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Performance and efficiency of different control techniques in an electrical heater

Rendimiento y eficiencia de distintas técnicas de control en un calefón eléctrico

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Abstract

Water heating in the Ecuadorian residential sector has become a space for research and development, due to the attempt to mitigate the current spending of people and at the same time contribute actively to the energy efficiency processes that are gaining strength in the country. This paper conducts a comparative analysis between different techniques for controlling the water temperature in a residential system using an electric heater. The response of a direct phase control AC / AC converter was analyzed, which allows to delay the firing angle of the AC wave and the response of the ON / OFF control that activates or deactivates the heater during a pre-established number of half-cycles of alternating current. For the tests, a prototype of electric heater was implemented with a coil of 14 meters based on electrical resistances. Then, with the temperature responses generated from each converter, the transfer function of each system was identified, since both differ in its heat transmission technique and, thus in its mathematical model. Afterwards, a PID controller was tuned for each system, obtaining good results of temperature response in both cases, but only one was efficient regarding energy saving.

Keywords: control, PID, AC / AC converters, temperature, water, efficiency

Resumen

El calentamiento de agua en el sector residencial ecuatoriano se ha convertido en un espacio de investigación y desarrollo, debido al intento de mitigar el gasto corriente de las personas y a la vez contribuir de manera activa a los procesos de eficiencia energética que van tomando fuerza en el país. En el presente documento se muestra un análisis comparativo entre diferentes maneras de controlar la temperatura del agua para un sistema residencial utilizando un calentador eléctrico; se analizó la respuesta de un conversor AC/AC de control de fase directa que permite retrasar el ángulo de disparo de la onda de corriente alterna y la respuesta del control ON/OFF que activa o desactiva el calentador durante un número preestablecido de semiciclos de corriente alterna. Para las pruebas se instaló un prototipo de calentador eléctrico con un serpentín de 14 metros a base de resistencias eléctricas; con las respuestas de temperatura que se generan de cada conversor se procedió a identificar la función de transferencia de cada sistema ya que ambos difieren en su técnica de transmisión de calor y a la vez en su modelo matemático. Posteriormente se procedió a sintonizar un controlador PID para cada sistema, obteniendo buenos resultados de respuesta de temperatura en ambos casos, pero solo uno resultó eficiente en ahorro energético.

Palabras clave: control, PID, conversores AC/AC, temperatura, agua, eficiencia

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1. Introducción

The liquid petroleum gas (LPG) is the most commonly used energy source in Ecuador for heating water and cooking food, but starting from the change of the energy matrix, these type of devices are subject to a tax of 100 % over its commercial value, according to article 82 of the tax regime regulation [1], which is the reason why it has been decided to promote the use of other type of heaters as alternative to the significant cost increase of LPG heaters.

Original patents of a gas heater are shown in [2] and [3]; note that these devices have been in the market for a considerable time. The method of operation of these devices is found in [4], while a complete study of control techniques for this type of heater can be observed in [5]. One of the main problems of these devices is their high pollution, as mentioned in [6] based on a study conducted in the city of Loja – Ecuador; this problem generates major drawbacks in the health of persons. A pertinent analysis about these health issues can be found in [7].

On the other hand, the heaters that use GLP have a greater or smaller operating cost depending on the value of the GLP in each region; [8–10] show comparative studies between the use of a GLP heater and other residential water heating alternatives, such as, solar heaters or natural gas heaters. The benefit of one or other system specifically depends on the price of each energy source, taking into account that this will depend on the resources of each nation; there are countries with enormous hydric sources, such as Ecuador, and countries which have easy availability of petroleum derivatives, while in some developed nations, such as Germany, it has been chosen to regulate the self-consumption; more than one million households incorporate solar panels. Recently Spain also adopted this way by eliminating the solar tax [11], action with which the Government expects an increase in the self-consumption to benefit national resources.

A valid alternative for replacing the water heating systems that use GLP, for increased security and reduced generation of contaminant gases, are the electric heaters. According to [12], electric heaters play an important role in heating systems, and convert to heat 99 % of the energy they consume, i.e. the electric power is almost the same as the thermal power. In [13], various authors show the efficiency of an electric heater with a control technique to regulate the temperature.

