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CONTROL OF A HEAT PUMP COMPRESSOR WITH VARIABLE FREQUENCY DEVICE DRIVEN BY PID

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ABSTRACT: Integrating advanced control technologies to enhance energy efficiency and environmental sustainability in heat pump systems is of growing significance. This article offers a comprehensive review on the utilization of Proportional-Integral-Derivative (PID) control and Variable Frequency Drive (VFD) technology to govern the compressor's operation in a heat pump. The primary objective is to optimize energy consumption and thermal output under varying loads and environmental conditions, thus enhancing the heat pump's performance.

The article delves into the fundamental principles of heat pump operations, emphasizing the compressor's pivotal role in maintaining the delicate balance between energy consumption and desired thermal output across applications, spanning residential HVAC to industrial processes. The PID control algorithm is introduced to adapt the compressor's speed and power consumption dynamically. The VFD is incorporated into the control system, enabling variable speed compressor operation for a responsive reaction to load fluctuations. Combining PID and VFD control is explored to achieve peak system performance and energy efficiency.

Through practical experiments and simulations, the research investigates the influence of PID and VFD control on energy efficiency, stability, and performance. The results underscore substantial energy savings and environmental impact reduction potential, particularly in scenarios with variable thermal loads and fluctuating environmental conditions.

This study advances our understanding of advanced control strategies in heat pump technology and underscores the pivotal role PID and VFD control play in creating energy-efficient heating and cooling solutions. The findings offer practical implications for diverse applications, from residential settings to industrial processes, and provide insights into sustainable heat pump technology use in the context of energy conservation and climate change challenges.

Keywords: Heat pump, PID, VFD, compressor.

1. INTRODUCTION

In recent years, due to their potential to provide environmentally friendly and efficient heating and cooling solutions, CO_2 (Carbon dioxide) refrigerant heat pumps attract great attention. At a time when climate change concerns are increasing and the need to reduce greenhouse gas emissions is emerging, CO_2 Refrigerated heat pumps offer a promising alternative to traditional heating and cooling systems. Since this type of heat pumps require work above the critical point,

called transcritical, due to the properties of the fluid, it becomes necessary to make improvements using different methods during operation.
Transcritical heat pumps use CO_2 as both a refrigerant and heat transfer medium. It is characterized by their use and operation of this substance above its critical point [1]. This unique thermodynamic property allows transcritical CO_2 It enables systems to achieve high energy efficiency, making them suitable for a variety of applications such as space heating, water heating and cooling. The use of as a natural refrigerant with low global warming potential aligns with sustainability goals and regulatory initiatives to reduce environmental impact [2].

Academic articles on transcritical CO_2 illuminate important aspects of heat pumps. These studies encompass optimization studies [3], exergy analyses [5], experimental investigations [10][12][13][15], performance evaluations [6], and industrial applications [14]. For instance, Wang et al., in their 2022 study, provide a comprehensive review of the use of CO_2 in heat pumps as water heaters, addressing both the energy efficiency and environmental impact of the system [1]. In another study conducted by Wang et al. in the same year, the optimization of the heat pump system using transcritical CO_2 was examined, investigating the potential to enhance system performance [3]. Additionally, a 2023 study by Biswajit et al. comparatively analyzed the environmental impact and energy efficiency of a transcritical heat pump system used in milk processing plants, emphasizing the significance of this technology in industrial applications [5].

Studies on alternative control methods to the classical on-off operation of the compressor, which is the main element of heat pumps, and studies on different positioning of some important parameters in heat pumps have gradually increased in recent years. The basis of some of these methods is that the compressors accelerate and slow down according to the target temperature and never turn off. For example, controlling the speed of compressors with a PID controller is one of these methods. For a specified temperature value, the controller can adjust the compressor speed in the most efficient way [16]. Apart from the PID method, different applications such as artificial intelligence and fuzzy logic have also been used, and the differences, advantages and disadvantages of these methods compared to classical methods have been examined both theoretically and experimentally.

