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THE INFLUENCE OF THE SUPPLY VOLTAGE ON THE PERFORMANCE OF A DOMESTIC REFRIGERATOR

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Abstract. *This study evaluated the influence of the power supply voltage on the efficiency of a domestic refrigerator. Tests were performed with voltages between 103 V and 127 V. In these experiments, temperatures, compressor vibrations and electrical parameters were monitored. It was determined that the power consumption was independent of the voltage. However, it was observed that a lower voltage resulted in a reduction of as much as 28% in the reactive power and an improvement of 18.9% in the power factor. This result represents a reduction of 15.6% in the apparent power required from the system. It was also verified that the Coefficient of Performance (COP) was unaffected by the voltage. Thus, the variation in the power voltage proved to be ineffective in increasing the efficiency of the refrigerator, but it is effective in reducing the electrical energy loss to power suppliers.*

Keywords: *Domestic refrigerator; Energy efficiency; Supply voltage; Power factor.*

1. INTRODUCTION

In most countries, electric power distribution networks provide alternating current. The RMS value of the voltage falls within a tolerance that is defined by the regulatory agency in each locality. In the U.S., for example, the American National Standard for Electric Power Systems and Equipment - Voltage Ratings, ANSI C84.1-2006, specifies permissible voltage ranges for the system and electrical equipment. For a nominal value of 120 V, this standard requires that the voltage should be between 114 V and 126 V (ANSI, 2006). In Brazil, the Brazilian Electricity Regulatory Agency (ANEEL) specifies the distribution system performance for voltage levels. In a distribution system with a rated voltage of 127 V, for example, the voltage should be between 116 V and 133 V to be considered acceptable (ANEEL, 2012). Despite the allowed variations, power providers always seek to ensure that the supply voltage equals the nominal value. However, during emergencies, power companies may alter the line voltage to reduce peak demand (Scalley and Kasten, 1981), (Chen et. al., 1982). One of the first indications that voltage reduction might be used to reduce load during emergencies was presented by Bauman et. al., 1941. During this procedure, sometimes called System Voltage Reduction (SVR), the service voltage can drop below the minimum (Scalley and Kasten, 1981). Generally, this reduction is of relatively short duration after which the voltage is returned to normal.

Stimulated by the energy crisis in 1973, some have suggested that permanent voltage reductions might contribute for energy saving. In 1977, the Conservation Voltage Reduction (CVR) as a method of energy saving was implemented in California by the Pacific Gas and Electricity Company. In the tests performed in four primary distribution circuits it was verified an approximate reduction of 1% in energy consumption for every 1% of voltage reduction (Kirshner and Giorsetto, 1984). Other utilities also conducted their CVR tests and the energy savings associate with voltage reduction ranged from 0.3% to 1% of load reduction for every 1% of voltage reduction (Wang and Wang, 2014).

Subsequently, studies were conducted to determine whether reducing the supply voltage to the minimum allowed by the ANSI reduces the overall energy consumption. In the study presented in Kirshner and Giorsetto, 1984, it was determined that the energy consumption of residential, commercial and industrial customers could be reduced by 0.76%, 0.99% and 0.41%, respectively, by lowering the supply voltage. These findings were consistent with the results obtained in Wamock and Kirkpatrick, 1986. The study presented in Hood, 2004, evaluated the effects on the power consumption and the operating cost of domestic appliances resulting from a 5% increase in the network voltage. That study considered the resistive, inductive and capacitive loads of more than 20 typical domestic appliances. It was determined that the voltage had a minimal effect on the consumer energy costs.

Among all domestic appliances, is worth mentioning the household refrigerator. Refrigerators can be found in 99% of North American homes (EIA, 2001) and in 96% of Brazilian homes (PROCEL, 2007). Although this appliance consumes energy at a very low rate, the large number in use and the fact that they typically operate 24 hours a day represent an appreciable potential for energy savings. There are some aspects about the effect of the supply voltage on the household refrigerator that still need to be analyzed. Most studies concerning supply voltage variation, (Bauman et. al., 1941; Kirshner and Giorsetto, 1984; Wang and Wang, 2014; Wamock and Kirkpatrick, 1986) and (Bames and Simonelli, 2013; Wang and Wang, 2014; Chen and Chan, 1987), for example, focused on the effect of these variations on the overall electric system consumption. In the works that addressed refrigerators, Chen et. al., 1982, and Hood, 2004, for example, no mention is made about the air temperature inside the refrigerator compartment and about the room temperature registered during the tests. These two parameters define the condensation temperature and the evaporation temperature that strongly influence the compressor load. For a given room temperature, when temperature inside the refrigerator compartment increases, the compressor load and power consumption also increase mainly due to the increase in the mass flow rate of refrigerant that must be produced by the compressor (Tassou, 1993; Aprea and Renno, 2009; Maia, 2014; Binneberg, 2002). When the temperature inside the refrigerator compartment decreases, the mass flow rate of refrigerant produced by the compressor will also decrease, and thus the compressor load.

