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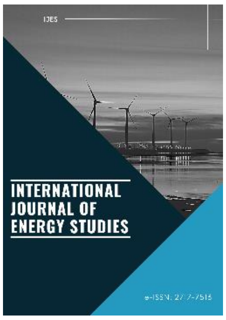

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Investigation of the three-phase heat pump drying system's impact on power quality of the electrical grid

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Highlights

- The impact of a heat pump dryer on the electrical grid was investigated.
- Issues in three-phase heat pump drying (HPD) systems were identified and recommendations were made for enhanced sustainability and clean energy.
- Implementation of soft starters is imperative for compressors to effectively mitigate the adverse effects caused by in-rush current.
- A balanced distribution of single-phase devices within three-phase HPD systems is required to reduce current imbalances and prevent energy losses.
- Individual or group compensation is necessary to enhance the power quality of HPD systems.

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ABSTRACT

In this study, the impact of an experimentally designed Heat Pump Drying (HPD) system on the electrical grid was evaluated. For this purpose, eggplant slices were dried in the experimental HPD system under controlled humidity and temperature conditions. In the HPD system, condenser of heat pump and an external electric heater with a power rating of 550 W were placed at the inlet of the drying chamber. A controller was used in the drying chamber to maintain a constant air temperature of 35 °C and humidity levels between 20% and 40%. This controller effectively activated the compressor and the external heater individually or in groups to achieve the desired drying conditions. Throughout the experiment, a Fluke 435 II power analyzer was employed to examine the impact of the HPD system on the electrical grid. Parameters such as active power, reactive power, power factor, displacement power factor, harmonics, imbalances, and energy consumption were recorded for the system. The obtained data were analyzed in accordance with energy quality standards, and issues were identified. Suggestions for improving the energy quality of the system were subsequently proposed.

Keywords: Heat pump drying, Humidity and temperature control, Energy quality, Harmonics, Reactive power

1. INTRODUCTION

The food drying industry plays a vital role in extending the shelf life of products, reducing storage costs, and minimizing food waste. Various drying techniques, such as solar drying, microwave drying, freeze-drying, spray drying, and convective-heat pump drying, are widely employed for food drying. Among these techniques, HPD has gained prominence in recent years due to its low energy consumption and environmentally friendly characteristics [1]. In contrast to traditional hot-air dryers, HPD systems operate with lower energy consumption and do not emit harmful gases into the atmosphere. Furthermore, research has shown that agricultural products dried with HPD systems exhibit improved color and aroma quality [2–4]. Consequently, the use of heat pumps for food drying is on the rise, alongside their applications in various climate control systems. In heat pump drying systems, the control of drying chamber air temperature significantly affects product characteristics [5]. Consequently, drying time, device operating times, and energy consumption values vary accordingly. However, in addition to energy efficiency, the impact of this technology on the electrical grid should be considered. Energy quality in the electrical grid is critical across various sectors, from industrial processes to residential use. The stability and reliability of the electrical grid are fundamental factors of energy quality. Therefore, the effect of heat pump drying systems on energy quality is gaining increasing importance with the wider adoption of these systems. While studies in the literature have examined the impact of heat pump drying systems on electrical grids and energy quality, a comprehensive study on this topic is lacking. One of these studies Akmal et al. [6] investigated the effect of a laboratory-operated heat pump on a low-voltage (LV) grid. Akmal et al. [6] noted that in many cases, the voltage dropped below 90% of its nominal value, and transient voltage drops exceeded legal limits even when soft starters were used. In the study by Navarro-Espinosa and Mancarella [7], the impact of heat pump systems on LV distribution networks was evaluated. It was observed that when a two-phase soft starter was used, the heat pump system caused damage to the three-phase compressor motor, which is a main component of the drying system. Therefore, precautions should be taken to prevent negative effects on the grid, and solutions that do not harm system components are important [8].

This study aims to comprehensively examine the impact of heat pump drying systems, which are increasingly used to produce value-added products, on power quality of the electrical grid. It also provides suggestions on how to manage these impacts. Additionally, this study explains the concept of energy quality and discusses important issues such as energy fluctuations, harmonic distortions, and power problems, along with potential solutions. It is expected that this study will serve as a valuable resource for both academic researchers and industry professionals.

2. MATERIALS AND METHODS

2.1. Introduction of the Experimental Heat Pump Drying System

In the HPD system shown in Figure 1, a fan circulates air through a closed duct system to facilitate the drying process. The air, before entering the drying chamber, passes through an internal condenser where it gets heated. This heating occurs by transferring heat from the refrigerant flow. Simultaneously, the refrigerant itself, which supplies the heat to warm the drying air, goes through a process of condensation. It is then directed to the evaporator by way of a thermostatic expansion valve, which reduces its pressure and temperature.

After being heated and having its relative humidity reduced, the drying air enters the drying chamber, where it interacts with the product. Through heat and mass transfer, the air absorbs moisture from the product, resulting in high relative humidity. Following this, the moisture-laden drying air is directed over the evaporator. As it passes over the evaporator, moisture within the air condenses on the evaporator tubes. These tubes maintain a temperature below the dew point temperature, facilitating the removal of moisture from the drying air. This process readies the air for reuse in the drying cycle.