The authors in [14] make a very complete summary of some types of electric heaters, and explain different techniques for temperature control.

Currently, the most important drawback of electric heaters is their high energy consumption, since a high electric power is required for heating a certain flow of water; in general, this power is generated by a neckline that remains connected to the electrical network at 100 % of its power while a water faucet is open, thus representing an elevated portion of the payment corresponding to the electrical service, moreover if this device stays on various hours per day.

The proposal presented in this work results from the combination of power electronics and the theory of automatic control systems, to develop a prototype that regulates the power dissipated in an electric neckline, thus reducing the energy consumption and also improving the response in the water temperature.

To observe this type of response, regarding both the efficiency and the temperature response, two static AC/AC converters were put into operation, to command the on and off of four electric necklines, a full cycle converter and a direct phase control converter; the direct benefit can be found in [15]: both types of converter can be implemented with the same power electronics circuit (see Figure 1).

The microprocessor utilized to control the system was one of the versions of the Arduino, which provide certain degree of versatility. According to [16], an automatic faucet that enables a high temperature of the fluid (around 40 °C) can be designed using an Arduino Mega 2560 plaque, without problems of electromagnetic noise nor interferences.

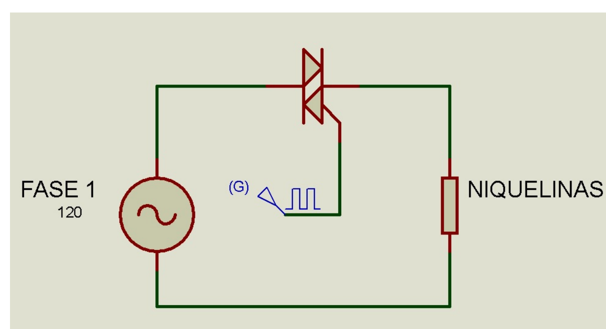

Figure 1. Simulation scheme of the AC/AC converter.

The operational principle of Arduino is analyzed in [17], besides the interest of persons for utilizing this plaque because it employs an easy to use simplified version of C++.

According to [18] Arduino has memory, capacity of autonomous processing, compilers of programming languages such as C, and physical ports to interconnect with devices that provide certain stability and reliability in their utilization.

It is mentioned in [19] that, due to their low cost, Arduino microcontrollers are used in engineering applications that commonly involve instrumentation, machine and structures monitoring, and control of mechanical systems.

For the implementation of the PID control system, it is necessary to measure the physical variables to be controlled. In this case, the controlled variable is the temperature, which is measured using a NTC thermistor of a vehicle; these types of sensors are reliable, because they are designed to work in contact with water, and have very low cost. In [20], the authors present a simple explanation of the operation of the NTC thermistors, and how they transform the temperature signal into an electric signal.

It is mentioned in [21] that a circuit consisting of a source, a thermistor and a resistor should be installed for conditioning the thermistor; this circuit generates a voltage divisor that is read by the microprocessor. The temperature sensor maintains its characteristic exponential curve; thus it is required to acquire the value with the thermistor equation in the microprocessor.

An analysis of the control circuit by phase angle is included in [22]. The operation of this type of control is based on an angle of delay to turn on the necklines, both in the positive and negative semi-cycles of the commercial electrical sinusoidal wave. Therefore, by varying the firing angle, the power in each neckline is controlled and the temperature transfer is regulated. It is mentioned in [23] that the switch or circuit element that controls the on and off of the necklines may be a TRIAC or a set of 2 SCR in antiparallel connection.

The authors in [24] analyze the operation of the ON/OFF control, namely control by integral cycle. Its operation is based on turning a load on and off various occasions in a period of time, such that the necklines are on for a known number of cycles, which may change according to the requirements of temperature.