The compressors employed in household refrigerators are designed to start-up considering that all parts are at the same temperature (room temperature). This condition occurs almost solely when the refrigerator has just been installed or when the refrigerator has been switched off for a long time for defrost and cleaning, for example. Because compressors are designed for this situation, the single-phase electric motors that drive them often operate for much of the time at partial load. This aspect may represent an opening to employ voltage variation in these systems focusing energy saving. The results obtained in this process may be more advantageous if the voltage is selected after the temperature inside the refrigerator compartment reaches the real operating temperature.

In this study, the influence of the supply voltage on the performance of a low-cost household refrigerator was evaluated. It was investigated the impact of the supply voltage on the system power consumption and in the thermodynamic performance. In this work were considered thermodynamic aspects related to the process of refrigeration using vapor compression cycles that were not considered in past studies on the effect of voltage variation in these systems. It was analyzed not only the effect of the voltage variation on the electrical parameters but also on the operating temperature and on the compressor vibration mode. Furthermore, since the voltage reduction was performed after the system reached its operational temperature, it was possible to perform a superior voltage reduction (almost 19% of nominal value) than that observed in the literature review carried out in this work. This is the first work that investigates if the voltage variation also promotes changes that can make the system operate in a condition that can affect its efficiency or lifespan.

2. MATERIALS AND METHODS

The test article used in this study was a low-cost household refrigerator, a Consul model CRC28 EBANA. According to the manufacturer, this refrigerator has a volume of 239 liters and consumes electricity at a rate of 22.7 kWh/month. The refrigerator has a capillary tube as expansion device and a hermetically sealed compressor with a low starting torque manufactured by Tecumseh, model THK1330YDS. The refrigerant used is R134a. The specifications of the compressor are Cooling Capacity 96.7 W (±5%); Nominal Power 75 W (±5%); Nominal Current 0.96 A (±5%); Efficiency 1.29 W/W (-9.04%/+10.5%); Operating Frequency 60 Hz; Operating Voltage Range 100-140 V.

The compressor motor is a split-phase single-phase motor. The primary winding on the stator is connected to the supply, and a secondary winding is used for starting. The secondary winding is disconnected when a PTC-type relay reaches a predetermined temperature. After the secondary winding is disconnected, the primary winding turns the motor.

To monitor temperatures, nine T-type thermocouples were installed. In order to keep the refrigerator as it was manufactured, the thermocouples were placed outside the line of refrigerant, in the pipe wall. The following points were measured: the exterior (to measure room temperature) (T0), the compressor inlet (T1), the compressor base (T2), the compressor outlet (T3), the midpoint of the condenser (T4), the evaporator inlet (T5), the evaporator outlet (T6), inside the freezer compartment (T7), and inside the refrigerator compartment (T8).

The effect of the voltage on the compressor motor rotational speed was evaluated using four accelerometers. Three accelerometers were installed on the compressor housing (each of the accelerometers was aligned with one of three orthogonal axes, X, Y and Z) and the fourth one was installed on the side of the refrigerator shell to determine whether the voltage level produced any variation in the vibration of the case. Because the compressor is hermetically sealed, the accelerometers were also used to estimate the motor rotational speed at each voltage.

The temperature and vibration data were collected using a data acquisition system consisting of a frame (NI cDAQ NI-9178) on which were installed four N9211 modules, which were connected to the thermocouples, and one N9233 module, which was connected to the accelerometers. Communication between the data acquisition system and a computer was established using a USB cable. A graphical user interface and software that allowed the automation of the measurement, the processing and the storage of the data were developed using the programming platform LabVIEW.