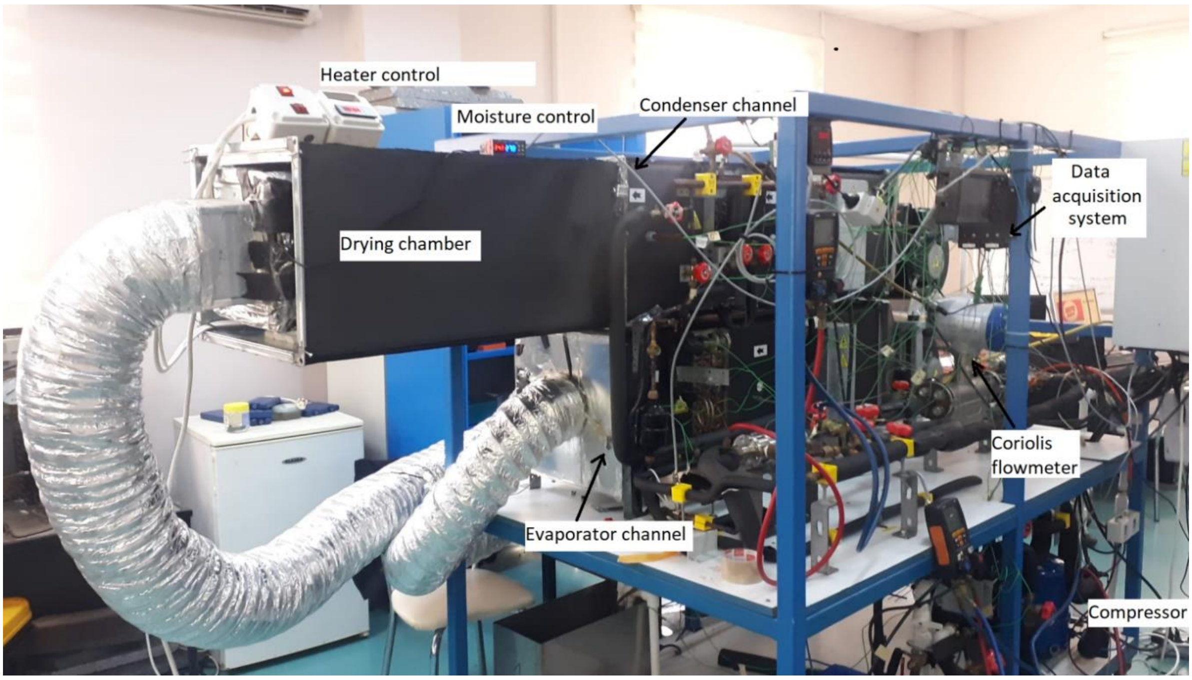

Figure 1. The heat pump drying system

Throughout this process, the drying air experiences a slight cooling effect. To counteract this cooling, the condenser reheats the cooled drying air before it is reintroduced into the drying chamber. Meanwhile, the refrigerant circulates within the evaporator tubes, where it absorbs heat from the drying air, undergoes evaporation, and is subsequently drawn in by the compressor before eventually reaching the condenser. Table 1 and Table 2 provide detailed specifications for the various components of the system. Notably, the compressor, heating resistor, and two fan motors consume 880 W, 550 W, and 800 W of power, respectively. However, it's worth mentioning that the utilization of speed controllers for the fan motors effectively reduces their power consumption. The three-phase compressor utilized in the system operates on direct drive and depending on the refrigerant flow cycle it might sometimes draw less current and power rate might be less 880W. In addition to the primary components mentioned, the system incorporates controllers that facilitate sensor readings and contactor activation, contributing to overall power and energy consumption. More comprehensive measurement results for all system components will be discussed in subsequent sections. Figure 2 illustrates the pathways taken by the refrigerant and airflow within the heat pump drying system.