A technique for tuning PID controllers is explained in [5]. In this work it was chosen to utilize the Matlab ARMAX model to obtain the transfer function of each system, and subsequently tune two effective controllers by means of the same software. The automatic tuner of Matlab performs an iterative analysis to find the best proportional (Kp), integral (Ki) and derivative (Kd) parameters of the PID regulator. The author in [25] mentions that although much more robust new control techniques have been developed, the proportional-integral-derivative (PID) controller is the control strategy mostly used in industrial applications; it is estimated that more than 90 % of the control loops utilize a PID controller, because it is a simple and effective strategy, and it does not require a great theoretical foundation to be utilized in common processes.

2. Methods

The main objective of this work was to develop a prototype capable of heating water from a daily state in the Ecuadorian mountain range, i.e. from approximately 17 °C to 40 °C, and by means of the prototype, provide evidence of the control technique that has the best performance in maintaining the temperature and in energy efficiency.

The prototype is constituted by a coil with a length of 14 meters, constructed based on 4 electric necklines that are connected and disconnected from the commercial electrical network of 220 VAC, as indicated by the control techniques.

The control by integral cycle varies the number of cycles in which the necklines remain open, with the aid of a PID regulator. A cycle refers to a complete period of the sinusoidal wave of the commercial electrical network.

On the other hand, the control by phase angle varies the firing angle that activates the necklines. If the period of the sinusoidal wave is 16.66 ms, each semi-cycle lasts 8.33 ms, and thus the firing angle may vary between 0 and 8.33 ms to turn on and off the necklines, according to the temperature requirements.

2.1. Power of the necklines

The power is dimensioned considering a flow of 4 liters per minute and a pipe with a 3/8 inches' diameter. The required area of the pipe is given by

$$A = \frac{\pi}{4} \times \theta^2 \tag{1}$$

The velocity of the water for the aforementioned flow is determined as is

$$v = \frac{Q}{A} \tag{2}$$

If the objective is to heat 4 liters of water each minute, it is determined that each liter of water should remain exposed to the heater for 15 seconds, and thus the length of the heating pipe is given as

$$L = v \times t \tag{3}$$

It is concluded from the calculations, that it is required a heating coil of at least 14 m long. Then, the volume of water inside the coil is calculated as

$$V = A \times L \tag{4}$$

The next step is to determine the heat that needs to be transmitted, which is given by

$$Q = m \times c \times \Delta T \tag{5}$$

Where:

Q is the heat, m is the mass of the substance, c is the specific heat of the water, and ΔT is the variation of the temperature.

Then, the mass of water contained in the coil is calculated with the desired variation of the temperature, the volume of water in the coil and density of the water. AT last, the required power for the necklines is obtained as

$$P = \frac{Q}{t} \tag{6}$$

It is concluded that the required minimum power is 6500 watts.

2.2. Configuration of the flow sensor

The flow sensor is configured, determining the number of pulses generated by this element when a liter of water passes through it.

The flow is determined counting the number of pulses generated by the sensor in a second by means of an interruption, as shown in the flow diagram of Figure 2.

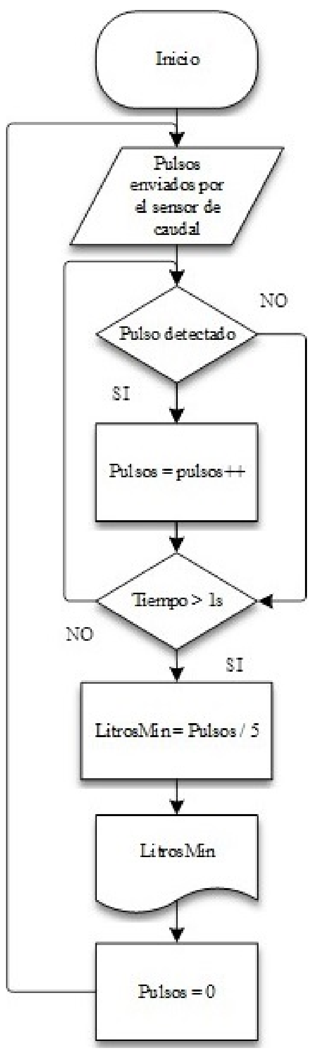

Figure 2. Calibration of the flow sensor.