A multimeter (KRON, model Mult-K Plus) was used to measure the electrical parameters, including real power, reactive power, power factor, current and voltage. Because the current could have exceeded the rated value of the multimeter, a transformer was used to reduce the current through the meter. This transformer reduced the current to a third of the input value. A residential dimmer switch was used to vary the voltage applied to the compressor motor.

The tests consisted of switching on the refrigerator with the nominal line voltage, waiting for the unit to reach the steady state, then adjusting the voltage to the previously defined values. Four tests were performed, one each at operating voltages of 127 V, 119 V, 110 V and 103 V. These operating voltages were chosen based on the operating ranges specified by the compressor manufacturer. In these experiments, the temperature, the power consumption, the current, the voltage and the vibration were monitored for a period of 54 minutes. This length of time corresponds to approximately five on/off cycles of the compressor. The measurements of real power were used to calculate the energy consumed by the refrigerator. The integral of real power (in Watts) with respect to time is the amount of energy consumed in Joules. This result was converted to units of kWh/month to evaluate the effect of the voltage on the monthly electricity consumption rate.

A vibration analysis was performed to evaluate the influence of the voltage level on the compressor rotational speed. It is known that the compressor vibrates because it is not perfectly balanced. The frequency at which this compressor vibrates because of the mechanical imbalance is equal to the frequency of its rotation. The vibration frequency due to imbalance will change when there is a change in the rotational speed.

For the cooling capacity analysis, a specific test with a thermal load was performed to determine the capacity of the refrigerator to remove heat at a given voltage. The test was performed only with the minimum and maximum voltages used in the tests (103 V and 127 V). For these tests, a 0.0015 m3 bottle filled with pure water was used for the load. A thermocouple was placed inside the sealed bottle. These tests lasted 6000 seconds for each voltage, and the water temperature was monitored throughout the tests. During the tests, the refrigerator was not opened in order to keep the indoor humidity constant during all the experiments.

3. RESULTS AND DISCUSSION

An uncertainty analysis using a 95% reliability interval was performed to estimate the errors in the experimental data. Table 1 shows the room temperature and the uncertainty interval in which it is believed that the true value occurred. It can be observed that the temperature remained stable in all of the tests and therefore had a negligible influence on the results. Table 1 also presents the nominal voltages used in the tests and the respective measurement uncertainties. The maximum variation observed in the supply voltage was 1.8 V.

Table 1 –Room temperature and supply voltage measurements

Reference voltage	127 V	119 V	110 V	103 V
Room temperature (°C)	21.2±0.4	21.4±0.7	21.3±0.7	21.2±0.7
Measured Voltage (V)	127.4±0.9	119.0±1.8	110.7±1.5	103.3±1.2

When an electric motor is switched on, the inrush current required to generate the starting torque can be as much as 10 times greater than the nominal (steady-state) current. These current peaks increase the power consumed by the electric motor (Parekh, 2003). It was observed that, regardless of the motor supply voltage, the current peaks fluctuated greatly. These oscillations occurred because the current peak depends on the required torque, and the torque in turn depends on the state of the refrigerant during startup.

In the cases of lower voltages, more time was required to stabilize the motor current (Figure 1). This delay occurred because when the voltage was reduced, the motor torque was also reduced, and more energy was required to reach the final rotational speed. Higher inrush currents were also observed in the tests with higher voltages. The motor current did not increase after the reduction in voltage. This occurs because when the temperature inside the refrigerator compartment decreases, the mass flow rate of refrigerant produced by the compressor will also decrease, and thus the compressor load. After three seconds, the current stabilized close to 1 A for all values of voltage employed in this work.