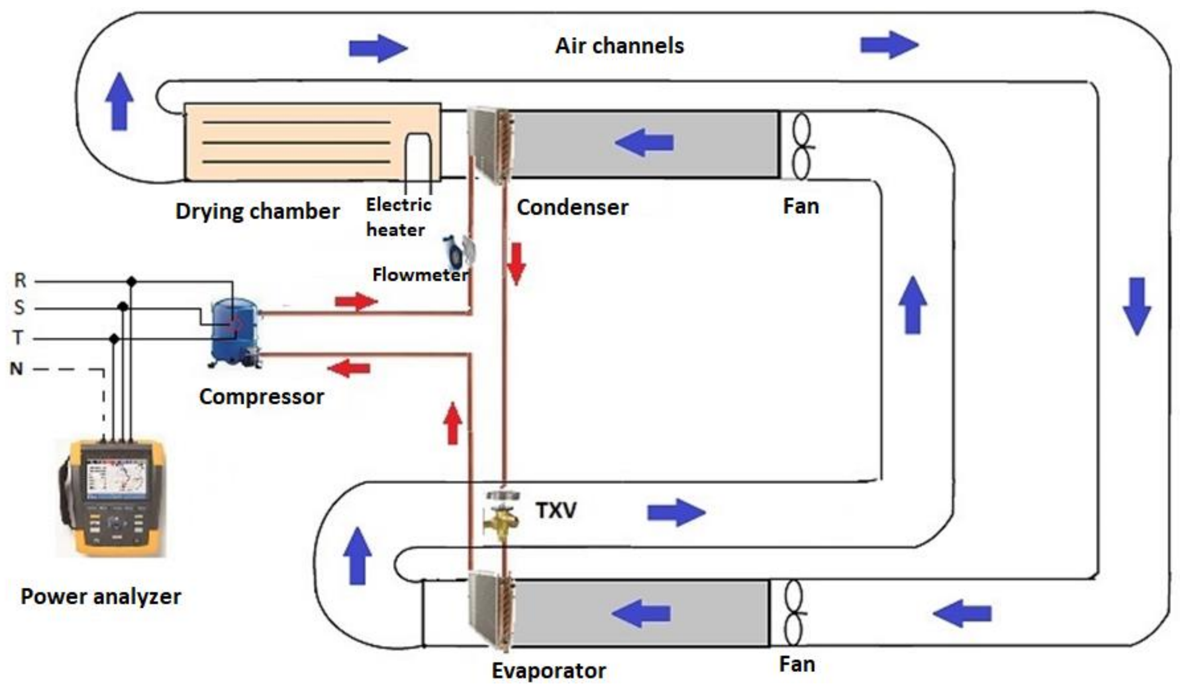

Figure 2. Paths followed by refrigerant flow and airflow in the HPD system

Table 1. Specifications of the HPD system equipments

Equipment	Type	Specifications
Condenser	Air-cooled	9.9 m², Overall heat transfer rate: 52 W m^{-2} K^{-1}
Compressor	Hermetic, Variable Frequency	Compressor power: 2 HP, Swept volume (cm^3/rev) : 38.12, 3-phase, Max 6A, 380-400 V, 50 Hz, 2900 rpm,
TXV	External Balanced Variable Orifice	Danfoss 068Z3386 TEN 2
Evaporator#1	Air-cooled	6.6 m², Overall heat transfer rate: 48 W m^{-2} K^{-1}
Fan	Radial	1250 RPM, 2200 M3 /h, 400 W
Electric Heater	Tube-Type Resistance	550 W

Table 2. Specifications of measurement instruments used in the system

Measured Parameter	Measurement Device	Measurement Range	Accuracy
Temperature	K-type Thermocouple	-100 – 1370 ºC	± %0,8
Pressure	Electronic Manifold	-1 – 60 bar	± %0,5
Airflow Velocity	Anemometer	0 – 30 m s^{-1}	±%2
Refrigerant Flow Rate	Coriolis Mass Flow Meter	0 – 5 kg s^{-1}	±%0,1

The heat pump compressor is activated through relative humidity control. A humidity sensor placed inside the drying chamber measures the humidity level, and when the relative humidity reaches the set value, the heat pump compressor automatically turns off. The airflow temperature passing through the drying chamber is maintained at a constant 35 °C. In cases where the heat pump is in the off position or the airflow temperature inside the chamber falls below the set value, the electric heater is activated, ensuring that the airflow temperature within the chamber remains constant at 35 °C. Table 3 provides details of the parameters used during the experiments. The COP heating of the HPD system was calculated as 3.8 under the given experimental conditions.

Table 3. Experimental Conditions

Parameter	Value
Chamber Internal Temperature (°C)	35
Airflow Velocity (m/s)	4,5
Product	Sliced Belt Eggplant
Ambient Temperature (°C)	26
Ambient Relative Humidity (%)	53
Refrigerant	R134a

2.2. Measurement Method for the Detection of Energy Quality Issues

Energy quality is a concept related to the stability, reliability, and cleanliness of electrical energy. This concept encompasses voltage fluctuations, harmonic distortions, frequency variations, imbalances, and other power issues within the electrical grid [9,10]. Good energy quality ensures the proper functioning of electrical devices and efficient energy consumption. In cases of low energy quality, apart from equipment that contaminates the grid, other electrical devices can suffer damage or reduced efficiency. Therefore, energy quality is a significant factor for the reliability and sustainability of electrical grids, and efforts should be made to minimize the effects that degrade the quality of electrical energy [11]. Energy quality can degrade due to several factors. These contributing factors include load fluctuations resulting from devices connecting or disconnecting from the grid, equipment causing voltage fluctuations and power losses due to high current demands when activated, generators of harmonics that disrupt waveforms and lead to energy losses and damage to sensitive electronic devices, as well as low power factor equipment that raises reactive power and results in energy losses. Effective grid management and energy quality enhancement are of paramount importance for industries, businesses, and residential users alike. A well-designed and properly controlled heat pump drying system should not pose energy quality issues. However, in the case of large-scale industrial systems or systems that are poorly designed and maintained, energy quality problems can arise. Therefore, it is imperative to ensure the correct design, installation, and regular maintenance of electrical equipment. In this context, an experimentally designed heat pump drying system's impact on the grid and its electrical characteristics were assessed using a Fluke 435 II power analyzer [12]. This device was integrated into a three-phase system, as illustrated in Figure 3a. Both current and voltage probes of the device were connected to all three phases and the neutral line, as depicted in Figure 3b. Over time, various parameters such as current, voltage, frequency, active power, reactive power, apparent power, energy consumption, power factor, displacement power factor, harmonics, and imbalance were continuously recorded at one-second intervals.

a) b)

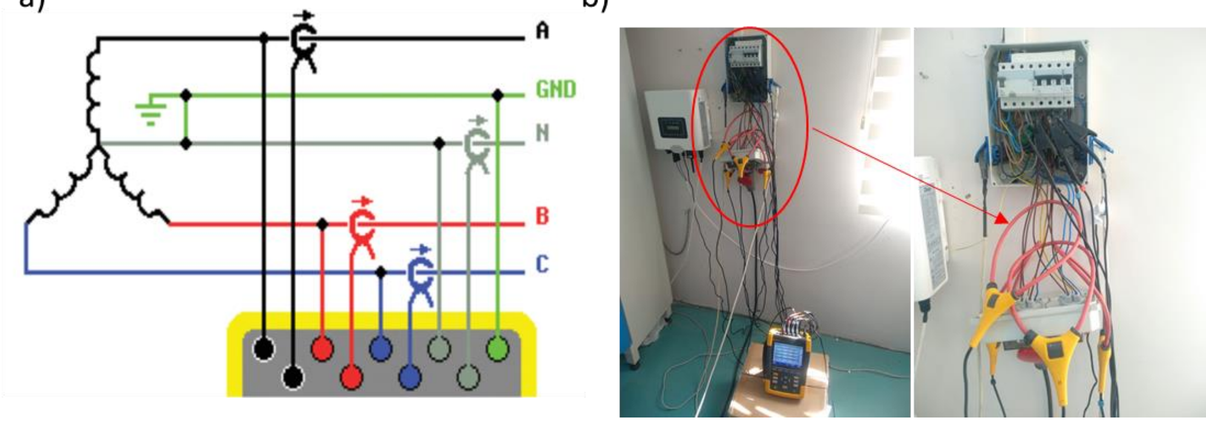

Figure 3. a) connection diagram of the probes to the three-phase system b) real image of the installation of the measurement setup into the system

2.3. Measurement Parameters and Evaluation Related to Electrical Energy and the Grid

In this section, we present data pertaining to the afore mentioned parameters in the form of time-dependent graphs, aiming to enhance interpretability. Data points related to these parameters have been overlaid on the same graphs for comparative analysis. First of all, Figure 4 shows the power factor values, which exhibit changes in tandem with the active and reactive power consumption of the system, along with their associated harmonic values. Active power, quantified in watts (W), signifies the actual power consumed by the system and represents the energy that effectively performs work. It holds significant importance in electrical calculations, distribution systems, and the assessment of energy efficiency. Reactive power characterizes the power within an electrical circuit arising from the phase difference between voltage and current waveforms. Reactive power is a form of non-productive power, and it is undesirable as it represents energy drawn from the grid without being converted into a usable form of work. It is associated with inductive loads, such as motors, inductors, transformers, or capacitive loads like capacitors, and its unit of measurement is Volt-Amps Reactive (VAR). To mitigate the effects of reactive power, various compensation strategies can be employed, including individual, group, or centralized compensations [13]. Reactive power measurement is typically not carried out in residential applications, which is why the reactive energy consumed by devices or power factors are not particularly cared by consumers. However, for minimizing their impact on the grid and avoiding penalties in commercial enterprises, individual compensation for heat pump drying systems is important.