In basic terms, some methods used to increase the efficiency of heat pumps can be listed as follows:
<u>Variable Speed Compressors:</u> Variable speed compressors can adapt the speed of the compressor motor to the heating or cooling load. This allows the heat pump to operate at different capacities, increasing efficiency and providing more precise temperature control.
<u>Smart Thermostats:</u> Smart thermostats use advanced algorithms and sensors to optimize the operation of heat pumps. It can learn users' preferences, adjust heating and cooling schedules, and even maximize efficiency by taking weather forecasts into account.
<u>Internet of Things (IoT) Integration:</u> IoT devices and platforms offer homeowners and building managers the ability to remotely monitor and control heat pumps. They can be used to optimize performance by providing real-time data and control options.
<u>Machine Learning and Artificial Intelligence:</u> Advanced machine learning and artificial intelligence algorithms can analyze historical data and continually adjust heat pump settings to provide maximum efficiency and comfort.

One of the methods used to intervene in compressor speeds is the PID control method. PID controllers are a widely used control mechanism in many different systems. Achieving successful results in system diversity is possible by correctly adjusting the important parameters of this controller [17]. These parameters are called proportional gain (Kp), Integral Gain (Ki) and derivative gain (Kd), and it is aimed to optimize these three parameters to optimize the system gain [18]. The three parameters can affect the system together or can be applied separately, resulting in different controller shapes. In summary, Kp speeds up the response by increasing the system sensitivity, Ki tries to eliminate the steady-state error of the system, and Kd tries to minimize the amount of deviation of the system from the resulting data [19].

One of the common uses of PID controllers is motor speed control. In addition, it is very suitable to be used as a control mechanism in heat pumps containing compressors driven by an AC motor [20]. In heat pumps, in order to reach the target temperature as soon as possible, it will be sufficient to control the compressor speed and keep the temperature constant at this point with minimum energy consumption.

PID has become one of the important issues in improving the energy performance of heat pumps and cooling systems. For this reason, studies on the use of variable speed compressors using the classical on-off method of compressors and the PID method are quite common. Comparison of two control methods in terms of energy use appears to be COP-oriented [21][22]. Monophase AC compressors compress at a constant speed at a frequency of 50Hz when operated with mains voltage. The heating capacity of the system is proportional to the compressor speed. Therefore, the preferred way to change the heating capacity is to change the frequency of the AC voltage. Although the frequency range is defined as 25-75Hz, both low and high frequencies have some negative effects on compressors. Lubrication problems, unwanted temperature increases and deformation of the windings are the most common problems. For this reason, the frequency range to be operated in variable speed compressors must be carefully selected according to the compressor characteristics.

In PID controllers, the control mechanism is made with a microcontroller. Accordingly, PIC (Peripheral Interface Controller), Arduino, PC etc. systems can be used as system administrator. The entire system consists of a hardware part and a software part that ensures the smooth operation of the control mechanism. In summary, the controller, whose hardware and software is completed, obtains information about the system with the help of sensors, calculates the error between the target value and the instantaneous value and takes the necessary position to reach the target. Analysis of the difference between the instantaneous value and the target value is done with three parameters: making a decision according to the current situation with Kp, compensating for past mistakes with Ki, and operating the controller in this direction by predicting the future course with Kd. [23].

In this study, which was conducted as an example of control methods, it was tested whether the compressor of a heat pump system could work with a PID controller according to the determined target temperature. PID controller was used as the decision-making mechanism of the frequency-controlled speed changer unit to be added to a compressor operating according to the classical on-off method, and the reactions of the motor speed when reaching the temperature were examined experimentally.

2. MATERIAL

Water to water Heat Pump System: In order to determine a system for PID control, a heat pump system that had been used in other studies before was chosen. The block diagram of this system, which uses a semi-hermetic single-phase AC compressor with CO2 refrigerant, can be seen in Figure 1.

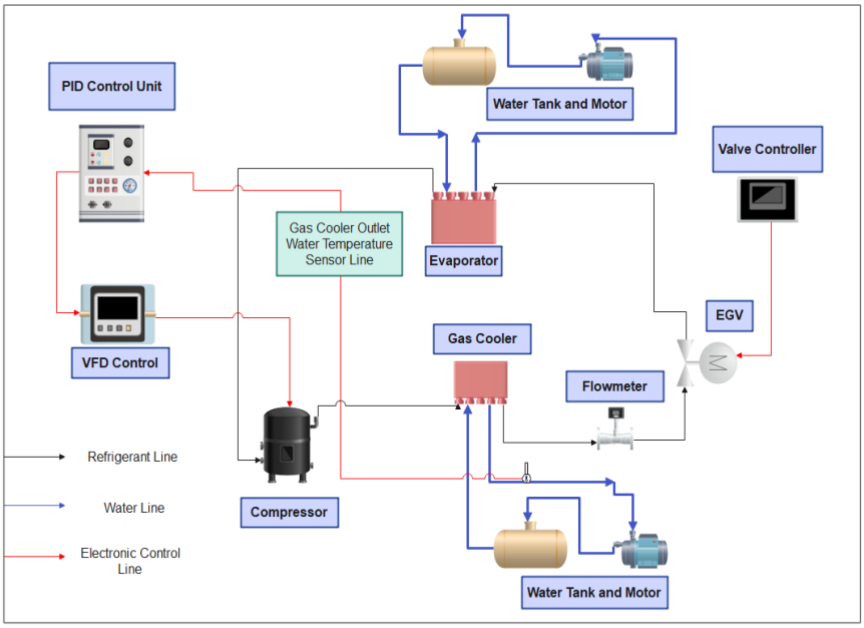

Figure 1 . Heat pump system block diagram

R744 fluid, which comes out of the compressor at high pressure and temperature, transfers its heat to water in reverse flow in the gas cooler. The pressure of R744, whose flow rate is measured at the gas cooler outlet, is reduced to evaporation pressure by passing through the electronic expansion valve whose opening percentage is kept at different fixed values. The refrigerant, combined with the counterflow water in the evaporator, evaporates and returns to the compressor, completing the cycle. The main purpose of the system is to heat the water in the gas cooler for heat transfer with the refrigerant. A thermocouple for this temperature value is placed at the gas cooler water outlet so that the target temperature can be read and processed by the PID control. The temperature information read from here reaches the PID controller. The final version of the test system used is seen in Figure 2.

Figure 2. Heat pump system to be tested

Compressor Speed Controller: A speed control device must be used so that the compressor can operate at variable speeds other than the classical on-off system. Since the system to be tested uses a single-phase compressor, a single-phase motor speed controller was preferred. This device, whose speed can be changed with the help of the potentiometer on it, has a 0-10V industrial control input. When 0V is applied to this input, it operates at the set minimum speed, and when 10V is applied, it operates at the maximum allowed speed, and the intermediate voltage values correspond linearly to the speeds in this range. Due to the compressor features, the minimum speed is 45 Hz and the maximum is 55 Hz. It was determined as . The speed controller can be seen in Figure 3.

Figure 3. Motor speed controller

PID Controller: It is the part that will produce the 0-10V voltage needed by the speed controller and drive it at the appropriate speed. The PID device, which will make a decision based on the temperature information it receives from the gas cooler water outlet, will interpret

this information according to the state of the system and control the compressor speed control circuit.
PID control includes three basic parameters:

a) Proportional (P): This parameter determines the strength of the control action based on the current error (difference between the desired set point and the actual process variable). A higher P value indicates a more aggressive response to errors.

b) Integral (I): The integral term takes into account the accumulation of past errors over time. It helps eliminate steady state errors and moves the process variable closer to the desired set point over time. Increasing the I value provides a control system that is more sensitive to persistent errors.

c) Derivative (D): The derivative term predicts the future trend of the error, dampening rapid changes and preventing the set point from being exceeded. D provides a higher value and provides stronger damping, but can lead to instability if set too high.

PID controllers are generally tuned manually or using automatic self-tuning procedures. Self-tuning usually involves the controller changing its settings to optimize these parameters without manual intervention. Self-tuning methods include Ziegler-Nichols, Cohen-Coon, and model-based techniques. Self-tuning procedures generally aim to minimize error and achieve the desired control performance by adjusting these parameters. The PID device used has a manual control feature as well as a self-tune feature. The PID device can be seen in Figure 4.

Figure 4. PID Control device

Temperature sensor: The temperature information at the gas cooler water outlet is the most important parameter of the system. The PID device will design the system control accordingly and manage the speed control unit. For this reason, the importance of the information obtained here is high. An immersion type K-Thermocouple was used to measure the water temperature here. The temperature sensor used can be seen in Figure 5.

Figure 5. K type thermocouple

PC: temperature data and compressor frequency values will be used in interpreting the results of the study. These values will be transferred to the computer in real time via RS485 protocol. This data will later be used to prove the accuracy of the operation of the PID control. For this reason, a PC was used with the RS485 USB module.

3. EXPERIMENTAL

The experimental setup consists of a heat pump unit, Variable Frequency Drive (VFD), PID controller and temperature sensor. The heat pump unit, which includes the compressor and gas cooler, forms the core of the system. The VFD is connected to the compressor and provides variable speed control. A PID controller is made responsible for real-time adjustments of the compressor speed to maintain the target temperature value. Temperature sensors are placed at the outlet of the gas cooler to continuously monitor the water temperature. Communication and data collection between system components was provided via RS485 and a computer was used for data processing and control. This procedure can be seen in Figure 6.

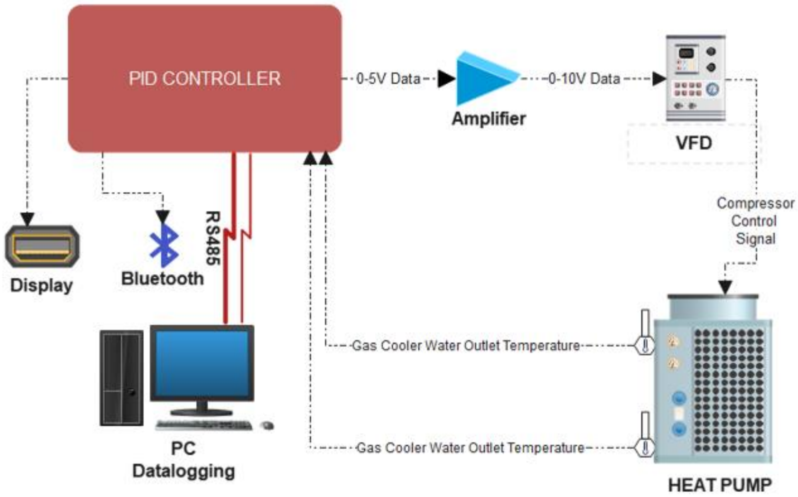

Figure 6. Control system block diagram.

- **Control strategy**

The PID control strategy is vital to achieve the desired heat pump performance. PID controller worked to precisely control the compressor speed. Proportional, integral and derivative gains are determined by systematic experiments to achieve a balance between precision and stability, this is called self-tuning. The control loop will continuously calculate the necessary adjustments in compressor speed based on the deviation to a given target temperature and predict future responses.

- **Data collection and analysis**

Data collection and analysis plays a central role in evaluating system performance. A computer was used as the data collection and control system. Through RS485 communication, real-time data will be collected about the water temperature at the outlet of the gas cooler and the current compressor frequency. The resulting data was recorded and processed to evaluate the heat pump system's efficiency, stability and ability to consistently achieve and maintain the target heat value.

- **Experimental procedure**

When all the components are brought together, the control part includes the heat pump, VFD, PID controller and PC with RS485 connection. After the system was energized, a process was first initiated to select the parameters of the PID device using the self-tune feature. After approximately 8 minutes of operation, the PID controller determined the Kp, Ki and KD parameters as 88.1, 1.76 and 1462.6, respectively. This situation can be seen in Figure 7.

Figure 7. PID parameters determined by self-tune

After determining the PID controller parameters, the system was operated with these parameters and the temperature of the water leaving the gas cooler was observed with the help of the sensor in the gas cooler.

4. RESULTS AND DISCUSSIONS

In the first experiment, the target water temperature was 45°C. The compressor was operated under the control of the PID controller so that the VFD device adjusted the frequency value. Meanwhile, the water temperature at the gas cooler outlet was recorded at ten-second intervals. When the temperature information was converted into a graph against time, the situation in Figure 8 emerged.

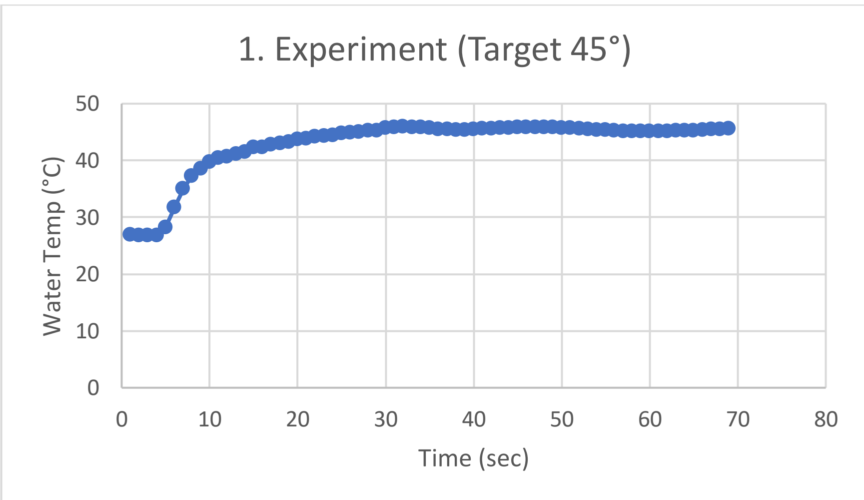

Figure 8. Temperature-time graph for 45°C gas cooler water outlet temperature target

After the temperature of the water in the tanks became normal, a lower temperature value of 40°C was targeted and the experiment was repeated. As a result, the temperature-time graph in Figure... was obtained with similar procedures.

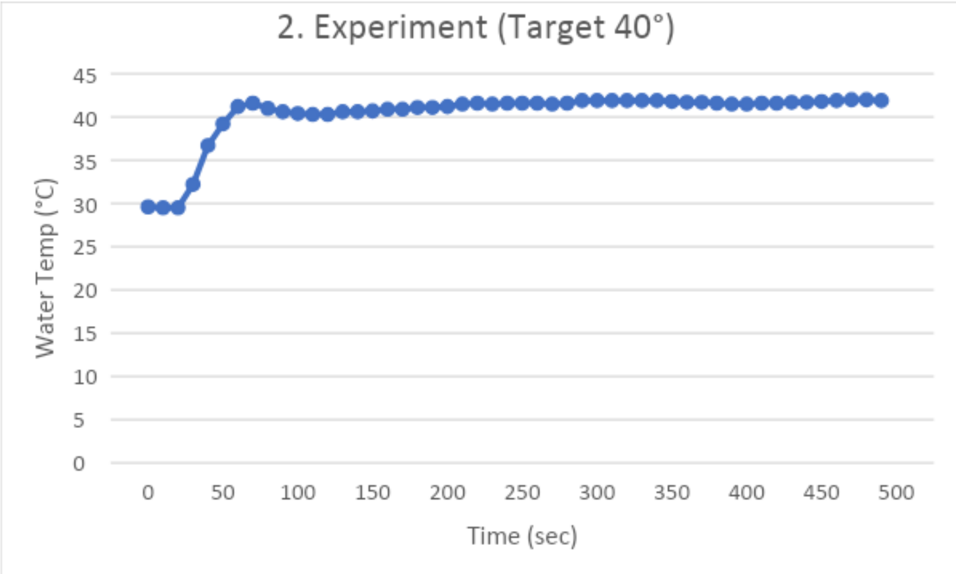

Figure 9. Temperature-time graph for 40°C gas cooler water outlet temperature target

The experiment was repeated this time for a higher target temperature of 50°C and the results were obtained. The temperature-time graph for this situation can be seen in Figure 10.