2.3. Configuration of the temperature sensor

The temperature is determined by means of a thermistor, whose specific characteristic is given by

$$\beta = \frac{ln\left(\frac{RT1}{RT2}\right)}{\frac{1}{T1} - \frac{1}{T2}} \tag{7}$$

where T1 is the temperature given in Kelvin degrees, β is a parameter of the sensor, RT1 is the resistance of the thermistor, RT2 is the reference resistance of the thermistor and T2 is the reference temperature of the thermistor.

To calculate the β parameter, it is necessary to have resistance values at two different temperatures of the thermistor, and those values should be simply substituted in equation (7). A voltage divisor that indicates the variation of temperature is used to acquire the signal of the thermistor, but without linearizing the sensor to keep a more reliable reading.

Further the programming is done, to enable applying the values that determine the real temperature, as can be seen in the flow diagram of Figure 3.

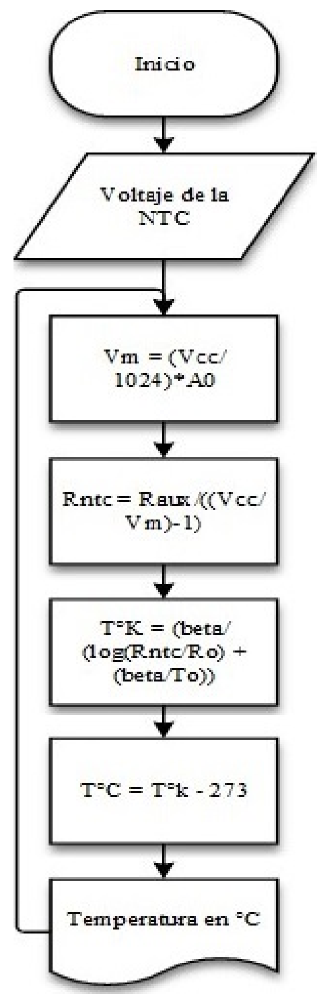

Figure 3. Reading of the temperature sensor.

2.4. Programming of the ON/OFF control

The ON/OFF control is initialized with an interruption, generated by a pulse sent by a circuit that detects the zero crossing of the alternate current wave. This detection initializes a counter, which will be compared with the variable t_{on} that acts as the set-point of the system, and is controlled by an external device; this variable may take values in the range from 0 to 600 semi-cycles of the AC wave.

Values in this range were used because there are 120 pulses in one second, and the control is designed for a fixed period of 5 seconds. If the counter is smaller than t_{on}, a new comparison is carried out to verify if there is water circulating in the system. If both comparisons are true, the TRIACS are turned on (two per phase), otherwise the TRIACS are deactivated. At last, if the counter is greater than 600 it is reinitialized, thus starting a new cycle.

The information generated, such as the real temperature and the value of set-point, are sent through the serial port to a software designed in Matlab, to obtain information to model the system and to analyze the operation.

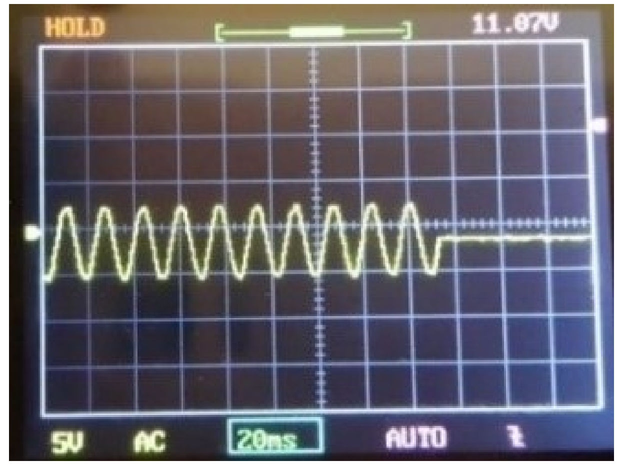

Figure 4. ON/OFF control signal.

