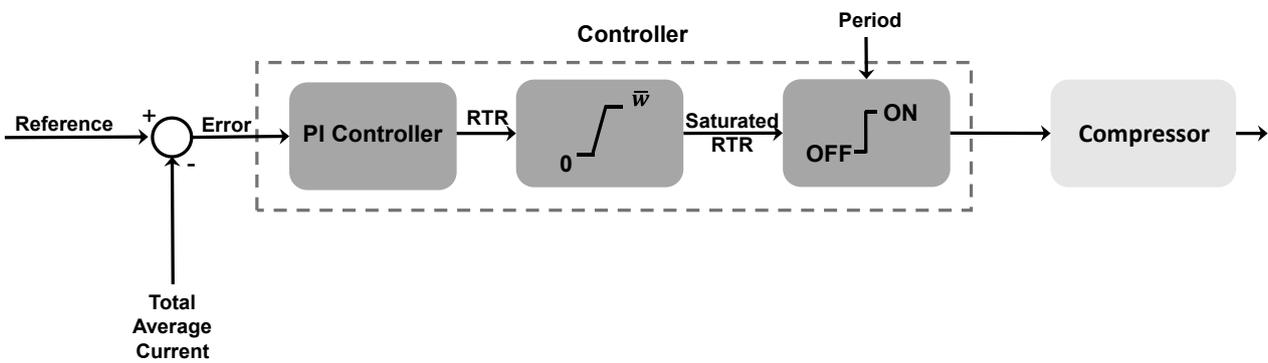


Figure 5. **Block diagram of proposed control.**

As the RTR of a compressor cycle represents the ratio between the compressor on time and the total cycle time (on and off), its values range from 0 to 100%. It is therefore necessary to treat the control action signal established by the PI, which is first saturated and then normalized according to the following expression:

$$\begin{cases} u_s(i) = \text{sat}(u) \begin{cases} 2\bar{w} \\ 0 \end{cases} \\ \text{Saturated RTR}(i) = \frac{u_s(i)}{2\bar{w}} \end{cases} \quad (3)$$

where, \bar{w} represents a constant used as the saturation limit and normalization of the control signal, u_s represents the saturated control signal and Saturated RTR the control signal that will be effectively sent to the system after all stages of signal processing.

The tuning of the parameters k_p and T_i of the PI controller, related to the proportional and integral gains, respectively, was carried out through the Good Gain Method, according to which the system is gradually stimulated in closed loop until good stability is achieved. After that, the system was operated in closed loop and the gains were adjusted until the system response time results were satisfactory.

The last controller block represented in Fig. 5 is responsible for quantifying the period in which the actuator will be on and off from the RTR and the period of the next cycle. In order to obtain the compressor on time for the next cycle, the RTR value is multiplied by the estimated total period and, to calculate the compressor off time, the compressor on time is subtracted from the estimated total period. However, once the compressor on and off times are set, a check is made to ensure that the minimum compressor off time is long enough to allow for system pressures to equalize, as fixed speed compressors have problems. starting point if pressures are not equalized.

5. RESULTS

The performance of the proposed control logic was evaluated in three different situations, pulldown time, transient steady state and defrost rejection. Basically, the desired characteristics for an efficient temperature regulator are fast disturbance rejection and reference tracking with low amplitude oscillations. Figures 7 and 8 show the results of tests performed for ambient temperature conditions of 16°C and 25°C, respectively. It can be observed in Fig. 6(a) that the refrigerator is able to lower the internal temperature of the cabinet in approximately 1 hour, stabilizing around 0°C. In

Fig. 6(b) the behavior of the controller during the pull-down is observed, which starts with a maximum action on the actuator (RTR=100%). After this cycle, the PI action is triggered to regulate the TAC. It is possible to notice in the first hours of testing the control reference being changed twice, starting at a high value (used for conditions of 32°C), and changing to a low value (used for conditions of 16°C), as that the initial heat load of the refrigerator is rejected. It is worth noting that the final error obtained in the process variable is null, since the controller has an integral and anti-windup action.

Still in Fig. 6(a), it is possible to observe a defrost event, which increases the temperature of the freezer compartment to ~0°C, increasing the compressor current after the event, a fact that leads the controller to impose hard control actions to reject the disturbance as soon as possible. Since a large part of this thermal load injected into the system is rejected, reducing the value of the current to levels close to those found before the event, the refrigerator returns to regulate the temperature around 0°C.

