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(Research Article)

Development of a PID-Controlled Refrigeration System for Reduced Power Consumption

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Abstract

Refrigerator systems are used for food preservation as well as other applications. However, the cost of running the system is high due to rising fuel and electricity prices. Traditionally, these systems are controlled by On/Off controllers. This study proposes the use of a proportional-integral-derivative (PID) controller algorithm to reduce costs for domestic and industrial refrigeration without negatively affecting the system performance.

To accomplish this, a physical model was developed, comprising a domestic refrigerator, microcontroller, and MATLAB computer software for analysis. A mathematical model of second-order lead and second-order lag transfer function was also developed for a typical refrigerator system. The physical model was connected, and open-loop temperature-time response data was collected for system modeling. In addition, Data were collected from industries namely Fan Milk Industry and Benue State University Teaching Hospital Mortuary for a robust system analysis. All data sets were imported into MATLAB's system identification toolbox to estimate model parameters. The ultimate gains, frequency, and period were determined for each feedback closed-loop model, allowing the application of Ziegler-Nichols and Tyreus-Luyben PID tuning settings. The closed-loop models were then simulated in MATLAB to evaluate system performance.

Simulation results showed that the Tyreus-Luyben model performed better, and offered better temperature response, less undershoot, and faster settling time than the Zeigler-Nichols method. Both PID models outperformed the traditional On/Off controller, with energy consumption reduced to less than one-third of the conventional method. The study concludes that PID controllers are a better alternative to On/Off systems when properly tuned.

Keywords: Refrigerator; PID-controller; Microcontroller; Temperature response; and Energy Efficiency.

1. Introduction

Perishable food can be kept for a long time with the help of refrigeration. Refrigeration plays a significant economic role in promoting global trade and preserving the quality of agricultural and fishery products in addition to preventing deterioration. In a little more than a century after its invention, refrigeration has solidly established itself as a method of preservation for a wide range of perishable items [1],[2],[3]. Temperature is one of the most crucial elements impacting the efficacy, security, and storage (or shelf) life of agricultural and food goods. Immediate refrigeration processing (cooling and/or freezing) following the harvest, as well as storage and transit in a low-temperature

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environment, are advised for perishables to maintain the highest quality of food. A cold chain, where the temperature is consistently kept at the proper levels, can create and maintain a low-temperature environment. Today, the bulk of goods are processed and preserved by refrigeration; for instance, 70% of all food sales in Europe are made in supermarkets. Since the refrigeration system is necessary to maintain the cold chain's minimum temperature at a negative value, the entire cold chain uses energy [4].

Since a large amount of the energy lost in cold stores results from improper equipment use and proper control commissioning, auditing current refrigeration equipment, checking controls and set points, reducing heat loads, improving defrosting, lowering temperature lifts in refrigeration plants, enhancing compressor and system performance, and implementing planned maintenance are the main steps in evaluating potential energy-saving opportunities [5],[6].

The cost of energy consumption in a cold room or refrigerator depends on several variables, including the room's size, the cooling system's effectiveness, the cost of electricity in the area, and how long the room is in use. As these systems use a lot of energy to keep the temperature low, operating a cold room can be fairly expensive on average. To reduce the cost of energy consumed in a cold room or refrigerator system, managing the temperature of cold rooms is important [7], [8]. Controlling the temperature of cold rooms presents a number of difficulties, including maintaining a constant temperature, which is challenging due to changes in ambient air temperature and the heat produced by refrigeration equipment, improving the energy efficiency of the refrigeration equipment because it is well-established that there must be energy losses during energy conversions, and reducing condensation, which promotes the growth of mold and bacteria and thus affects the efficiency [9].

The temperature of cold rooms can be controlled using a variety of control modes. The on-off control scheme and the PID control system are two examples of the two control schemes. An on-off control mode is a form of control system that alternately turns on and off the refrigeration compressor to keep the refrigerated space's temperature within a specific range. The controller compares the refrigerated space's temperature to the intended temperature set point and activates or deactivates the compressor as necessary to maintain the required temperature. An on-off controller results in poor temperature response in attaining a steady state, high energy consumption, and a restricted control performance where the output is not proportional to the error.[10],[11],[12],[13].

However, this high cost of energy consumption can be minimized with the right mode of temperature control and this study seeks to optimize the cost of energy consumed by a PID temperature-controlled refrigeration system. A PID (proportional-integral-derivative) controller is a sort of control system that is frequently used in refrigeration to keep the temperature of the chilled room within a particular range. The compressor speed or cooling output is adjusted by the controller as necessary to maintain the desired temperature by continuously comparing the temperature of the refrigerated space to the intended temperature setpoint. The proportional term, which is based on the current error between the temperature and the setpoint; the integral term, which accounts for the accumulated error over time; and the derivative term, which accounts for the error's rate of change, are the three control terms that the controller uses to determine the proper adjustment. A PID controller can offer better energy economy and more accurate temperature control than an on-off controller by utilizing these three terms [8]. The control scheme has a large range of tuning settings, each of which produces a distinct performance in terms of energy consumption [14],[15].