2.5. Programming of the direct phase control

In the programming of the direct phase control, a counter is initialized once the pulse generated by the zero cross circuit is detected. This counter will be compared with a variable Set Point, which is similarly controlled by an external device that takes values in the range from 0 to 180. Considering that a semi-cycle of the alternating current wave last 8.33 milliseconds, a Set Point of 0 represents a delay time of 0 ms for the firing, while a Set-Point of 180 represents a delay time of 8.33 ms.

Since the timer of the microprocessor was defined at a frequency of 46.28 microseconds, this should be multiplied by values from 0 to 180 to have the counter of the timer in the range from 0 to 8.33 milliseconds, respectively.

If the counter is greater than the Set Point, a new comparison is carried out to verify if there is circulation of water in the system. If both comparisons are true, the TRIACS are turned on and thus the necklines; otherwise, they are deactivated.

At last, once the TRIACS have been activated, the counter is reinitialized waiting to be activated by a new interruption.

3. Experimental results

3.1. Test of the operation of the ON/OFF control

Once the ON/OFF controller was put into operation, its normal functioning was verified by means of an oscilloscope. Figure 4 shows the waveform of how the necklines are turned on and off, during a certain number of alternating current semi-cycles.

3.1.1. Test of the operation of the direct phase control

After the control by phase angle was programmed, its correct operation was verified observing the form of the voltage wave across the load with the aid of an oscilloscope. It can be seen in Figure 5, that the alternating current wave is varying its firing angle.

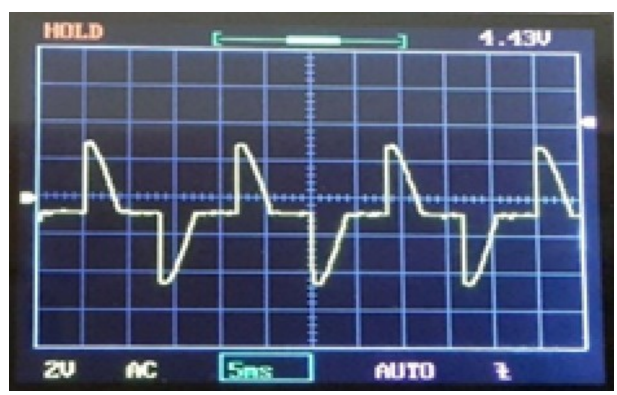

Figure 5. Wave form of the control by phase angle.

3.2. PID and ON/OFF control

3.2.1. Data collection

Once the communication port and the bounds in the Matlab software are configured, data of real temperature of the system and values of set-point are collected during 17 minutes and 33 seconds, thus obtaining a total of 30111 data points.

Once the data sampling is finalized for different values of Set Point, the plot shown in Figure 6 was obtained.

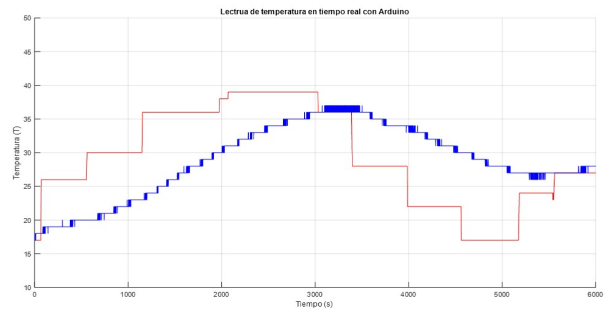

Figure 6. Real-time reading of temperature (ON/OFF).

3.2.2. Tuning of the PID control

With the data collected, the transfer function was obtained, corresponding to the system with ON/OFF control.

$$Ft = \frac{0.0185s + 2.389e^{-8}}{s^2 + 0.0003364s + 2.087e^{-8}} \tag{8}$$

Using the PID Tuner tuning tool provided by Matlab, the response shown in Figure 7 was obtained corresponding to a steady-state with an excessively long stabilization time; this situation was confirmed in the physical prototype.