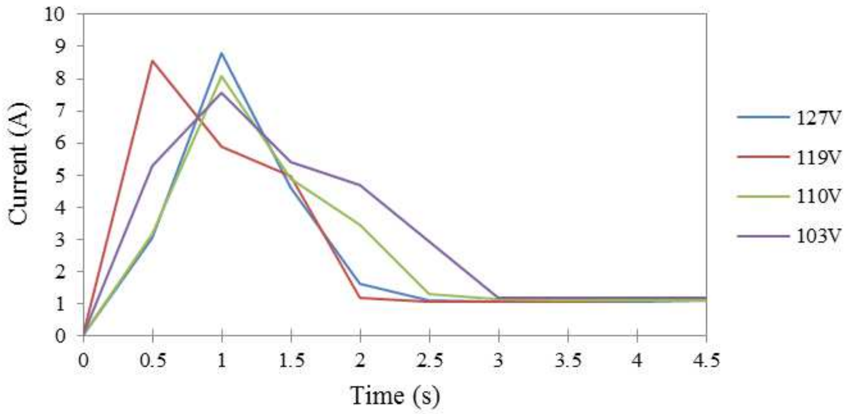

Figure 1 – Current vs. time following startup of the compressor motor

Figure 2 shows the real power consumed in each test. The real power is the power consumed by the refrigerator to produce work, and this power is what the consumer effectively pays for. The variation in power was directly proportional to the variation in current because the voltage remained constant during the tests. From the real power, it is possible to determine the refrigerator duty cycle. It is clear that this cycle was practically identical in all tests and showed no significant changes when the voltage was varied, as shown in Table 2. As this test was executed with no thermal load, the main reason for the time cycle variations may be related to the refrigerator thermostat accuracy. In the interval from t=30 s to t=250 s, the average real power was nearly 73.0 W. The data shown in Figure 2 were used to calculate the energy consumed by the refrigerator in each test.

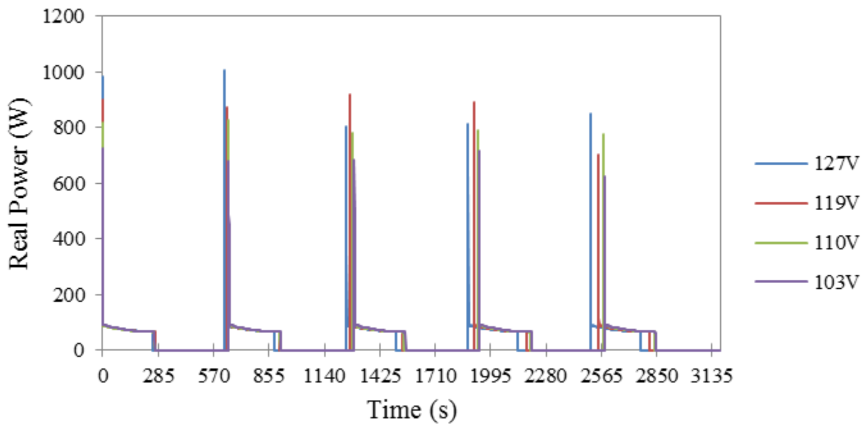

Figure 2 - Real power vs. time during operation of the refrigerator

Table 2 - Average times of the duty cycles

Voltage (V)	Average on time (s)	Average off time (s)	Average cycle time (s)
127	256.9	370.3	627.2
119	268.8	369.0	637.8
110	267.0	376.4	643.4
103	266.5	379.1	645.6

Reactive power is the energy used to create and maintain the magnetic fields in the motor, and this energy does not produce work. In a domestic refrigerator, the compressor motor must be designed to start when all parts of the refrigerator are at room temperature. In this condition, the refrigerant mass that must be moved by the compressor is greater than in the normal cycle of operation, and thus a higher motor torque will be required. This normally happens only when the refrigerator is first installed or when it has been switched off for a sufficiently long time that the internal temperature is equal to room temperature. Because compressors are designed for this situation, the single-phase electric motors that drive them can expend much more work than necessary when the internal temperature decreases and therefore produce a large amount of reactive power over time. The tests revealed that the reactive power was greatly affected by differences in the supply voltage. By reducing the supply voltage from 127 V to 103 V, the motor reactive power decreased from 103 VAR to 74 VAR, which represents a reduction of approximately 28%. For a domestic consumer, the reactive power is irrelevant because it is not considered in the cost of energy. However, this reactive power is problematic for power companies. High levels of reactive power in the network can cause overheating of cables and conductors, causing accentuated voltage drops and other losses.

The power factor is the ratio between the real power and the apparent power. When reactive power decreases, more the apparent power approaches the real power, and the efficiency of energy use increases, consequently power factor also increases (Figure 3). From t=30 s to t=250 s, the average power factors for the lowest and highest voltages, 103 V and 127 V, were 0.69 and 0.58, respectively. The improvement in the power factor was 18.9%. The refrigerator employed in this study represents a load of 73 W (real power). To operate this load at a power factor of 0.58, it is necessary to supply an apparent power of 128.7 W. For the same load with a power factor of 0.69, the apparent power required is 105.8 W. Therefore, the refrigerator employed in this study required 15.6% less power from the system when operating with a supply voltage of 103 V.