Several models of refrigerator components have been developed, these models focus on cabinets, evaporators, condensers, and compressors separately rather than the full refrigeration cycle [16]. A few of these models as discussed.

Parise ref. [17] describes one way to model an evaporator by assuming that the total heat transfer coefficient is constant for both the saturated and superheated portions of the evaporator. The incoming air temperature, dry air's mass flow rate, heat capacity, and evaporator area are all model inputs. In another study, O'Neill and Crawford ref. [18] present the relationships between fined tube evaporators in a paper. The conductance relations are provided as a function of the airside, refrigerant side, tube, and tube/fin contact resistances even though the paper's primary focus is heating exchanger optimization. Beecher and Fagan ref. [19] show airside heat transfer correlations for various fin designs. Fin and tube spacing modifications are among the different configurations. The information is displayed visually along with curve fits that provide empirical equations for Nu as a function of Gz and additional important factors. In a recent study, Domanski ref. [20] discusses the findings of research on the uneven distribution of air across an evaporator. To analyze intricate refrigerant circuitry, a tube-by-tube approach was adopted. Different air velocity profiles are used to compute the heat transfer parameters. The model is also validated using experimental data, such as recorded velocity profiles. The predictions agree with the measured data by 8.2%. Also, Rite and Crawford ref. [21] presents the impact of icing on evaporator performance. The test evaporator has 5 fins per inch of fin spacing and is a conventional aluminum plate and fin-and-tube device. For various relative humidities, the air side pressure drops, conductance (VA), and icing rate are provided as functions of time.

In addition, Kempiak ref. [22] investigates a mobile air conditioner condenser's three-zone modeling. For each of the three zones, a constant heat transfer coefficient is assumed (desuperheating, two-phase, and subcooling). Similarly, Nitheanandan et al. ref. [23] investigate the heat transmission during condensation inside tubes. In this two-phase modeling, the various flow regimes are examined for both the low and high mass flux cases. For every area of two-phase flow, heat transfer correlations are determined using experimental data. Since the data are significantly scattered, overall correlations are challenging.

Furthermore, Stoecker and Jones ref. [24] provide a fundamental study of reciprocating compressor performance and modeling. The authors provide two methods for compressor modeling: volumetric efficiency analysis and bi-quadratic least squares fit. Since it is based on physical data that can be observed and used to forecast compressor performance, volumetric efficiency analysis seems to be a more effective technique for modeling a compressor. Rice and Fischer ref. [25] also revealed a more in-depth compressor study in a report outlining the Oak Ridge National Lab heat pump concept. Internal efficiency and heat loss parameters for a reciprocating compressor are modeled using internal energy balances. This implies that several physical compressor characteristics, such as total displacement, clearance volume ratio, motor speed, shaft power, motor efficiency, mechanical efficiency, and isentropic compression efficiency, must be specified by the user. Performance characteristics, such as refrigerant mass flow rate, compressor can losses, etc., are obtained by concurrently solving energy balancing equations and system-defining equations. Rottger and Kruse ref. [26] look at how the compression process may be applied to the correlations found in an ideal gas law. These demonstrate performance variations of up to 10% when the compressor calculations are made using perfect gas relations. This highlights how crucial it is for compressor simulation models to take real gas behavior into consideration.

This study will investigate the energy cost optimization of a PID-controlled refrigerator system; develop the mathematical model describing the dynamics of temperature response to electrical power supply in the refrigerator system; estimate the parameters of the proposed mathematical model using data acquired from the physical model and design a PID control scheme for the physical model, simulate the scheme with the mathematical model using Ziegler Nichol and Tyreus-Luyben controller setting. This finding will be beneficial to a number of corporations and businesses such as those selling frozen foods, frozen chicken and fish, and ice cream as well as mortuaries where bodies are stored under cold freezing temperatures.

2. Proposed method

This work aims at reducing the energy consumption of refrigerating units by designing a PID controller and comparing its performance with the traditional ON and OFF system. To achieve that, the mathematical model of a second-order lead-lag relationship between the voltage supplied to the refrigerator compressor and the temperature of the refrigerator cabinet will be developed, focusing not just on the individual components separately but on the full refrigeration cycle. Data acquired from the physical model will be fitted into the model which will be used as the mathematical model for the physical setup. The performance of the ON and OFF controllers will be simulated for the open loop response. A PID controller is then designed using Ziegler Nichols ultimate cycle controller tuning and Tyreus Luyben controller tuning method. The closed loop response will be simulated for each setting and performance compared.

3. Research method

The vapour compression cycle that will be simulated was developed based on the fundamental law of energy conservation and some based model assumptions. The vapour compression cycle is shown in figure 1.