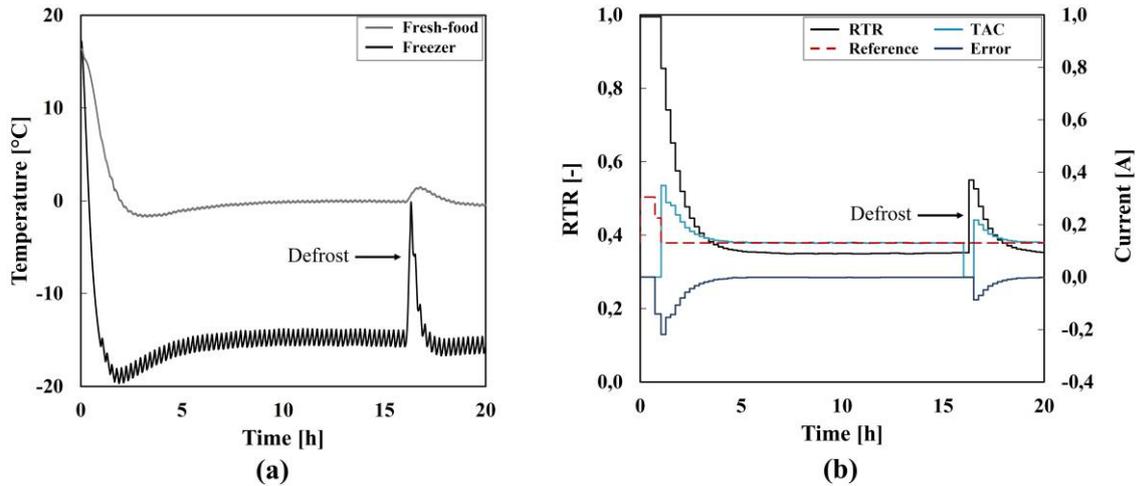


Figure 6. Experimental tests results at 16°C: (a) temperatures and (b) control variables.

In Fig. 7(a) the behavior of the system can be observed for a situation in which the environment is maintained at 25°C. During the temperature drop, the fresh-food temperature reach values lower than 0°C for a couple hours. After this event, the refrigerator temperature increases and tends to fluctuate at values close to those reported in other tests, around 0°C. Again, in Fig. 7(b), it is observed that the controller starts with a maximum control action in the pulldown condition. After this first cycle, the PI action controls the TAC of the compressor, thus regulating the temperature of the refrigerator. Still in this test, it is possible to observe a defrost close to 20 hours of test, in which the freezer temperature is increased to ~0°C. Once the thermal load injected into the system is rejected, the refrigerator returns to regulate the temperature at the same level as it was before this defrost.

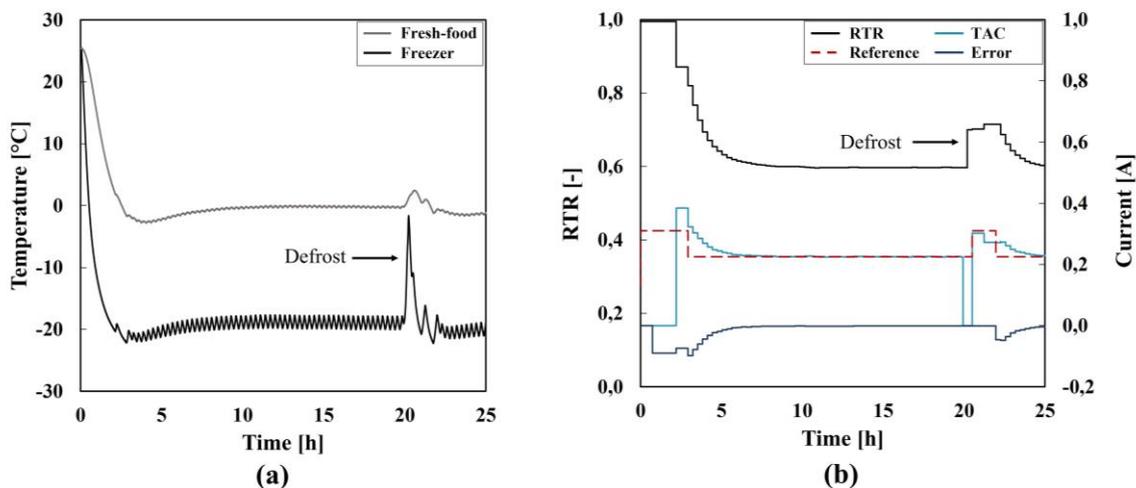


Figure 7. Experimental tests results at 25°C: (a) temperatures and (b) control variables.

Figure 9 shows how the current logic responds to an ambient temperature change, in this case the ambient is changing from 16°C to 25°C. In Fig. 8(a) it is possible to see the ambient change at 5 hours of test, after this almost no alteration is seen at the fresh food temperature, but at the freezer a temperature drop can be noted going from -15°C to -17°C. In

Fig. 8(b) the control variables are shown, right after the ambient change, the control Reference changes, thus increasing the error and applying a harder control action to prevent the internal temperatures to vary so much.