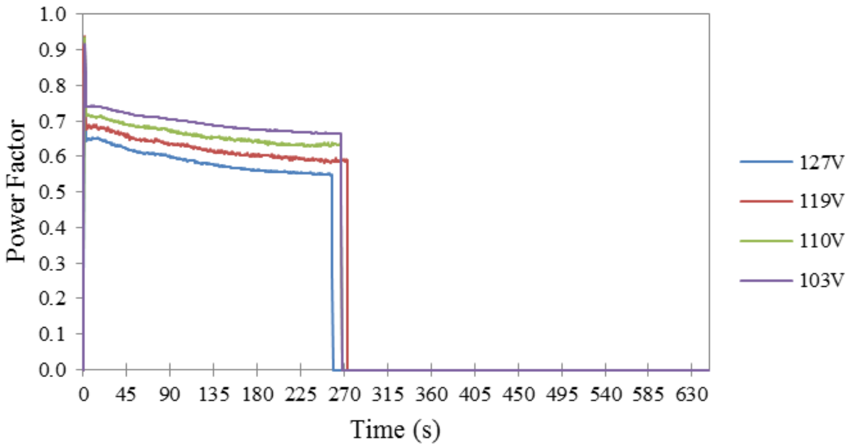

Figure 3 – Power factor vs. time during the first On/Off cycle

To calculate the energy consumed, data from five complete cycles at each voltage were used. The integral of the real power shown in Figure 2 was obtained numerically using the trapezoidal integration rule. The values of the energy consumed in each test are shown in Table 3.

Table 3 – Energy consumption in the four tests

Voltage (V)	Energy Consumed (J)	Energy Consumed (kWh)	Time (s)	Energy Consumed kWh/month
127	100,445.6	0.03	3136.0	23.06
119	103,039.1	0.03	3189.5	23.26
110	102,641.2	0.03	3217.0	22.97
103	102,996.5	0.03	3228.0	22.97

The calculated consumption using the nominal conditions of operation (127V), is consistent with the consumption measured by the manufacturer, showed on section 2. Slight variations in energy consumption were observed. The data indicate that the differences in the voltage levels used in this study did not significantly alter the energy consumed. The maximum difference was 0.29 kWh/month. Although the peak current and power were greater at higher voltages, the time required for the current to stabilize at 0.96 A (the motor nominal current) offset these higher peaks, and the energy consumption was practically unchanged.

In Figure 4, the compressor shell, the condensation and the evaporation temperatures measured for each voltage are presented. Since the compressor and the electrical motor are in the same casing, an increase in the temperature could not only degrade the electrical motor insulation but also alter the lubricant oil viscosity and its ability to lubricate. After this happens, compressor failure can occur soon. The data acquired from the thermocouples indicated that there was no appreciable change in temperature due to the difference in the supply voltage of the compressor motor. The temperatures in the compressor shell, condenser and in the evaporator remained stable, what shows that no variation at the thermal load happened. The fact that the compressor shell temperature remained stable is an indication that the voltage levels tested in this study did not contribute to increase the heat produced by the compressor. The small differences observed are probably related to the thermostat accuracy.

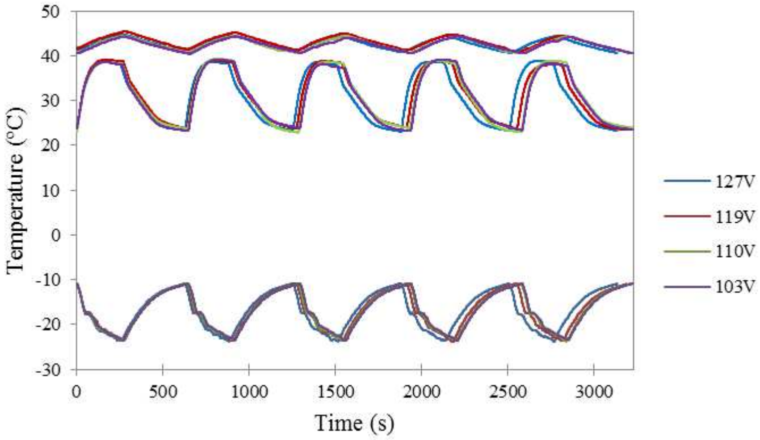

Figure 4 – Compressor shell, condensation and evaporation temperatures vs. time during refrigerator operation