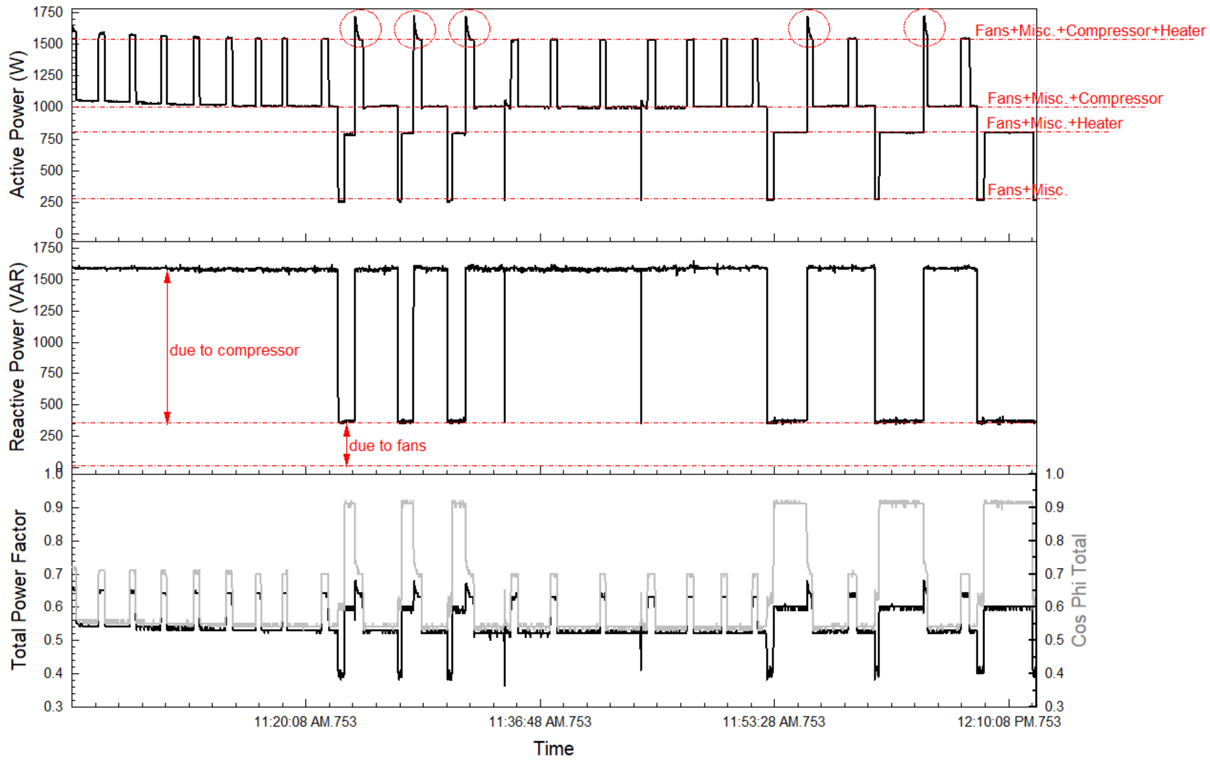

Figure 4. Active power, reactive power, total power factor, and displacement power factor values drawn by the HPD system.

The power factor is a crucial metric representing the efficiency of an electrical circuit in utilizing electrical energy. It quantifies the ratio of active power (P) to apparent power (S), falling within the range of 0 to 1. A power factor closer to 1 signifies more efficient energy utilization. Mathematically, the power factor is determined by calculating the cosine of the angle between apparent power and active power [13]. A power factor nearing 1 indicates that active power is nearly equal to apparent power, signifying minimal harmonic distortion in the system. It's important to note that while a power factor of 1 corresponds to an absence of phase difference between current and voltage, it doesn't guarantee that the power factor is precisely 1. This is due to the potential influence of current harmonics from harmonic sources on the source current that contributes to apparent power. The calculation of the power factor involves the combination of two components: the displacement power factor, arising from the phase difference between current and voltage, and the distortion power factor, resulting from the presence of total harmonics [12,14]. Consequently, upon analyzing the obtained results, a notable distinction between the power factor and the displacement power factor (cos φ) becomes evident. When analyzing the data in Figure 4, it can be observed that the fan motors and controllers providing the air flow draw around 265 W of power. With the addition of the heater, the power consumption increases to approximately 800

W, and when the compressor is added, it reaches around 1000 W. As a result of measurements with all elements of the HPD system in operation, it was determined that the total power drawn from the grid is approximately 1530 W, as shown in Figure 4. When examining the graph, it is observed that the heater and the compressor operate at different times based on the data from the humidity and temperature sensors. The circular sections in the active power curve represent the load created on the grid when the compressor is activated. Such loads cause fluctuations in the grid and degrade energy quality. In the experimentally designed HPD system, the compressor is directly driven, causing unwanted conditions in the grid. Figure 8 shows that the peak current for the compressor is 3.66 A and it stabilizes at 2.69 A when it becomes steady-state. The measurement results indicate that the starting current drawn from each phase is 1 A, but the maximum value is 2.7 A. Driving the compressor with a soft starter can eliminate such sudden loads. Nonetheless, it is crucial to consider the study conducted by Kudelina et al. [8] in 2021, which underscores the importance of selecting a suitable soft starter for three-phase systems and the potential harm to the compressor motor when employing a two-phase soft starter.

The heater briefly goes out of operation when the compressor is activated. This indicates that, in addition to the compressor's moisture removal function; it also raises the temperature inside the drying cabinet. If the temperature drops below 35 °C, the resistive heater turns on and off to maintain the cabinet temperature at 35 °C. The compressor's deactivation is not very frequent. The on-off periods of the compressor are clearly visible in the reactive power curve. There is no significant change in the reactive power curve during the on-off periods of the heater as seen in the active power curve. The reactive power curve takes shape with the activation and deactivation of the compressor. From this curve, it can be observed that when both the compressor and fan motors are active, the reactive power drawn is 1600 VAR, and when only the fan motors are active, it is 360 VAR. This indicates that both the compressor and fan motors are not individually compensated. When the power values drawn are integrated over time, the total energy consumed by the HPD system during the operating time (69 minutes, 11:03-12:12) is found to be 1181 Wh, 1529 VARh, and 2121 VAh for active, reactive, and apparent energy, respectively. It is evident that the active power, which is the actual working power, is almost twice the value drawn from the grid, indicating unnecessary pollution of the grid and energy losses. Systems should be designed to consume as little reactive energy as possible, thus ensuring that the energy used for work and the energy drawn from the system are close to each other. In terms of energy consumption, the HPD system does not appear to be efficient, and improvements can be made through compensation in this regard. The HPD system consumes 1600 VAR of reactive power in addition to its 1530 W active power usage, which significantly reduces the power factor. When examining Figure 4 closely, it can be observed that the moments when the compressor is deactivated correspond to the moments when cos φ is at its highest. However, the presence of harmonics generated by the fan motor drives leads to the largest differences between cos φ and the power factor. During these moments, a significant portion of the power drawn from the system is consumed by the fans, and the fan motor speed controllers introduce harmonics into the grid.