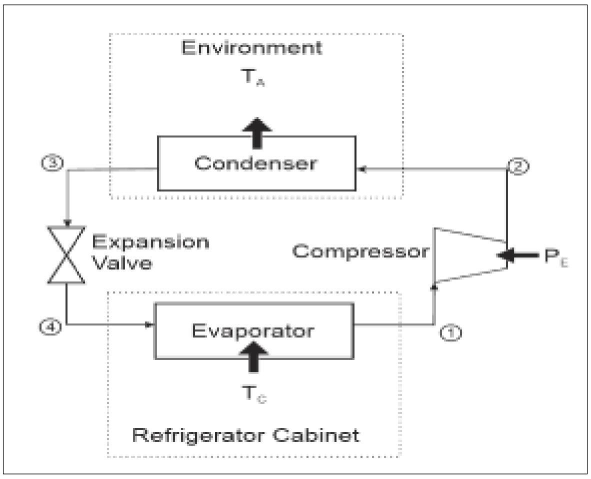

Figure 1 Schematic representation of the vapour compression cycle

The mathematical model of a second-order lead-lag relationship between the voltage supplied to the compressor and the temperature of the refrigerator cabinet for the Vapour compression cycle was developed.

Thus, the model for the vapour compression cycle is written as

$$\frac{T_c(s)}{V(s)} = \frac{K_p(\tau_1 s+1)(\tau_2 s+1)}{(\tau_{p_1} s+1)(\tau_{p_2} s+1)} \quad \text{........(1)}$$

Where k_p is the process gain, τ_{p_1}, τ_{P2}, τ_1 and τ_2 are

time constant. The model agrees with some relevant studies [27], [28]. These studies collectively support the claim that there is a second-order lead and second-order lag relationship between the voltage supplied to the refrigerator compressor and the temperature of the refrigerator cabinet.

3.1. Procedure

To acquire temperature time response data from the physical model of a domestic refrigerator rating 0.5hp, the entire set-up was connected to a power supply as shown in Figures 2 and 3 respectively. Using the Arduino Add-on for Simulink, the voltage supply signal is sent to the compressor via USB and the Arduino Mega 2560. Instantly the temperature sensors of dS18b20 begin to read the temperature signal and send it back to the Simulink Environment via the Arduino. The Arduino acts only as an interface between Simulink and the refrigerator. Temperature data signals are logged onto the Simulink environment.

For the industrial refrigerators, open-loop data was collected from two industries. The considered industries are Fan Milk Company (cold room of size 200 tones) in Ibadan and Benue State University Teaching Hospital Mortuary (cold room of size 50 tones) in Makurdi whose activities resonant with refrigeration.

Figure 2 Physical set-up connection to acquire the measured data from the domestic refrigerator

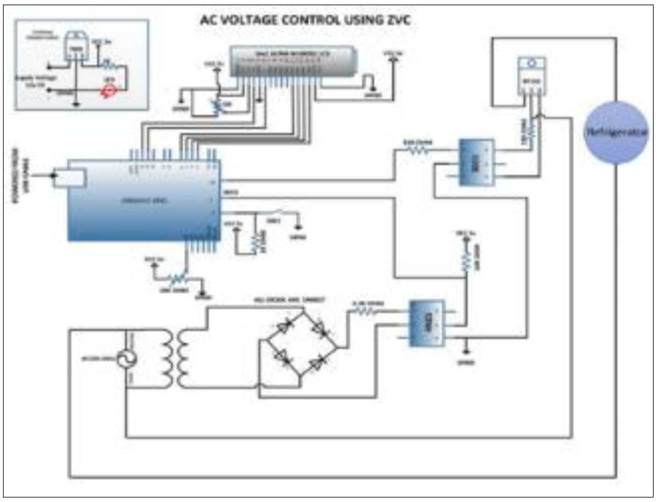

Figure 3 Set-up circuit diagram to acquire data from the domestic refrigerator

3.2. Process System Identification

The simulation is run for the on and off controller design. Scope data is stored and imported into the System Identifications Toolbox. The data is fitted into the proposed model to estimate model parameters and to identify goodness of fit. For the PID controller, the PID settings are first set to zero and the procedure is followed as described for the on-off tuning.

3.3. Feedback Controller Design

3.3.1. Zielger Nichols ultimate cycle controller tuning

The characteristic equation for the process transfer function is converted from the Laplace domain to the frequency domain. The frequency domain is then used to theoretically calculate the ultimate gain and ultimate period. Using the Ziegler Nichols settings presented in Table 1, the ultimate gain and ultimate period will be used to determine the desired tuning parameters as proposed by Ziegler and Nichols (Table 1).

Table 1 Ziegler-Nichols Model Jalali [29]

PID Type	**K_p**	**$\tau_i = K_p/K_i$**	**$\tau_d = K_d/K_p$**
P	$0.5K_u$	-	-
PI	$0.45K_u$	$0.833P_u$	-
PID	$0.588K_u$	$0.5P_u$	$0.125P_u$

3.3.2. Tyreus Luyben controller tuning

The ultimate gain and ultimate period determined previously were used to determine the desired tuning parameters (Table 2).

Table 2 Tyreus-Luyben Settings Luyben [30]

Controller Type	**K_p**	**$\tau_i = K_p/K_i$**	**$\tau_d = K_d/K_p$**
PI	$0.313K_u$	$2.2P_u$	0
PID	$0.45K_u$	$2.2P_u$	$0.16P_u$

3.3.3. Simulation of the Performance of the Controlled Refrigerator System

The tuned parameters were entered into Simulink block diagrams. The voltage-controlled action is viewed at the controller output. The output is linked also to a scope to view the plot of the simulation results such as the fall time, settling time, peak time, maximum peak ratio and steady state error.

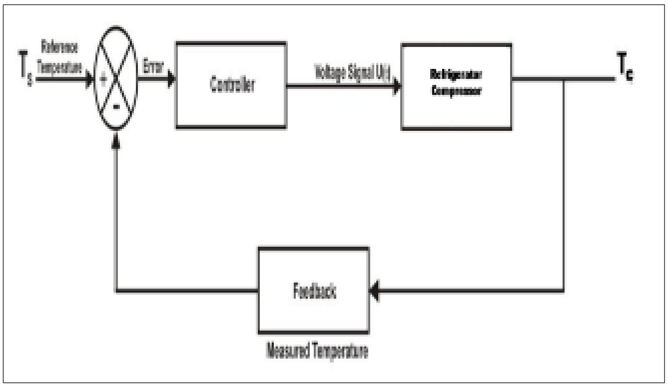

Figure 4 Block Diagram of a Controller-based Refrigerator System

4. Results and Discussion

After running the experimental set-up on the on/off controller mode of the fridge, the experimental data was plotted as shown in Figure 5 for a constant AC voltage of 230 V, 50 Hz.

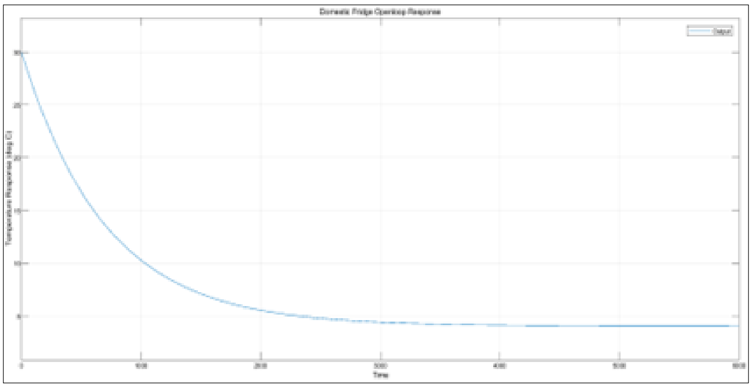

Figure 5 Open Loop Response for the Domestic Refrigerator (on-off Controller)

Figure 5 shows decay from 30ºC to about 4ºC in 3859 seconds. This means that the system takes almost 1 hour and 4 minutes to attain a steady state which is quite slow. Energy consumed during this process of attaining a steady state can be minimized with a faster fall time. Since the response is expected to fit a second-order model, the plot obtained indicates that the physical model is actually an overdamped system as it has no overshoot [30], [31], [32].

The open loop transfer function was obtained by importing scope data into Mat lab System Identification Toolbox, the data was fitted to the proposed transfer function model which had 2 zeros and 3 poles and was found to have a 99.36% fit as shown in Figure 6.

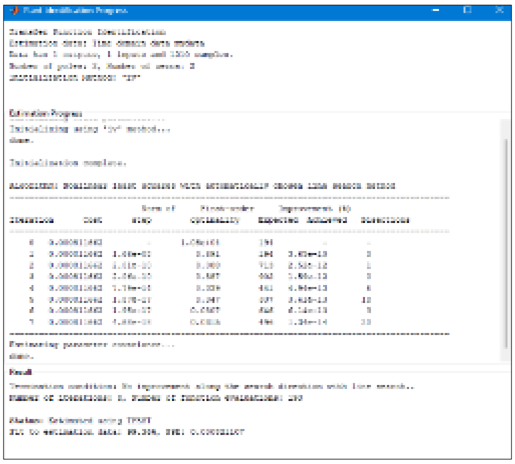

Figure 6 Goodness of Fit of the Model

From the proposed parameter estimation result, the open loop model transfer function is given

$$G_P = \frac{T_{(s)}}{V_{(s)}} = \frac{0.1306s^2+0.001913s+2.663\times10^{-6}}{s^2+0.02567s+0.0001512} \text{ ....(2)}$$

The developed model confirmed some relevant studies [33], [34].

To determine the PID controller tuning parameter, the ultimate gain and ultimate period of the feedback closed-loop response must be determined i.e.

$$1+K_u G_p = 0 \quad \text{...........(3)}$$

K_u is the ultimate gain and G_P is the plant model

Substituting the plant model, Equation (2) into (3) gives

$$1 + k_u \frac{0.1306s^2+0.001913s+2.663\times10^{-6}}{s^2+0.02567s+0.0001512} \text{ .... (4)}$$

By substituting $s = i\omega$, and applying the principle of equality of complex numbers.

The solved ultimate gain K_u = -13.42, ultimate period

$$P_u = \frac{2\pi}{0.012} = 523.59\text{seconds.}$$

And Angular frequency ω = 0.012rad/sec.

The negative ultimate gain obtained shows that the PID controller designed for this vapour compression cycle is a **direct-acting** controller as opposed to the normal conventional **reverse-acting** controller which has positive gains [30]. This is largely because an increase in the process variable leads to an increase in the controller output. To properly explain why this is so, it is imperative to remember that this is a cooling down process. At the initial stage, the set-point temperature will always be below the measured temperature value, so the error will be negative. Since the controller gain is negative, the controller output is eventually positive which implies an increase in the manipulated variable which is the voltage supplied to the compressor thereby causing the compressor to increase the cooling activity. Once the process gets to a temperature below set, the error signal becomes positive so that the controller output becomes negative due to the controller. This implies that lower voltage is applied to the compressor resulting in decreased cooling action hence temperature rise. The tuning parameters for Ziegler-Nichols and Tyreus-Luyben tuning methods are evaluated using the values given in Tables 1 and 2. The results are presented in Table 3.

Table 3 Tuning Parameters for Ziegler-Nichols and Tyreus-Luyben

Tuning Method	**Proportional gain (K_c)**	**Integral Time Constant (τ_i)**	**Derivative Time Constant (τ_D)**
Ziegler-Nichols	-7.89	261.795	65.41
Tyreus- Luyben	-6.04	1151.90	83.77

The Ziegler Nichols and Tyreus Luyben Settings were inputted into the gain blocks respectively, the closed-loop response for Ziegler Nichols and Tyreus Luyben settings are shown in Figure 7 and Figure 8.

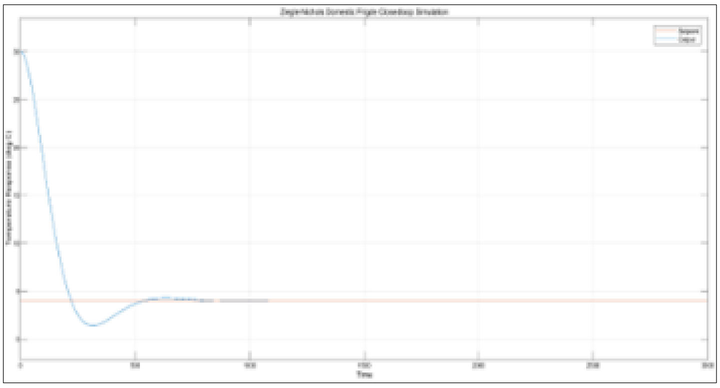

Figure 7 Ziegler Nichols Closed loop Simulation Response

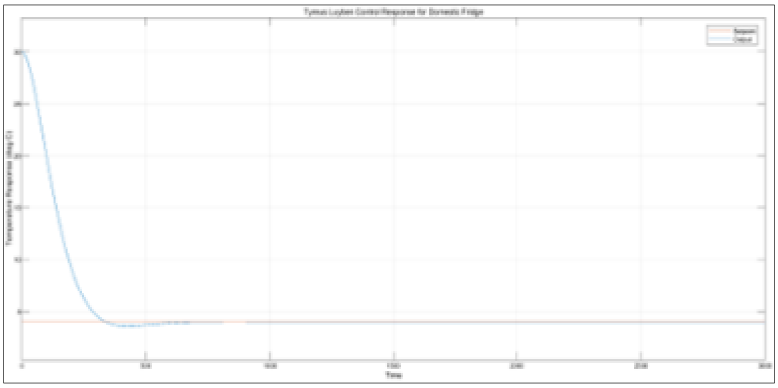

Figure 8 Tyreus Luyben Closed loop Simulation Response

Ziegler Nichols Response shows an undershoot below steady state. Also, the negative undershoot extends far 0°C which is not the original intent of the cabinet (not the freezer compartment). As seen from negative undershoot, Ziegler Nichols settings show fairly good performance and attain steady state at 831 seconds. This method is a widely used controller tuning technique. It relies on step-response data to determine the controller's parameters. It is known for its simplicity and ease of implementation [30], [35], [36].

Tyreus-Luyben Settings offers a better temperature response and performance than Ziegler-Nichols as seen both in figure 7 and figure 8 respectively. It offers lesser undershoot, shorter fall time and a faster settling time of about 765seconds as opposed Ziegler Nichols which attained steady state of about 831 seconds. This finding is in line with ref. [37] study. Both closed loop models had shorter settling time than the open-loop model.

According to Luyben [30], the Tyreus-Luyben tuning method is a popular technique used to tune PID (Proportional-Integral-Derivative) controllers. It aims to minimize overshoot and achieve a faster settling time by adjusting the controller's parameters.

The energy requirement for the steady-state phase (when the system is eventually stable with no oscillations) of the response is the same for both open-loop and closed-loop systems. However, energy consumption differs during the transient phase due to the differences in settling time. The amount of energy consumed for the open loop is given by Equation 5; but for the closed loop, the approximate area under the graph gives the amount of energy consumed during the transient and the steady state phase.

$$\text{Energy Consumed(kWh)} = \frac{\text{Settling Time(s)} \times \text{Compressor Power Rating(kW)}}{3600} \quad (5)$$

While the cost of energy required to attain steady state is given by Equation 6

$$Cost\ of\ Energy\ Consumed(N) = Electricity\ Tarrif\,(N/kWh) \times Energy\ Consumed(kWh) \quad (6)$$

Table 4 Energy consumption during transient response for open loop domestic refrigerator

Model	Settling Time (s)	Compressor Power (kW)	Energy Consumption (kWh)	Unit Cost of Energy (N/kWh)	Cost of Energy Consumed on Startup (₦)
On/Off Control	3859	0.373	0.400	63.33	₦25.32

To further establish the real-world application of this study, dynamic response data was collected from two industries whose activities resonate with refrigeration. The industries were Fan Milk Industry in Ibadan and Benue State University Teaching Hospital Mortuary in Makurdi. Their dynamic data showed a gradual fall in temperature from that of the ambient environment. Their open-loop response plot is shown in Figures 9 and 10 respectively.

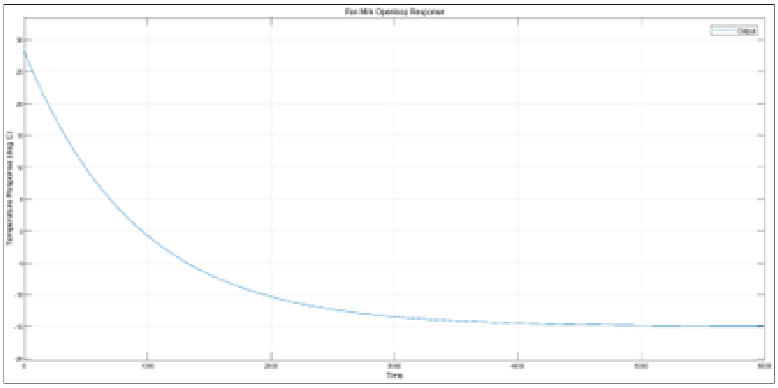

Figure 9 Openloop Dynamics Plot for Fan Milk (on-off controller)

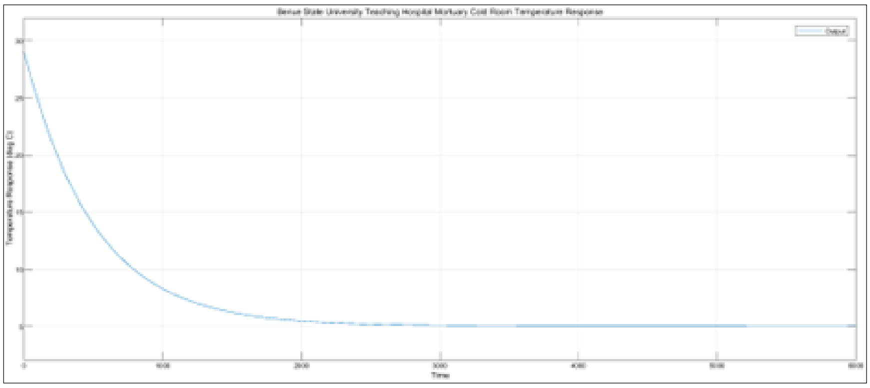

Figure 10 Openloop Dynamics Plot for BSUTH Mortuary Cold room (on-off controller)

The open loop dynamics plot for Fan milk industry shows that temperature falls from 26°C to about -15°C in about 5371sec which is quite slow (Figure 9). This might be due to the large power consumption by the compressors. The cold storage room that holds 200 tones is kept at a temperature of -15°C.

Figure 10 shows the open loop dynamic data plot for the cold room mortuary of Benue State University Teaching Hospital. It shows a faster fall in temperature when compared to Fan milk. In about 4239 seconds, it has attained a steady state and looks more like a first-order response than a second-order over-damped system response. The faster response could be attributed to a shorter temperature range i.e. from ambient temperature of 29°C to 5°C hence lower power requirement.

To study their closed-loop dynamics, it is imperative to determine the parameters of the open-loop response dynamics using the same approach as was used. The data set for each industry was imported into the systems identification toolbox to determine the parameters of the model. It is believed that the same model applies to both domestic and industrial refrigerators since they operate by the same principles. Based on the output of the Systems Identification Toolbox; the models are:

$$G(s)=\left.\frac{T(s)}{V(s)}\right|_{\text{Fan Milk}}=\frac{0.1131s^2+0.005084s+9.29e-06}{s^2+0.02396s+0.0001425} \qquad \text{…………..(7)}$$

$$G(s)=\left.\frac{T(s)}{V(s)}\right|_{\text{BSUTH}}=\frac{0.1261s^2+0.001618s+4.194e-06}{s^2+0.02777s+0.0001927} \qquad \text{……………..(8)}$$

Both transfer functions had a goodness of fit of 99.92% for fan milk and 99.82% for mortuary. This is an indicator of how well the model can be used to analyze future outcomes of its inputs. The ultimate gain and period for each transfer function are determined using the same procedure as was used for domestic refrigerators. The result of the mathematical analysis is presented in Table 5.

Table 5 Ultimate Gain, Frequency and Ultimate Period of closedloop transfer function

Industry	**Ultimate Gain (K_u)**	**Frequency (ω)**	**Ultimate Period (P_u)**
Fan Milk	-4.72	0.0544	115.50
BSUTH Mortuary	-14.80	0.0123	510.82

Also, the corresponding Ziegler-Nichols and Tyreus-Luyben control settings are given in Tables 6 and 7 respectively.

Table 6 Ziegler-Nichols Tuning Settings

Industry	**K_c**	**τ_I**	**τ_D**
Fan Milk	-2.78	57.75	14.44
BSUTH Mortuary	-8.70	255.41	63.85

Table 7 Tyreus-Luyben Tuning Settings

Industry	**K_c**	**τ_I**	**τ_D**
Fan Milk	-2.78	57.75	14.44
BSUTH Mortuary	-8.70	255.41	63.85

Both industrial closedloop responses were simulated for each setting as shown in Figures 11, 12, 13 and 14.

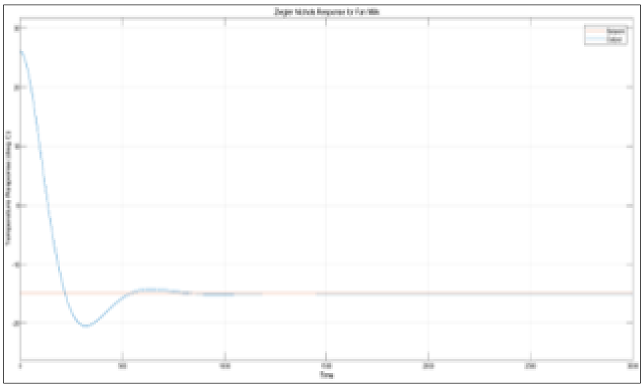

Figure 11 Ziegler Nichols tuning settings for Fan Milk closedloop response

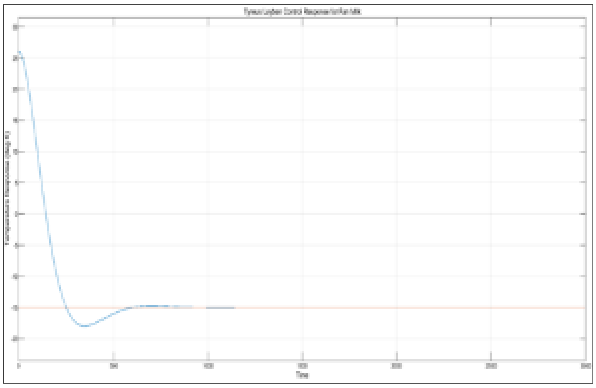

Figure 12 Tyreus Luyben tuning settings for Fan Milk closedloop response

The lowest temperature for Fan Milk was -20°C as seen in figure 11 and 12, showing a slight undershoot before settling down to steady state. As expected, the Tyreus Luyben settings offer lower undershoots, lesser fall time and a faster settling time than Ziegler Nichols response.

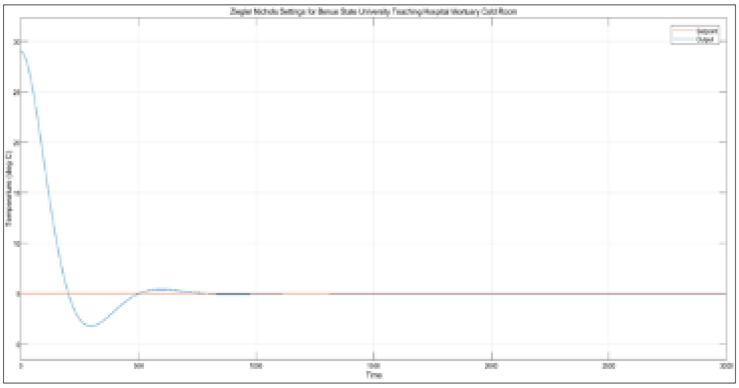

Figure 13 Ziegler Nichols tuning settings for BSUTH Mortuary closed loop response

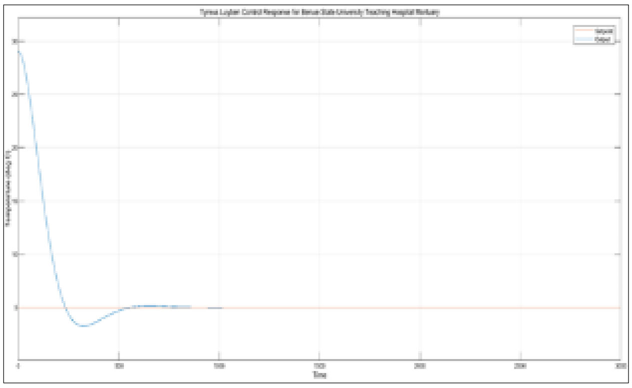

Figure 14 TyreusLuyben tuning settings for BSUTH Mortuary closed loop response

The lowest temperature for BSUTH Mortuary was 3°C as seen in figures 13 and 14. As expected, the Tyreus Luyben closed-loop model offered a better temperature response compared to Ziegler Nichols settings. These responses were like that of the domestic refrigerator used in the study since both industrial and domestic refrigerators use the vapour compression refrigeration cycle. It is therefore safe to conclude that Tyreus-Luyben tuning method is the optimal of the two tuning settings for domestic as well as industrial refrigeration systems.

The energy consumption was determined for each industry for the open loop model during the transient phase (equations 5 and 6); the result is presented in Table 8.

Table 8 Energy consumption during transient response for each industry

Model	**Settling Time (s)**	**Compressor Power (kW)**	**Energy Consumption (kWh)**	**Unit Cost of Energy (N/kWh)**	**Cost of Energy Consumed on Startup**
Fan Milk					
On/Off Control	5371	150	223.792	63.79	₦14,275.67
Benue State University Teaching Hospital Mortuary					
On/Off control	4239	2.238	2.635	72.78	₦191.78

Riemann sum numerical approximation approach was used to calculate the area under the graph to determine the energy consumption for the closed model during the transient phase as shown in table 9. The voltage-controlled action for the closed loop model for Ziegler Nichols and TyreusLuyben voltage versus time for both the domestic and industrial refrigerators are shown in figure 15.

Table 9 Calculated area under graph for the close loop model of the domestic Fridge and each Industrial Refrigerator

Area Under Graph (Vh)	Domestic Fridge	Fan Milk Coldroom	BSU Mortuary Coldroom
Ziegler Nichols	51.69273	68.08722	68.05514
Tyreus Luyben	47.67086	59.16673	53.04156

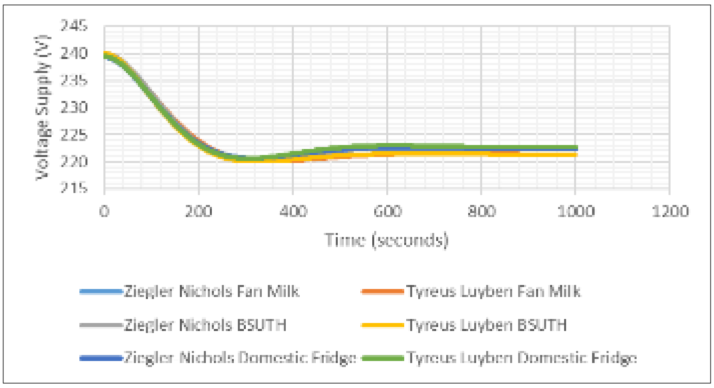

Figure 15 Control action showing Ziegler Nichols and Tyreus Luyben voltage versus time for each system at transient Phase

5. Conclusion

The study found that the ultimate gain was negative in all cases of the refrigerator indicative that the type of PID controller being used is a direct-acting controller as opposed to the conventional reverse-acting controller. The simulation results show the Tyreus Luyben control scheme exceeded the Ziegler Nichols in terms of performance in each case.

The study therefore concludes that the PID controller offers better and more energy-efficient performance than the conventional control with faster settling time in an attempt to attain a steady state.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest.

Author Contributions

This work was carried out in collaboration between all authors. Lawrence O. Agidike designed the study, collected the measured data, and arranged the results. Godslove I. Ebiega introduced the settings of the PID-tuned controller and supervised the analyses of the study. Ovis D. Irefu managed the literature searches of the study and designed the controller. Seyi J. Fanifosi performed the Data Curation and Data Analysis.

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