Reducing the supply voltage of the compressor motor reduces the torque. This reduction in torque can increase the motor slip, and this slippage may result in a reduction of the rotational speed of the compressor and an increase in the motor temperature. To evaluate these aspects, accelerometers were used to measure the vibration spectrum of the compressor in each test. From the analysis of these spectra, it was possible to indirectly determine the compressor speed. For each voltage, 250 samples of vibration data were collected. These data were collected at intervals of 0.5 seconds. Only the spectra at t=120 s following startup of the refrigerator were analyzed. Figure 5 presents the compressor vibration amplitudes for the various supply voltages. Only the data from the accelerometer installed perpendicularly to the top of the compressor (i.e., in the Z-axis) were used because this sensor was located closest to the piston and thus provided the best measurement of the vibrations. However, the signals recorded by the other accelerometers also showed the highest peaks at a frequency of 60 Hz. It can be observed from vibration data that the vibration peak always occurred at 60 Hz, which shows that the voltage range used in the tests did not affect the rotational speed of the compressor. Only in the test employing 119V the vibration amplitude exceeded the value reached when employing the nominal voltage. The values observed in the other tests were similar or smaller in amplitude. This fact indicates that the voltage reduction range studied in this work did not alter significantly the system vibration mode as well as the noise generated by the refrigerator.

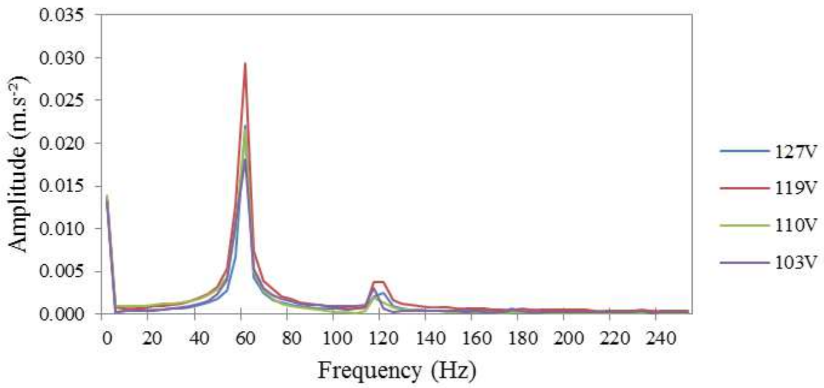

Figure 5 – Compressor vibration amplitude vs. frequency

To evaluate the effects of the voltage on the cooling capacity of the refrigerator, tests were performed using the supply voltages 104.13 ± 1.74 V and 127.27 ± 1.33 V. The room temperature was 21.4 ± 0.9 °C and 21.2 ± 1.0 °C for the lower and higher voltages, respectively. The cooling capacity value can be determined from the product of the refrigerant mass flow rate at the inlet of the capillary tube and the enthalpy change in the evaporator The mass flow rate is a function of the motor speed , the piston displacement volume , the volumetric efficiency and the refrigerant specific mass at the compressor inlet (Maia et. al., 2013). As can be observed in Figure 5, regardless of the supply voltage, the motor speed remained constant. The volumetric efficiency depends mainly on the ratio of the refrigerant pressure in this case. As the condensation temperature and the evaporation temperature differed only slightly between the two tests, it is reasonable to assume that the pressure ratio was practically unchanged.

The piston displacement volume is a fixed geometric parameter of the compressor. The density of the refrigerant at the compressor inlet is a function of the temperature at that point, which was the same for both voltages. The maximum difference observed between the data obtained for each voltage was no more than 1.8 ºC. The difference was less than 1 °C after 4800 s of operation. The cooling capacity additionally depends on the evaporator inlet and outlet enthalpies. These quantities in turn depend on the temperature and the pressure at these points. The values obtained were similar, indicating that the voltage only slightly influences the inlet and outlet temperatures of the refrigerant in the evaporator. If there were any variations in the enthalpies at these points, they were certainly small and had a minor influence on the cooling capacity of the refrigerator.