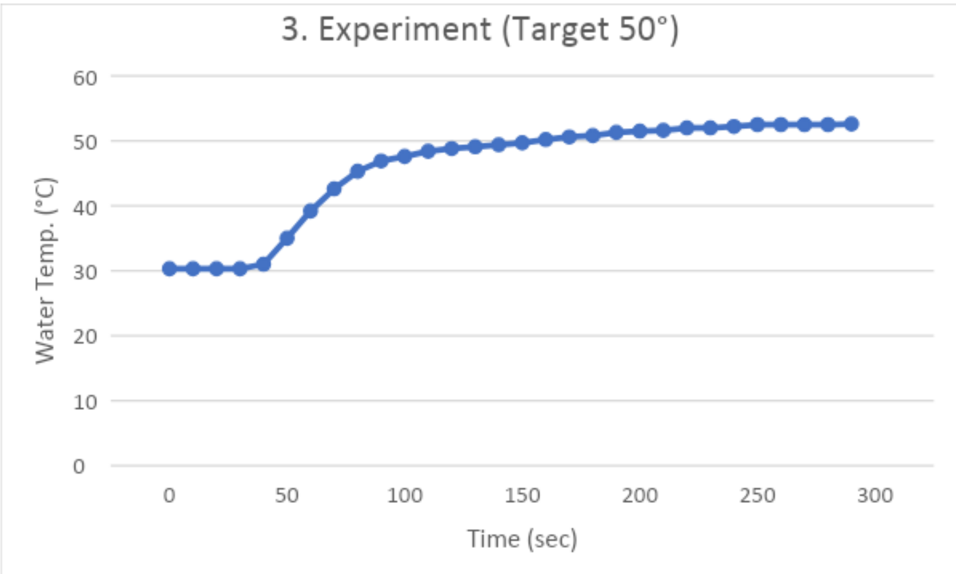

Figure 10. Temperature-time graph for 50°C gas cooler water outlet temperature target

The main goal of the study is to operate the heat pump compressor at variable frequency without shutting down, rather than the classical on-off method. For this reason, reaching the targeted temperature and keeping it constant at this temperature, as well as changing the frequency of the compressor according to the temperature, is one of the main conditions to be followed. For this reason, the frequency information during the work was transferred to the computer from the digital outputs of the VFD device. For example, the frequency information in the first experiment, where a temperature of 45°C was targeted, can be seen in Figure 11.

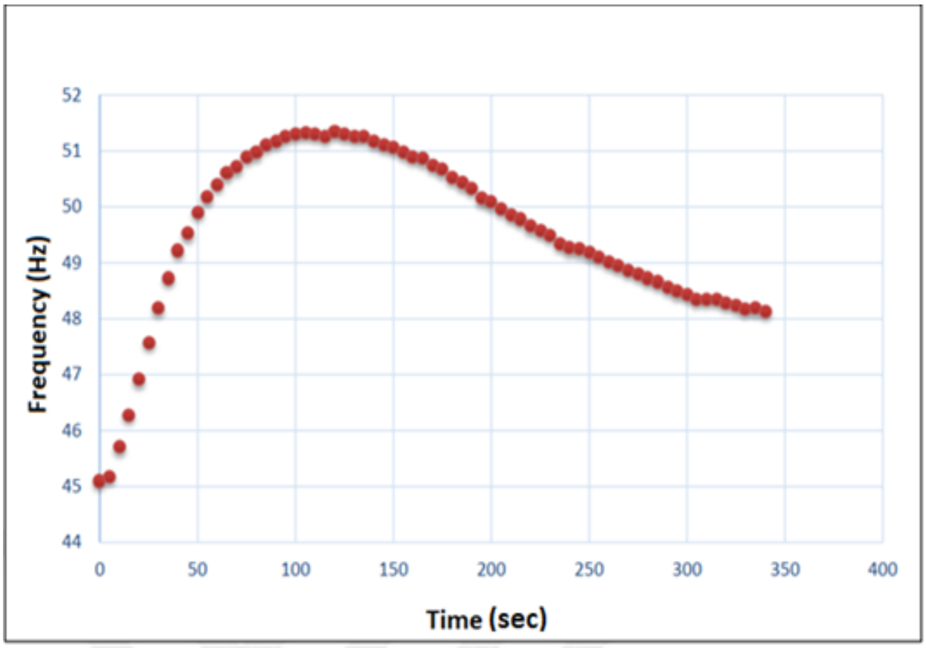

Figure 11. Compressor frequency-time graph for 45°C gas cooler water outlet temperature target

When the frequency value in the figure is examined, it is seen that the compressor starts to work from 45Hz, which is the first value that does not cause any problems in its operation. Then, the PID device detected that the target temperature was too far and the PID device sent the necessary signal to the VFD device to increase to higher frequencies. Compressor 52 Hz. This value is higher than the city network frequency. When the target temperature is approached, the VFD device reduces the frequency with the PID signal.

The frequency values observed for the second experiment are given in Figure 12. Here, the temperature sensor sent a value according to the rapidly rising water temperature and the compressor speed decreased prematurely. Later, when it was seen that the target water temperature was not reached, it was accelerated again.

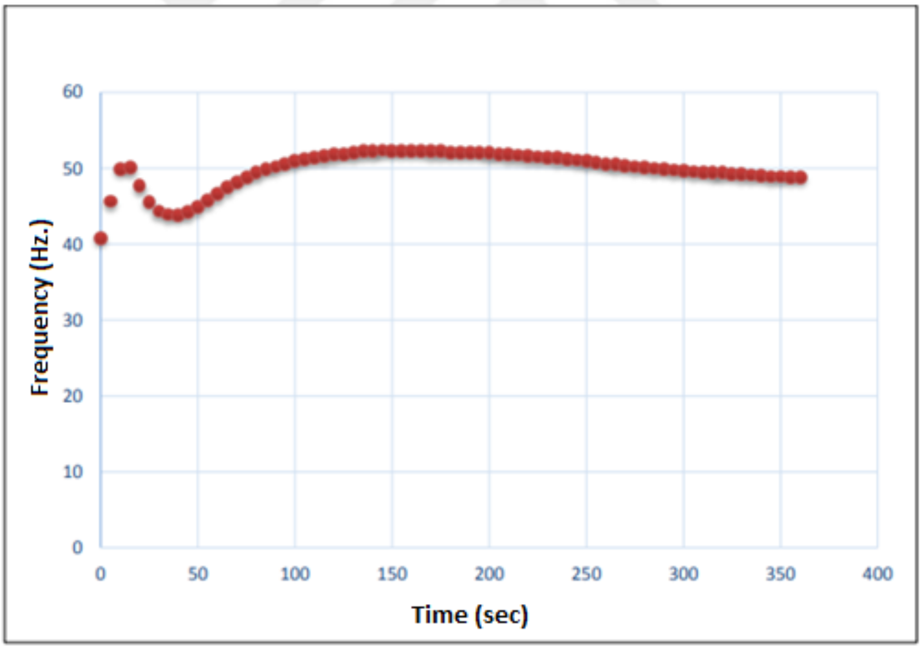

Figure 12. Compressor frequency-time graph for 40°C gas cooler water outlet temperature target

5. CONCLUSIONS

PID controller may be preferred in heat pumps instead of classical on-off. More detailed studies with more parameters (pressures, refrigerant and water flow rates, etc.) can be carried out in future studies.

More parameters can be added to be under the control of the PID controller, as these controllers have important effects on system optimization.

The established PID algorithms show that while the frequency tries to quickly reach 55Hz, it approaches the target water temperature at the same speed. Therefore, the PID circuit reduces the frequency at a similar rate and slows down the compressor. Then, it returns to an increasing trend again. Therefore, the fluctuations in classic PID charts start a little early. This issue needs to be examined further in future studies.

One of the performance determining parameters of heat pump systems is COP values. More detailed studies can be carried out through experiments to calculate this value.

The next studies will be about studying full system parameters such as temperature, pressure and flow. Also this control procedure will be applied to dıfferent types of heat pumps such as air to water.

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