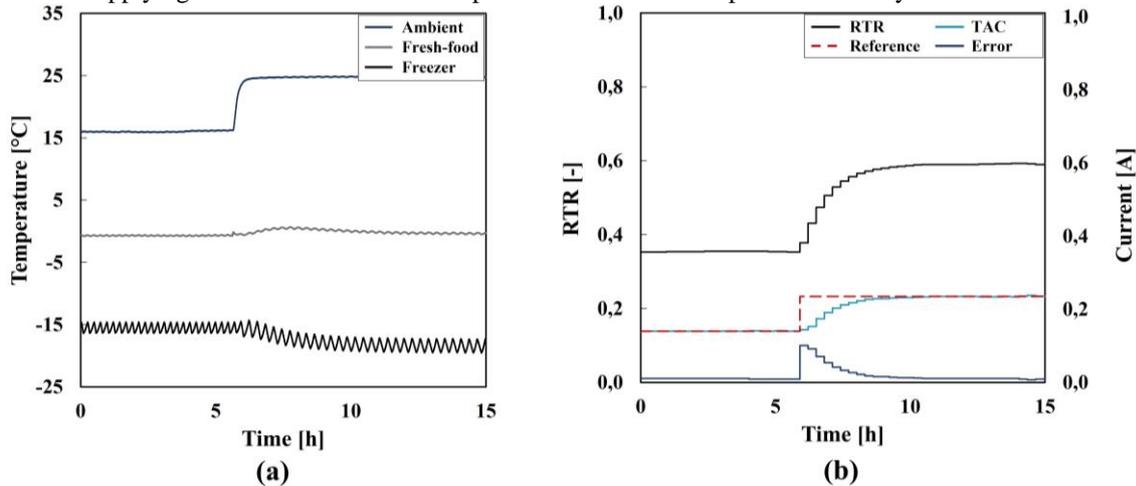


Figure 8. Experimental tests results for ambient temperature change from 16°C to 25°C: (a) temperatures and (b) control variables.

Figure 9 shows a performance comparison between the original product control (baseline) and the current control proposed in this work for ambient temperatures of 16°C (Fig. 9a) and 25°C (Fig. 9b). For this figure, the red cycle represents when the pulldown is finished, the pulldown time metric adopted is the time for the fresh food compartment to reach 5°C since the beginning of this event. In Fig. 9(a) similar pulldown times can be observed, with the baseline logic performing the temperature drop in 1.0 hour and the current control in 1.2 hours. It is also verified that both logics can regulate the internal temperature of the two compartments within the same hysteresis band. In Fig. 9(b) the pulldown times are equal, with the original and the current logic completing in 1.8 hours, in this case the Current Logic was controlling the compartments temperatures 2°C above the baseline but still inside good levels.

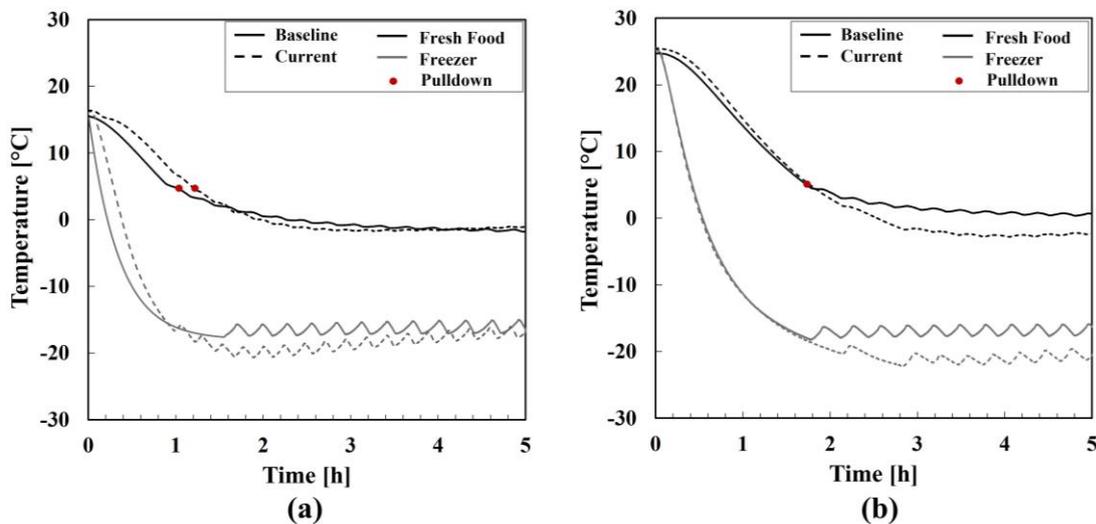


Figure 9. Experimental tests comparison between the baseline and current control: (a) 16°C and (b) 25°C.

6. CONCLUSIONS

A method for regulating the internal temperature of a domestic refrigerator based on the compressor current has been proposed. For that, the compressor current was measured using an electronic board embedded with a current sensor and a PI controller with anti-windup action. During all pulldown situations, the product was able to lower the temperature in times close to those obtained through the product's original logic. Regarding the defrost events, it is possible to notice that the performance of the controller in disturbance rejection mode was quite satisfactory. At 16°C ambient temperature, this event can be quickly rejected using the dynamic reference change, caused by the increase in current consumed by the compressor when this disturbance reaches the system. In the test carried out at 25°C, an aggressive control action was observed in the recovery of the freezer temperature, returning to regulate the internal temperature close to 0°C after the event. In general, the proposed control strategy can measure the compressor current and regulate the temperature of the refrigerator within the hysteresis band of the original control, without impacting the overall performance of the product.

Due to the variable used with the control, the new logic can also be used as a redundant control system in case of product failure, reducing technical assistance costs.

7. ACKNOWLEDGMENT

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