During the tests, the temperature of the water (0.0015m3) in the bottle placed inside the refrigerator was monitored. The evolution of the water temperature for 6000 seconds is shown in Figure 6. Table 4 lists the initial and final values of the temperature of the water.

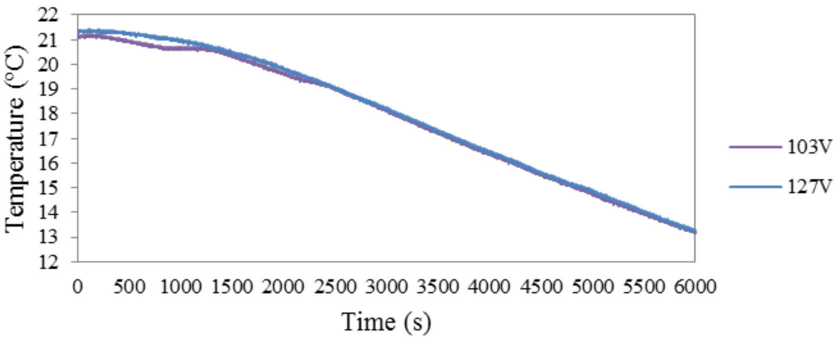

Figure 6 - Water temperature vs. time

Table 4 - Initial and final temperatures and temperature change of the water

Supply Voltage (V)	Initial Temperature (ºC)	Final Temperature (ºC)	ΔT (ºC)
104.1 V ±1.7	21.1 ± 0.4	13.2 ± 0.4	7.9 ± 0.1
127.3 V ±1.3	21.4 ± 0.4	13.3 ± 0.4	8.1 ± 0.1

It can be observed from Figure 6 that the temperatures trends were similar regardless of the voltage. From Table 4, it is clear that the initial and final temperatures were very similar in the two tests, and the change in the temperature after 6000 seconds differed by only 0.2 ºC between the two tests.

4. CONCLUSIONS AND FINAL COMMENTS

In this study, the influence of the supply voltage on the electrical and thermodynamic performance of a domestic refrigerator was evaluated. For the voltage values considered in this study, the temperatures obtained showed no appreciable variation. An analysis of the temperatures and the vibration spectra showed that the duty cycle times were practically unaltered, and the cooling cycles did not change with the voltage. From the data collected from accelerometers, it was determined that the compressor motor rotational speed was unaffected. It was also determined that the cooling capacity was not affected by varying the supply voltage of the compressor motor.

The main problem in reduce the supply voltage, is that the torque is also reduced, and this reduction could increase the motor slip, and this slippage could result in a reduction of the rotational speed of the compressor and an increase in the motor temperature. It was seen in the results that the rotational speed and compressor temperatures remained the same. Therefore, the motor maintained its standard operation, despite the voltage variation.

Using the electrical data collected, the energy consumed at each voltage was calculated. It was determined that there was no change in the energy consumption when the supply voltage was changed. There was only a 0.3 kWh/month difference, which is not appreciable in terms of the total consumption of the refrigerator. The cooling capacity remained the same, so it was concluded that the COP of the refrigerator did not change with the voltage. Therefore, this method proved to be ineffective for increasing the efficiency of the refrigerator.

Based on the electrical data, reducing the supply voltage reduced the reactive power by as much as 28%. The reason for this difference is that the motor is sized to start when all parts of the refrigerator are at ambient temperature. In this condition, the mass of refrigerant that must be moved by the compressor is greater than that encountered during the normal operating cycle, and thus the torque required is substantially higher. When the air inside the refrigerator has been cooled, the mass of refrigerant that must be moved by the compressor and the torque required decrease. Reducing the supply voltage decreased the torque, and the motor operated more closely to its work condition. As a result of the reduction in the reactive power, the compressor motor power factor increased by 18.9%. This improvement represents a reduction of 15.6% in the power required from the system to run the same load. In this work it was shown that it is possible to reduce the supply voltage without produce negative effects on the system efficiency and functioning. It may be of interest to power companies to employ systems that reduce the voltage supplied to domestic refrigerators to reduce the amount of reactive power consumed. The achievements may be even more advantageous if the voltage change is defined considering the operating temperatures and the current consumed by the motor.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE