Controller design for high-energy-efficient performance of a household refrigerator using inverter technology

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***Abstract*—This work presents the control design of a domestic refrigeration system by using a variable speed compressor (inverter technology) with the main purpose of reducing energy consumption and complying with Ecuadorian standards for this type of household appliances. A study on refrigeration systems is carried out, its operating principles are discussed and a comparison between conventional systems and the variable speed technology is performed. Additionally, an analysis of the refrigeration control is included and the variable speed controller is implemented in a prototype card, which was installed in a domestic refrigerator of 12 ft^3. The system exhibits a reduction of 27% in the consumption test regulated by the RTE INEN 035 and the NTE-INEN 2 206 norms, which demonstrates its high-energy efficient performance.**

***Keywords*—BLDC, high efficiency, inverter technology, speed controller, refrigeration.**

I. Introduction

According to the guide for the efficient use of electricity in Ecuador, the energy consumption of a refrigerator represents approximately 40% of the total consumption in the residential sector [1]. Therefore, it is important to improve the efficiency of refrigeration equipment, not only to reduce the consumption of electrical energy and the impact on electricity generation nationwide but also because the development of more efficient cooling systems helps to reduce environmental pollution [2].

The refrigeration system allows heat transfer from a low-temperature region to a high-temperature region. To achieve this transfer, different cooling methods can be used, such as steam compression, gas cooling, cascade cooling, absorption cooling, and thermoelectric cooling [3].

The operation of a traditional household refrigerator is based on steam compression, where the compressor works with a fixed speed. This system maintains the desired temperature within a range, called hysteresis, using an ON/OFF control scheme. This procedure causes the cooling system to work with a constant cooling capacity for a time that depends directly on the thermal load [3]. The difference between the cut-in, the cut-out, and the setpoint temperatures causes an embedded error in the thermostat that is set consciously according to the working principle of the ON/OFF controller. Moreover, if the difference is set at a too-small value, then the refrigerator will often turn on and off. As a consequence, the compressor may be irreparably damaged. The ON/OFF action also requires high starting currents around 4 to 10 times bigger than the nominal current. Therefore, the energy consumption of this refrigeration system is considerably high among household appliances.

Although several technologies have been investigated to improve household refrigerators [4], [5], [6], Ecuadorian manufacturing industries have not yet been able to adapt all the potential of these technological advances and improve the efficiency of their refrigerators. Therefore, in this work, we propose an energy-efficiency improving solution for compressors by using inverter technology. For the first time, this system is completely designed and implemented in a domestic refrigerator-freezer RENOVA 211, no-frost, from the artifact company Ecasa in Ecuador. This equipment has two doors and the freezer is top-mounted with a 2-star rating (freezer achieves temperatures below -12 °C and above -18 °C). Several standard experimental tests demonstrate the superior cooling capacity and energy-saving efficiency of this system compared to the traditional technology. The developed solution also offers low cost, easy installation, operation, and maintenance.

The remainder of this paper is organized as follows: in Section II, we provide details of the refrigeration system operation; in Section III, we describe the design and implementation of the refrigeration control system; in Section IV, we show and discuss the results obtained in different standardized tests. Finally, in Section V, the main achievements of this work are summarized.

II. Refrigeration system technologies

Vapor-compression refrigeration system (VCRS) is a cyclic process that performs a cooling fluid for exchanging heat. This cycle has four threads: expansion, vaporization, compression, and condensation [2]. A diagram of an elementary steam

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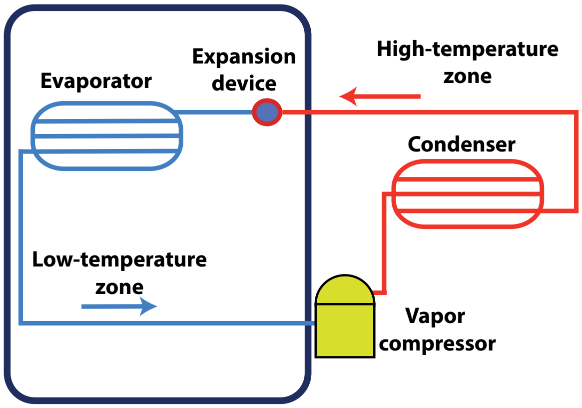

Fig. 1. Scheme vapor compression refrigeration.