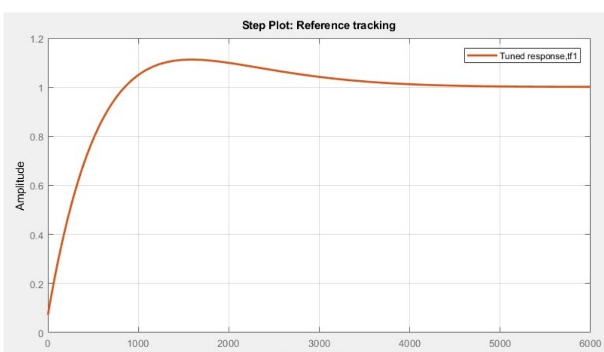

Figure 7. Temperature response for ON/OFF control with PID.

Once the necessary adjustments in the PID controller are carried out, the following PID constant parameters were obtained

$$\begin{aligned} K_p &= 13,534 \\ K_i &= 0,0126 \\ K_d &= 498,9476 \end{aligned} \tag{9}$$

3.3. PID and direct phase control

3.3.1. Data collection

The data were sent in the same manner than the utilized for the ON/OFF control, and the time of data collection was 17 minutes and 47 seconds, for a total of 30523 data obtained.

Once the collection of information was finalized, the plot shown in Figure 8 and the transfer function eres obtained.

$$Ft = \frac{0.00016s + 4.58e^{-7}}{s^2 + 0.002929s + 3.62e^{-7}} \tag{10}$$

The transfer functions corresponding to both control systems are different, due to the method utilized to transmit the temperature of the water.

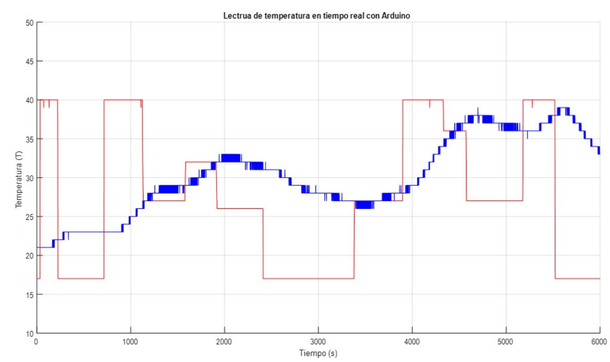

Figure 8. Real-time reading of temperature (direct phase).

3.3.2. Tuning of the PID controller

The tuning of the PID controller is carried out in a manner similar to the one utilized for the ON/OFF control, thus obtaining the plot shown in Figure 9 that represents the behavior of the system when this controller is applied.

After the speed of response and the robustness of the controller have been configured, the parameters of the PID regulator were obtained as

$$\begin{aligned} K_p &= 15,8519 \\ K_i &= 0,0126 \\ K_d &= 498,9476 \end{aligned} \tag{11}$$

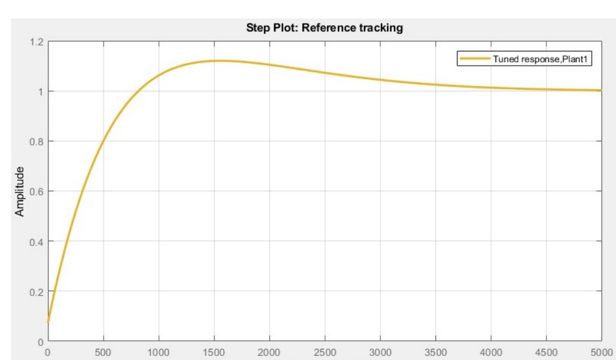

Figure 9. Temperature response for the direct phase control with PID.

3.4. Tests of the operation of the controllers with the implemented PID

3.4.1. Tests of the operation of the ON/OFF control with the implemented PID

Figure 10 shows the temperature response of the system with the implemented PID, where it can be observed that the temperature stabilizes at the set-point (red line) with an error smaller than one degree Centigrade; in addition, it can be seen that the stabilization time is around 500 seconds.