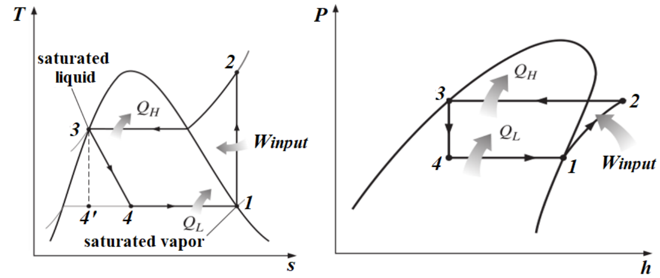

Fig. 2. Temperature vs entropy (left) and pressure vs enthalpy (right) diagrams of a refrigeration cycle [2].

compression cooling system is shown in Fig. 1. The red and blue lines represent a closed circuit of pipes, through which the refrigerant circulates.

In the blue pipes, vaporized refrigerant circulates at low pressure, called suction or vaporization pressure. In the red pipes, the refrigerant is a high pressure, called condensing pressure. At this value, the compressor discharges the refrigerant. The refrigerant enters the compressor as a saturated vapor, *state 1*, performs a work W and increases the refrigerant pressure to the condensation pressure. The objective of the isentropic pressure increase is to raise the coolant temperature to a value greater than the surrounding temperature in the high-temperature zone. Then the refrigerant gets into the condenser as overheated vapor, *state 2*, and comes out as a saturated liquid, *state 3*, due to the heat transfer Q_H to the surroundings. When the refrigerant is already in a liquid state, it is strangled by the use of an expansion valve or a capillary tube to decrease the pressure to the vaporization value before it enters the evaporator in the form of wet vapor, *state 4*, and evaporates by absorbing the Q_L heat of the low-temperature region.

In the diagrams temperature vs entropy (T-s) and pressure vs enthalpy (P-h) shown in Fig. 2, the refrigerant states are indicated during the refrigeration cycle in the different stages: isentropic compression in a compressor (1-2), heat rejection Q_H at constant pressure (2-3), strangulation with an expansion device (3-4), heat absorption Q_L at constant pressure in the evaporator(4-5).

The heat extracted by the refrigeration system is equal to the difference between the enthalpy of the refrigerant at the evaporator outlet h_1 and the enthalpy of the refrigerant at the evaporator inlet h_4. This difference is called the cooling effect, $\Delta h = h_1 - h_4$.

The cooling capacity ($\dot{Q}_L$) or cooling power of a VCRS corresponds to the rate of heat transfer extracted in watts or BTU/h. By definition, $\dot{Q}_L = \dot{m} * \Delta h$, where, $\dot{m}$ is the refrigerant mass flow over time in kg/s or pounds/h.

Moreover, the coefficient of performance (COP) of a refrigeration cycle is defined as $COP = \dot{Q}_L/\dot{W}$, where $\dot{W}$ is input power. Graphically, $\dot{W} = \dot{Q}_H - \dot{Q}_L$, then $COP = \dot{Q}_L/(\dot{Q}_H - \dot{Q}_L)$.

A. Traditional refrigeration control

The household refrigerator-freezer RENOVA 211, which is the starting point of this work, normally operates with a traditional control using a mechanical thermostat located in the freezer. The temperature of the refrigerator is dependent on the airflow that is regulated employing a manual butterfly-type damper.

Freezer operating temperatures range from -14 °C, cut-off temperature, and -12 °C start temperature. While the average temperature in the refrigerator is 5 °C. When using test packages [7], [8], the operating cycle is approximately 30%.

The equipment has an automatic defrosting system for the evaporator, which is controlled by a mechanical timer. This timer allows the compressor to work for eight hours before changing the flow of current to the defrost resistors. In the defrosting cycle, two resistances are energized. One of the evaporator (150 W) that performs the defrosting itself and the drip resistance (40 W), which prevents the formation of ice in the water collection tray. The time the resistors remain activated depends on the amount of ice accumulated in the evaporator. To turn off the resistors, a bimetallic thermostat is used that opens its contact at a temperature of 12 °C and closes it at -5 °C. After the opening of the bimetallic thermostat, the timer maintains its position for seven minutes to start the cooling process again.

B. Inverter refrigeration control

An inverter is a circuit that allows converting direct current to alternating current [9]. The term inverter in refrigeration is used commercially, to specify that the inverter circuit is used to vary the speed of the compressor. This ultimately allows regulating the cooling capacity of a refrigeration system, to perform a continuous temperature control [10]. Consequently, the energy consumption in the compressor is considerably reduced compared to the ON/OFF control [11].

In the simplified and control-oriented model of refrigeration systems [12], the effect of the compressor speed variation on the cooling capacity is analyzed. As shown in Fig. 3, for a refrigeration system in a stable state, if the compressor speed increases, the vaporization temperature drops, but the cooling

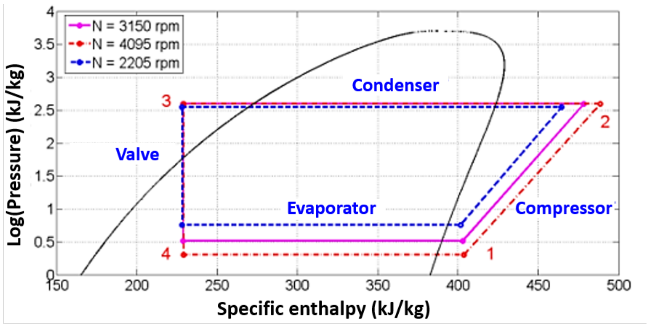

Fig. 3. P-h diagram for different speeds [12].

effect is maintained. Now, the cooling capacity is a function of the speed of the compressor.

The speed of the compressor also affects the COP. By keeping the cooling effect constant, as in the traditional system, the vapor overheating increases causing the compressor to work harder, which decreases the COP value [12]. Since the ON/OFF system does not operate with an optimal value of COP, the inverter technology offers an advantage from this point of view.

To continuously control the temperature, it is necessary to use a variable speed drive in the compressor motor of the cooling system, which can be based on inverters with TRIACs [13]. However, this implementation is challenging due to some of the drawbacks in a conventional domestic refrigeration system such as the dimensions of the compressor, the lack of a hermetic structure and the type of motor that is normally used. To solve these problems, some companies have developed hermetic compressors with brushless direct current motors (BLDC). Contrary to common DC motors, these motors have poles that must be switched electronically [14]. They behave like a synchronous motor, i.e. the magnetic field generated in the rotor and the stator rotate at the same frequency, with an advantage of not presenting displacement. They can be built to work with two or three phases, the latter being the most used.

III. Design and Implementation of the Refrigeration Control Systems

A. Hardware adaptation

To implement a refrigeration control with inverter technology in the RENOVA 211 equipment, it was necessary to replace some components that do not support this type of control.

First, the reciprocating compressor Samsung MSA151C-L1B was replaced with the motocompressor Samsung NC1MV43AMP, which is equipped with a voltage inverter that operates with a maximum power supply of 240 Vac. This compressor is designed to work with R-134a refrigerant. It has a variable cooling capacity between 180 to 580 BTU/h and requires a square wave control signal (maximum amplitude 15 V) from 40 Hz to 120 Hz.

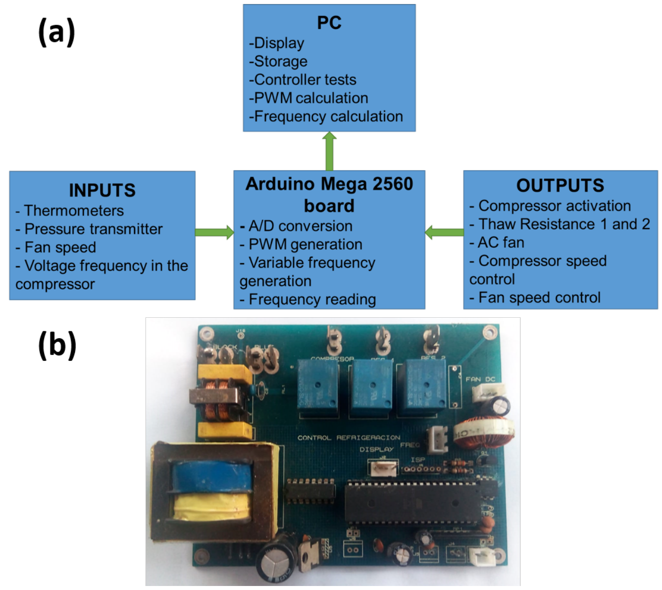

Fig. 4. (a) Data acquisition and testing circuit diagram. (b) Electronic circuit card with the controller.

To vary the ventilator rotation speed, the AC motor was replaced by a BLDC motor with a power of 4.5 W and a maximum idle speed of 3000 RPM.

The inverter technology also requires electronic signals from the control variable for its operation. Therefore, NTC thermistors coated with ABS plastic were selected as temperature sensors.

B. Data acquisition and testing circuit

Due to the time required during refrigeration system evaluations, greater than 24 hours, a data acquisition and testing circuit has been designed to obtain the temperature at the different control points requested by the NTE INEN 2 206 standard [7]. This circuit uses an Arduino Mega development card and a display interface designed in the software LabVIEW.

This acquisition and testing system allows its input circuits to measure the temperature at different points of the cooling system, the frequency of the voltage signal in the stator of the motor compressor, the speed of the evaporator fan and the pressure in the suction of the motor. The pressure was measured, to determine the evaporation temperature with which the cooling system was working. The output circuits energize the compressor, an AC fan, defrost resistors and vary the speed of the DC compressor and DC fan. Fig. 4 (a) and (b) depicts the system diagram with the main components and the electronic circuit card with the controller.

C. Transfer function approximation

Before designing the prototype card, it was necessary to obtain the dynamic characteristics of the cooling system illustrated in Fig. 5. Therefore, the temperature response of

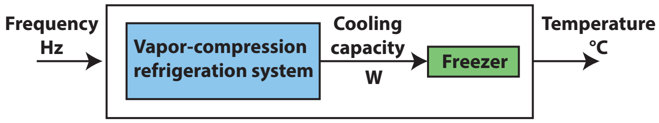

Fig. 5. Block diagram of the open loop system.

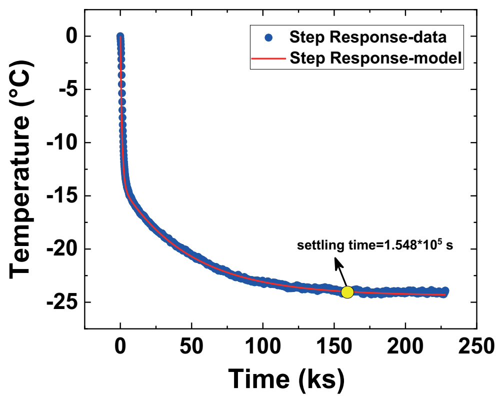

Fig. 6. Second order step response by using Matlab system identification tool.

the refrigeration cabinet (freezer) is evaluated according to the input frequency required by the compressor inverter.

The step response was obtained experimentally using the previously mentioned data acquisition and testing circuit. The temperature response (Fig. 6) exhibits a settling time of $1.548\text{x}10^5$ s and corresponds to an input of 80 Hz with a load of test packages as required for energy consumption tests in refrigeration equipment [7].

According to the response of the cooling system, an approximation was made as an overdamped second-order system whose temporal response is given by:

$$c(t) = K_1 e^{-a_1 t} + K_2 e^{-a_2 t} \tag{1}$$

where a_1, a_2, K_1 y K_2 are constants and t is the time. Using the Matlab System Identification Tool, the transfer function equation was obtained:

$$G(s) = \frac{-0.000151s - 5.413 * 10^{-9}}{s^2 + 0.000872s + 1.776 * 10^{-8}}. \tag{2}$$

The result of this transfer function is depicted in Fig. 6. Since it completely follows the experimental response, it is used for the controller design.

D. Control implementation on the prototype card

To autonomously operate the refrigeration system, the control was implemented on an electronic card (Fig. 4 (b)). Through signal conditioning, different peripheral devices are connected to the main control in the card, such as the compressor inverter, the DC ventilator, the defrost resistors, the NTC temperature sensors, and the user panel.

Considering the above-mentioned hardware, the system requires 3 analog inputs, 5 general-purpose pins for digital inputs and outputs, 2 USART communication pins and three pins for the used timers. Therefore, to fulfill these specifications, an atmega164p microcontroller has been selected, in which a cooling and defrosting control routines were programmed.

1) Refrigeration control: Several control methods can be applied to an inverter cooling system, most of them are focused on the continuously speed control by using PID algorithms, while others discreetly, or by steps, maintain the temperature of a refrigerated space by automatically selecting prefixed speeds.

Since the temperature in the freezer varies relatively slowly, this work uses a proportional-integral (PI) algorithm to send a square wave of variable frequency to the inverter, depending on the temperature difference at its input.

To determine the operation of the controller, it should be considered that the maximum compressor power is limited to 75 W by the inverter manufacturer specifications. Therefore, the inverter operates at a maximum input frequency of 120 Hz, which approximately corresponds to a compressor speed of 3200 RPM, and a minimum of 40 Hz.

For the same frequency, the power consumption decreases when the system stabilizes. This occurs because the suction pressure in the compressor and the evaporation temperature decrease. However, this pressure must remain greater than or equal to 1 PSI to avoid clogging problems due to the circulation of lubricating oil through the capillary.

It is important to clarify that the PI controller acts only if the error is less than 4 °C, to avoid that the integrative part of the control keeps the compressor operating at high speeds for a long time, which implies high energy consumption.

The PI control function is given by:

$$u(t) = Ke(t) + K_i \int_0^t e(t) \cdot dt \tag{3}$$

where u is the control signal, K is the proportional constant, e is the error between the setpoint and the measured value, and K_i is the reverse integration constant.

The controller parameters of Eq. 3 are obtained by using the PID Matlab tuner for a step input amplitude of -12 °C. Since this magnitude corresponds to the most typical setpoint for tests performed on refrigerators, such as storage, pull-down, and energy consumption tests, the controller is expected to have an optimal performance around this temperature. The values obtained from the toolbox were $K = -7.30318$ and $K_i = -0,016$ $(T_i = 456.4488s)$.

2) Defrost control: The thawing process should be executed at least once every 24 hours to avoid the accumulation of frost on the evaporator fins and should be last around 20 minutes. Therefore, the evaporator resistance must be de-energized when the sensor temperature located in the evaporator measures a value greater than or equal to 5 °C. After cutting off the source voltage of the evaporator resistance, the resulting liquid is drained. This step takes around 7 minutes. To accelerate the draining process, the resistance of the drain pan needs to be

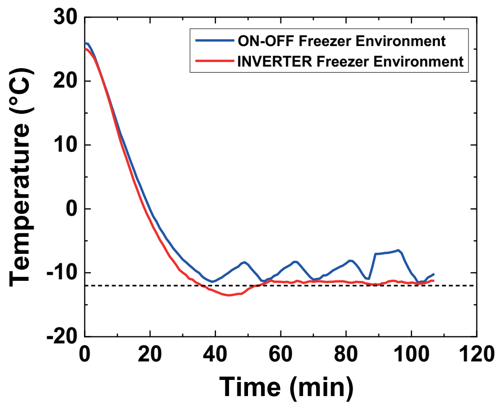

Fig. 7. Freezer temperature with ON/OFF and inverter control.

activated during the entire period. It is important to highlight that the first defrost takes place 12 hours after the electronic card has been energized, to ensure that the evaporator is free of ice in case of energy supply failures.

E. User control panel

A user-accessible control panel was designed and implemented in the upper door of the household refrigerator to change the temperature set in steps of 1 °C by using two push buttons. This control panel is connected to the electronic board through USART communication. Its main function is to display the temperature in the freezer and indicate the state of the compressor and the ventilator (on-off).

IV. Results and Discussion

A. Pull-down test

This test is performed to measure the time required to reach a specific temperature inside a refrigeration cabinet or freezer. During the test, the outside ambient temperature remains constant and the cabinet empty.

The initial temperature of the test is close to 25 °C, which corresponds to the value required for the equipment in subtropical climates. The temperature to be reached in the geometric center is -12 °C, which is the maximum temperature at which a freezer with a two-star rating can work, according to the NTE-INEN 2 206 standard [7].

Fig. 7 shows the results of the pull-down test for the conventional ON/OFF and the inverter technologies. Both controllers reach the specified temperature for the first time around 40 min (slightly sooner with the inverter). However, the main advantage is that the temperature remains constant in the inverter system without the need to turn off the compressor.

B. Automatic defrost test

In this test, the automatic execution of the thawing process every 24 hours is verified. Since the compressor stops working during the thaw and the instantaneous power corresponds only to the resistors, this value is used for calculation. By taken the time difference between the peaks of the instantaneous power (it is not shown for the sake of brevity), intervals of 25, 24.7 and 24.45 hours were obtained. Considering that each defrost cycle takes a maximum of 27 minutes, the defrosting periods are executed as scheduled.

During a thaw cycle, initially both defrost resistors are switched on at the same time and consume approximately 220 W. After 10 minutes, only the resistance of the water collection tray remains activated for 7 minutes more (drip time), which consumes 40 W. These times and powers meet the equipment requirements established by Ecasa.

C. Energy consumption measurement

The measurement of energy consumption is a test that lasts 24 hours and is regulated by the RTE INEN regulation 035 [8] and NTE-INEN 2 206 [7]. Some of the specification indicated in the regulation for this test are:

- The ambient temperature should be 25 °C for subtropical climates.
- The freezer must be loaded with test packages. They have a straight parallelepiped form wrapped in a plastic sheet and filled with 230 g of oxy-ethyl-methyl cellulose, 725 g of water, 43 g of sodium chloride and 0.8 g of 6-chloro-m-cresol per 1000 g.
- To measure the freezer temperature, *M* packages should be used. They are 500 g test packages with a temperature sensor inserted in their geometric center. The *M* packages must be distributed through the loading of test packages.
- The temperature of the fresh food compartment should be measured using copper or bronze cylinders suspended in the center of each compartment division.

To perform the measurements, a digital electrical parameter meter 8788 manufactured by Qingdao Qingzhi Instrument was used. The measuring device has an RS-232 communication port to configure and read the measured parameters through an instruction set. By using a computer and the software LabVIEW, the communication protocol established by the manufacturer was implemented to obtain the electrical parameters of voltage, current, voltage signal frequency, active power, reactive power, and power factor.

As depicted in Fig. 8, during an energy consumption test period, the temperature in the refrigerator is between 0 °C and 10 °C with an average of less than 5 °C. Therefore, the temperature condition (INEN regulations) in the refrigerator is met using a set point of -12 °C in the controller. In the case of the freezer and *M* packages, the temperature also meets the conditions. It is worth noting that the control temperature is the temperature measured at the point where the thermistor is installed. The temperature peak corresponds to the defrosting period, in which the temperatures of the *M* packages and the cylinders located in the refrigerator begin to increase. Since this peak value does not exceed the limits established for the measurement of energy consumption, no adjustment is required in the temperature setpoint.

The temperature conditions of the refrigerator and the *M* packages in the freezer for the measurement of energy

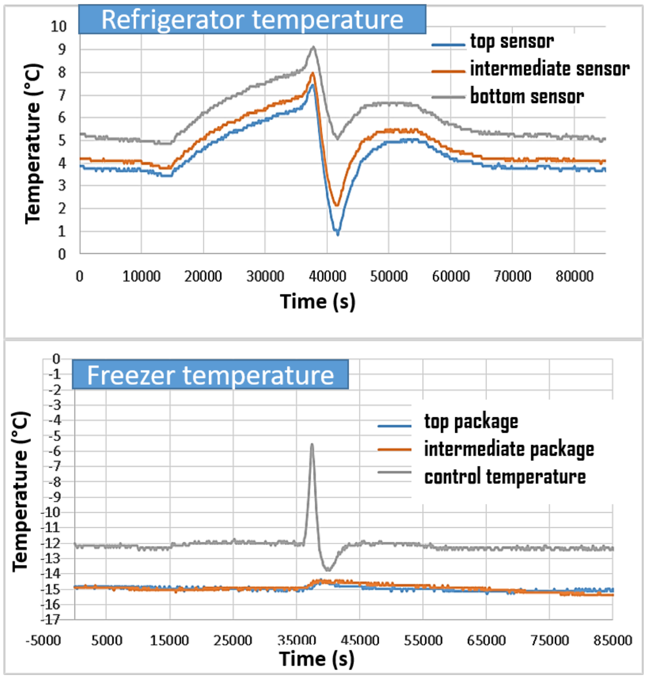

Fig. 8. Refrigerator (upper figure) and freezer (lower figure) temperature during consumption test.

TABLE I
ENERGY CONSUMPTION MEASUREMENT TESTS

Daily consumption (Wh/day)	Annual consumption (kWh/year)	Average temperature		
		M packages (°C)	refrigerator (°C)	freezer (°C)
712.43	260.037	-14.95	5	-12
695	253.675	-15.15	4.91	-12.1
774.27	282.609	-15.5	5.1	-13

consumption were met in three 24-hour periods and the results are indicated in Table I.

According to the tests carried out in the INEN physical and mechanical testing laboratory, RENOVA 211 refrigerators with traditional technology have a daily consumption of 1 kWh or 365 kWh of annual consumption. By taking the average energy consumption of the three tests, the inverter system annually consumes 265 kWh. This means a saving of 27%. Even if the traditional technology in improved equipment (thicker external walls of the cabinet) with a consumption of 315 kWh is compared with the inverter system implemented in this work, it still saves 16% of energy.

The energy-saving can be attributed to the way power behaves in each technology. On the one hand, the instantaneous power of the ON/OFF control for a constant load has high peaks at each start and value around 115 W when it is in normal operation as indicated in Fig. 9. On the other hand, the instantaneous power of the inverter system remains constant ($\sim$ 26 W) in almost the total operating time. The only exception is when the defrosting period ends because the system must compensate for the temperature increase in the cabinet. The average power is 28 W and 27 W for the ON/OFF and the inverter system, respectively.

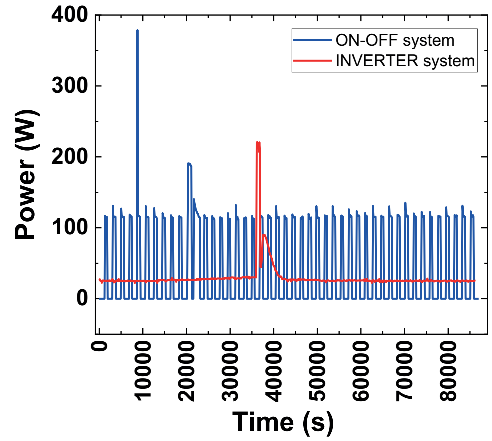

Fig. 9. Instantaneous power in the ON-OFF and the inverter system.

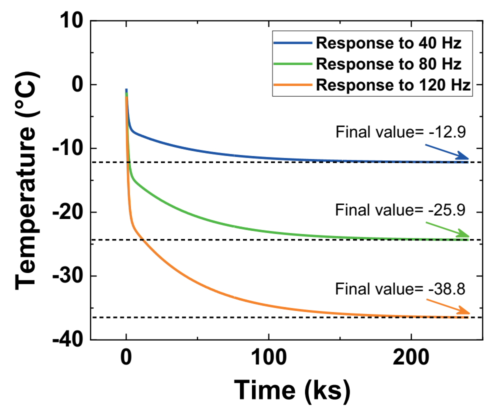

Fig. 10. Step response at different frequencies.

D. Transfer function validation

In section III, the refrigeration system was approximated to a second-order transfer function using the system response to a step input of 80 Hz to design the PI controller implemented in the prototype card. After the tests performed and the relationships between power and input frequency obtained, the validity of this function can be demonstrated.

Fig. 10 shows the theoretical temperature response of the freezer for different frequencies (minimum 40 Hz, average 80 Hz, and maximum 120 Hz). For the lowest frequency, the final value is -12.9 °C, which is approximately the same freezer temperature during the energy consumption test.

By using the minimum frequency of 40 Hz in the equation that relates the input frequency to the instantaneous power ($P_{in} = 5/8 * f_{in} + 5$), the value obtained is 30 W. As mentioned in the energy consumption results, the inverter system has an average power of 27 W working at -12 °C. Therefore, the relatively small difference of 3 W compared to the power calculated demonstrate that the transfer function correctly describe the real behavior of the refrigeration system.

This validation is not performed with the maximum frequency since the suction pressure should be equal to the vacuum pressure to lower the freezer temperature to -38.8 °C and this can cause system failures.

V. Conclusions

This work presents the design and implementation of an inverter controller for a high-energy-performance of a domestic refrigerator. A second-order transfer function is computationally obtained to calibrate a PI algorithm and is validated through a small difference (3W) between the measured and the calculated value of the average instantaneous power. Following the standard test methodology, the inverter technology demonstrates improvements in terms of mechanical and electrical efficiency, such as the reduction of the dimensions of the refrigeration cabinet, the proper distribution of the airflow in NO-FROST systems, and low electrical energy consumption (27%) by avoiding power starting peaks. The enhanced performance is attributed to the hardware adaptation (the BLDC compressor, BLDC ventilators, radial flow propellers, electronic sensors, and dynamic condensers) and the appropriate operation of the designed electronic card to continuously control the temperature.

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