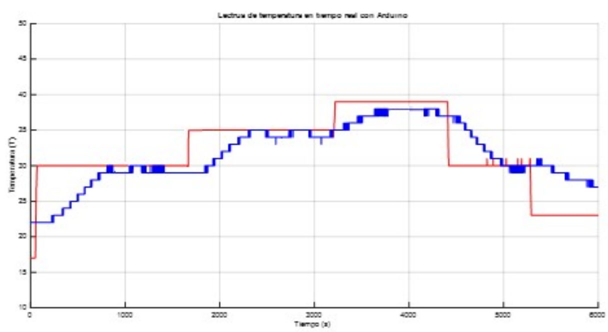

Figure 10. Operation of the ON/OFF control with PID.

3.4.2. Tests of the operation of the control by phase angle with the implemented PID

Figure 11 represents the operation of the control by phase angle, once the PID controller has been implemented. It can be seen that the temperature remains stable after 1000 seconds.

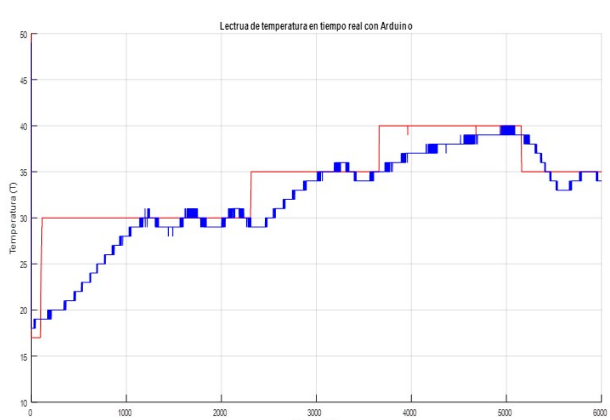

Figure 11. Operation of the direct phase control with PID.

3.5. Comparison of the controllers

3.5.1. Error elimination comparison between the direct phase control and ON/OFF control, after the PID has been implemented

Based on the data obtained after more than 17 minutes of testing for each control system, it is concluded that the ON/OFF control stabilizes the water temperature in almost half of the time than the control by phase angle.

As can be observed in Figures 10 and 11 after the temperature is stabilized, the direct phase control maintains the temperature value in a more effective manner than the ON/OFF control, namely, the direct phase control is more robust than the ON/OFF control.

3.5.2. Stability comparison between the direct phase control and ON/OFF control, after the PID has been implemented

Figure 12 shows the real-time water temperature response signal, using the ON/OFF control. It can be appreciated that the control system takes approximately 1000 seconds to heat the water up to 38 ºC (temperature of the test), and once this value has been reached it remains stable for the time of duration of the test, which was 90 minutes, with the exception of a small variation of 2 degrees Centigrade for the last 500 seconds of the test.

Figure 13 shows the real-time water temperature response signal, using the direct phase control. In this case it is observed that the water reaches the set-point of temperature in approximately 1100 seconds, almost two minutes later than the ON/OFF control, and it is observed that is has a variation of +/-1 degree Centigrade every 10 seconds. This may be due to a bad tuning of the PID regulator or to the slowness of the necklines in heating the water.

From this test it may concluded that, although the temperature responses are very similar regarding stability, robustness and stabilization times, the ON/OFF is more efficient.

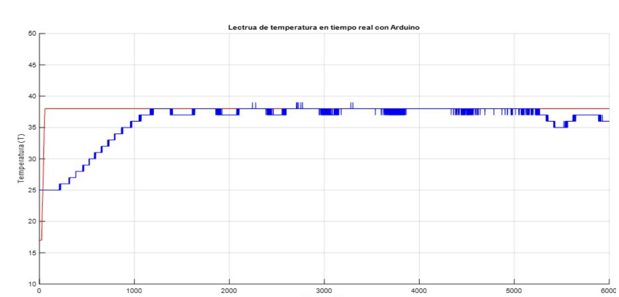

Figure 12. Stability test of temperature for the ON/OFF control with PID.

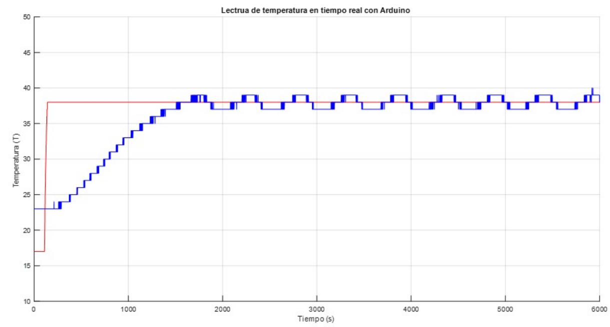

Figure 13. Stability test of temperature for the control by phase angle with PID.

3.6. Utilization cost of the control by phase angle, ON/OFF control, electric shower and gas heater

In the stability tests, each control system was utilized for 90 minutes. The electric consumption of each controller was measured considering such time, and it was observed that the ON/OFF control consumed 5.45 kWh, while the control by phase angle consumed 2.93 kWh. These measurements were directly obtained from an energy meter.

Taking into account that 5 persons consume 195 liters of water daily, and that the prototype has the capacity of heating 240 liters in one hour, the costs were calculated considering the aforementioned consumption for 22 days per month, which was estimated as the average water usage for personal hygiene activities.

With these precedents, an approximate cost of 8.66$ was calculated when utilizing the ON/OFF controller, and 4.97$ for the direct phase control.

The same projection was conducted for evaluating the consumption of the electric shower. A consumption of 8.98$ was determined considering a 4500 watts' shower, while heating the same amount of water with a gas heater will require about two Ecuadorian commercial cylinders, which represents a projected consumption of 4.59$ of GLP.

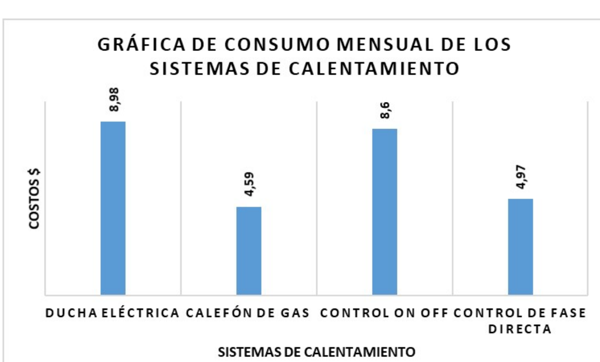

Figure 14. Monthly consumption of the heating systems.

Revising the utilization costs of the electric shower, the gas heater and the ON/OFF control, it is observed that the latter consumes 38 cents less than the electric shower, but 4.01$ more than the gas heater.

On the other hand, the utilization of an electric heater with control by phase angle consumes 4$ less than the electric shower, 3.63$ less than the heater with ON/OFF control and only 38 cents more that the GLP heater.

4. Conclusions

With the implementation of the water heating system, and after conducting tests of operation of such system, it was found that four necklines of 1650 watts each and a 14 meters long coil built with a copper pipe of 3/8 inches' diameter, were capable of increasing the temperature of 4 liters per minute of water from 17 to 40 °C, as was theoretically described in the calculation of the power of the heating resistances.

The prototype operates with a two-phase voltage of 220 VAV, with each phase of 120 VA feeding two necklines in parallel by means of two TRACS. Considering the power of the necklines, it can be said that each power element should withstand a current of at least 14.77 A. Once the tests of operation were carried out, it is concluded that the electric and electronic elements of the prototype efficiently withstand this value of current, and they can operate without any risk.

By means of the tests of operation of the temperature controllers, it could be appreciated that the ON/OFF control has a better response regarding operation than the direct phase controller, namely, the ON/OFF control has a lesser stabilization time and better steady-state performance.

From an analysis of costs, it was found that the direct phase controller has a consumption of 2.93 kWh at maximum temperature, and the ON/OFF controller consumes 5.45 kWh at the same condition. In other words, from the energy viewpoint the direct phase control is more advantageous than the ON/OFF control.

Based on an evaluation of the benefits of each controller, it is concluded that although the ON/OFF controller exhibits a better response in operation, the enormous saving of the direct phase control tilts the balance to its implementation in future works. It is also concluded that it is necessary to test more control techniques, such that the best model regarding response in operation and costs is found. It is also suggested to conduct a comparative analysis, to find the effect of the different control techniques on the electrical distribution network.

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