Harmonics typically originate from nonlinear loads such as switching power sources, computers, televisions, variable-speed motor drives, uninterruptible power supplies, lighting fixtures with electronic ballasts, and similar devices. These harmonic components can lead to various issues, including overheating of transformers, conductors, and motors, malfunction of electronic circuits, unexpected tripping of circuit breakers (residual current protection relays and fuses), and damage to capacitors due to overvoltage [15]. Some harmonic orders cause current to flow through the neutral line in three-phase systems, resulting in energy losses. IEEE (519-1992) defines maximum permissible limits for voltage and current distortion [16]. For voltage (THDv), this value is typically set at 5%, while for current (THDa), it is commonly accepted as 20%. The harmonic values provided by the HPD system to the grid have been measured and are depicted in Figure 5 and Figure 6. Figure 5 represents a histogram graph of total harmonic distortions, showing average values of 1.72%, 1.84%, and 1.86% for phases L1, L2, and L3, respectively, in terms of voltage, and 30%, 27%, and 17% for current harmonics. The lower harmonic values in the third phase can be attributed to the connection of fan motors to the first and second phases, with no external device connected to the third phase apart from the controller and compressor. While voltage harmonics remain below the specified limits, current harmonics for the first and second phases exceed the permissible levels. To mitigate this issue, it is recommended to either drive the fans directly or control them using a low harmonic generating driver.

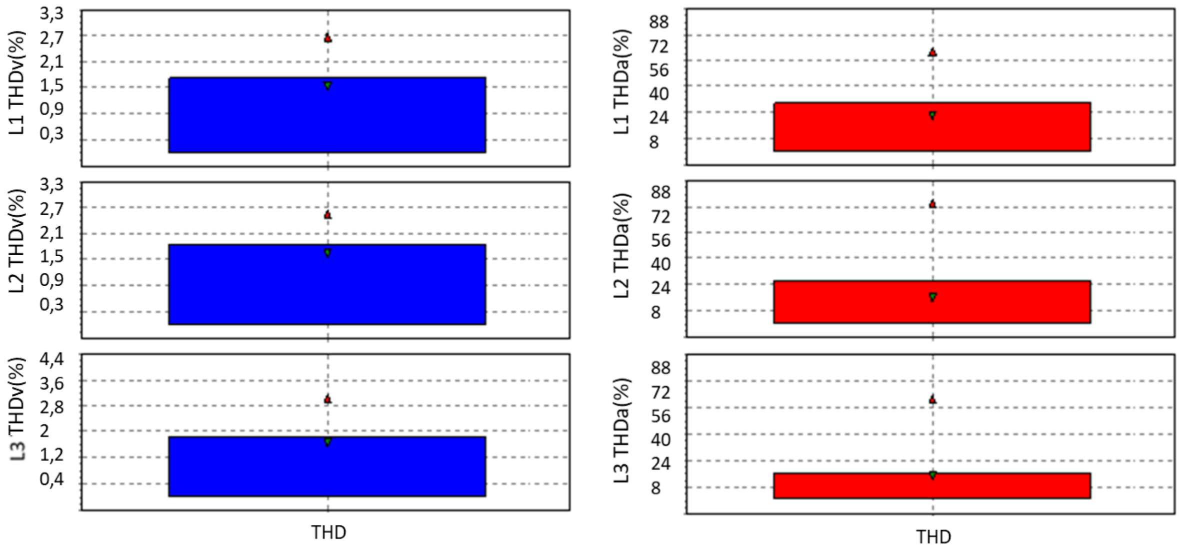

Figure 5. Histogram graph showing voltage and current harmonics for each phase.

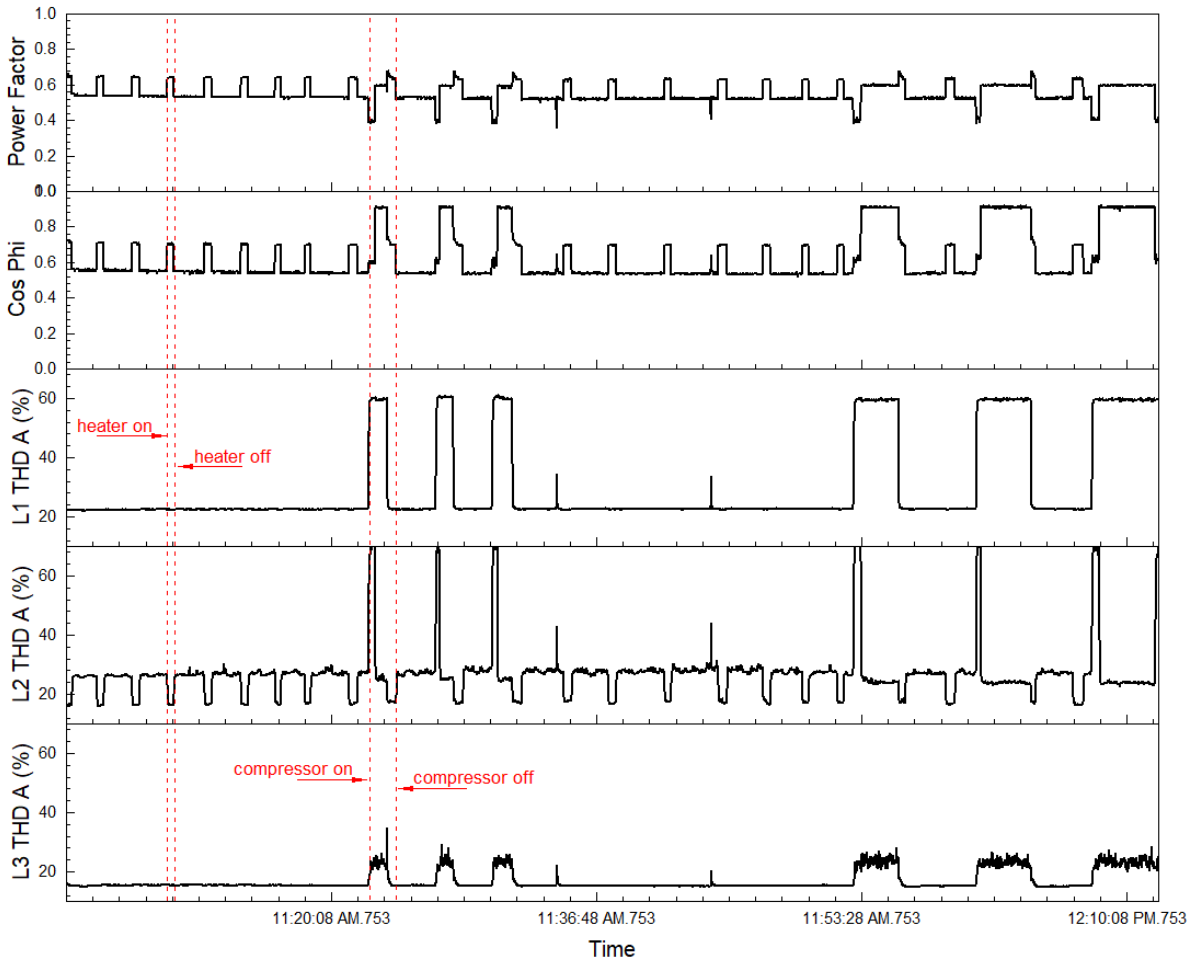

Figure 6. A graph illustrating the impact of harmonics on power factor.

Figure 6 illustrates that the disconnection of the high-power compressor results in a decrease in the main current and an increase in harmonics in each phase. While the disconnection of the high-power compressor significantly increases the displacement power factor (cos φ), high harmonic values substantially reduce the power factor. This indicates the necessity of power factor correction devices in each equipment used. Another issue related to energy quality is current and voltage imbalances. Current imbalance refers to the difference in electrical current between loads connected to a three-phase electrical system. This imbalance can occur due to uneven distribution of loads or events such as a phase line failure. Current imbalance can adversely affect the performance of electrical systems and damage electrical devices.

According to generally accepted standards, current imbalance ideally should be zero. These standards are defined by international norms such as IEC 61000-2-2 and IEEE Std 519-2014. In practical applications, it is recommended that the current imbalance ratio does not exceed 10%. Additionally, in Turkey, there is a standard called TS EN 50160 used to determine and regulate the voltage characteristics of electrical power systems [17]. This standard covers common electrical network parameters such as voltage values, frequency fluctuations, harmonics, voltage imbalance, transient voltage changes, voltage fluctuations, and flicker. According to TS EN 50160 standard, while the ideal limit for voltage imbalance is considered to be zero, in practice, this ratio should not exceed 2%. These standards are critically important for ensuring the reliability and stability of electrical power systems and aim to control issues such as current and voltage imbalances. Measurements were conducted to detect imbalances in the HPD system, and they are presented in Figures 7 and 8. Figure 7 illustrates the time-dependent variation of voltage values for all three phases, providing information about voltage imbalances that result from these values. It also displays the voltage value on the neutral line. Imbalances are determined by dividing the instantaneous values of all three phases by their averages and then taking the ratio of the phase that deviates the most from the average at that moment [12]. When examining the voltage imbalance curve, it is observed that this value ranges between 0.48% and 0.64%, which is below the regulatory limit of 2%. Ideally, the voltage on the neutral line should be zero, but due to unbalanced loads, it fluctuates between 1.2 V and 1.7 V. When multiplied by the neutral current, as we will see in the next step, this value represents the energy loss incurred on the neutral line.

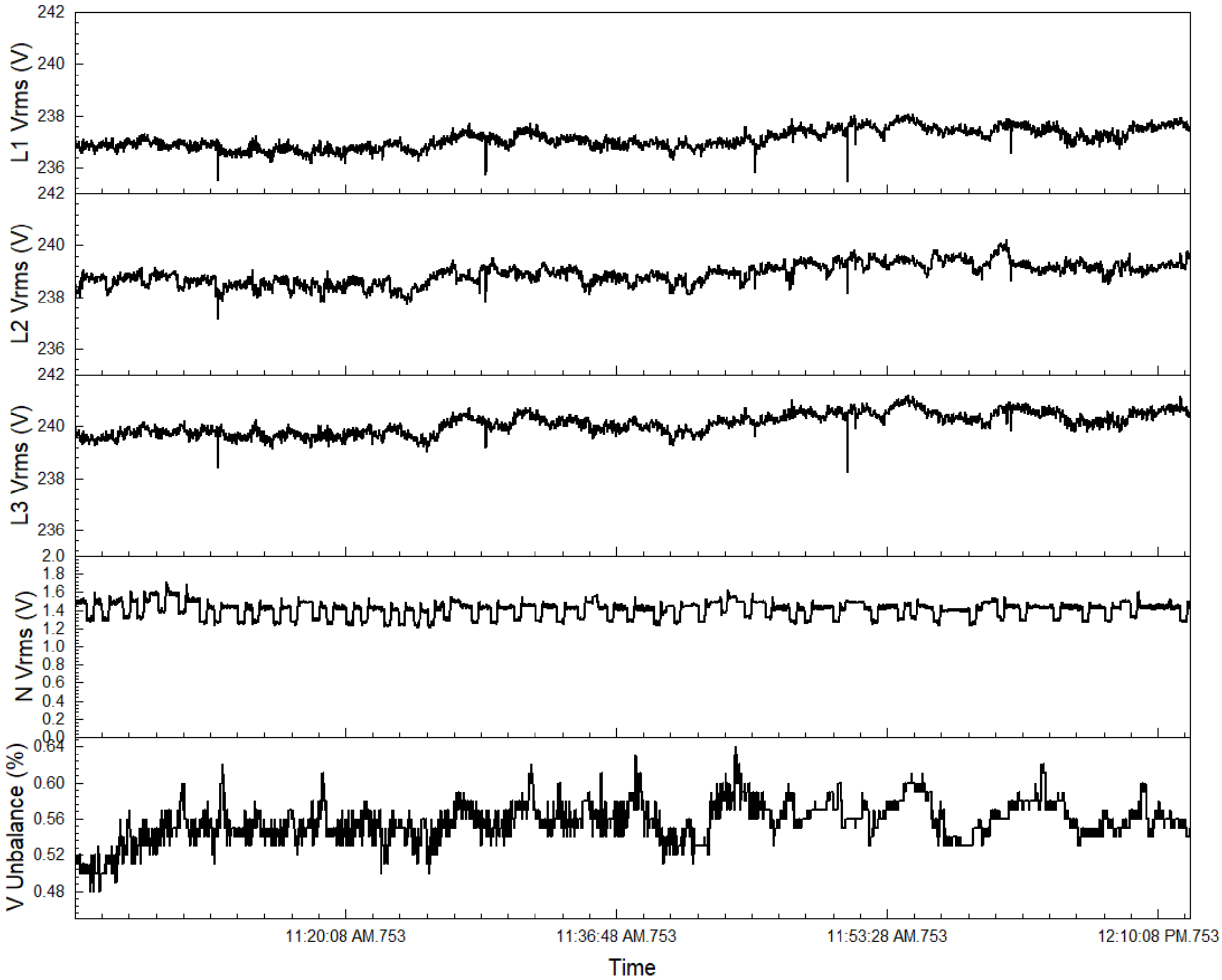

Figure 7. Time-dependent voltage values for all three phases and the neutral line, along with the voltage imbalance in the system.

In Figure 8, it can be observed that the fan motors are connected to the first and second phases, while the heating resistance is connected to the second phase (since the neutral line's energy consumption is close to zero in the third phase). In-rush currents related to the compressor are effective in all three phases. Filtering the in-rush current is crucial for all electrical grids, particularly PV systems, and can be achieved through the use of soft starters [8,18]. In three-phase systems, it is desired that the load distribution is the same; otherwise, the vector sum of phase currents will not be zero, and the resulting current will flow through the neutral line. As Figure 8 illustrates, there is a significant difference in the currents drawn between phases in the HPD system. This difference leads to both current imbalance and current flow through the neutral line ranging from 1.1 A to 3.3 A. This current flow causes heating and energy loss in the neutral line. Examining the current imbalance curve, it can be observed that this value ranges between 8% and 80%, and most of the time, it exceeds the 20% limit set by regulations. When the graph is carefully analyzed, it becomes apparent that one of the main factors contributing to this imbalance is the activation of the heating resistance, and the other is the deactivation of the three-phase compressor. When the three-phase compressor is operational, it draws high current from each phase, which averages out the current drawn from the phases, thereby reducing the imbalance ratio. However, since the heating resistance is connected to a single phase, when it is activated, it increases the imbalance ratio rather than reducing it, unlike the compressor. When designing three-phase systems, calculations should be made for the integration of single-phase devices into the system to distribute them in a balanced manner.

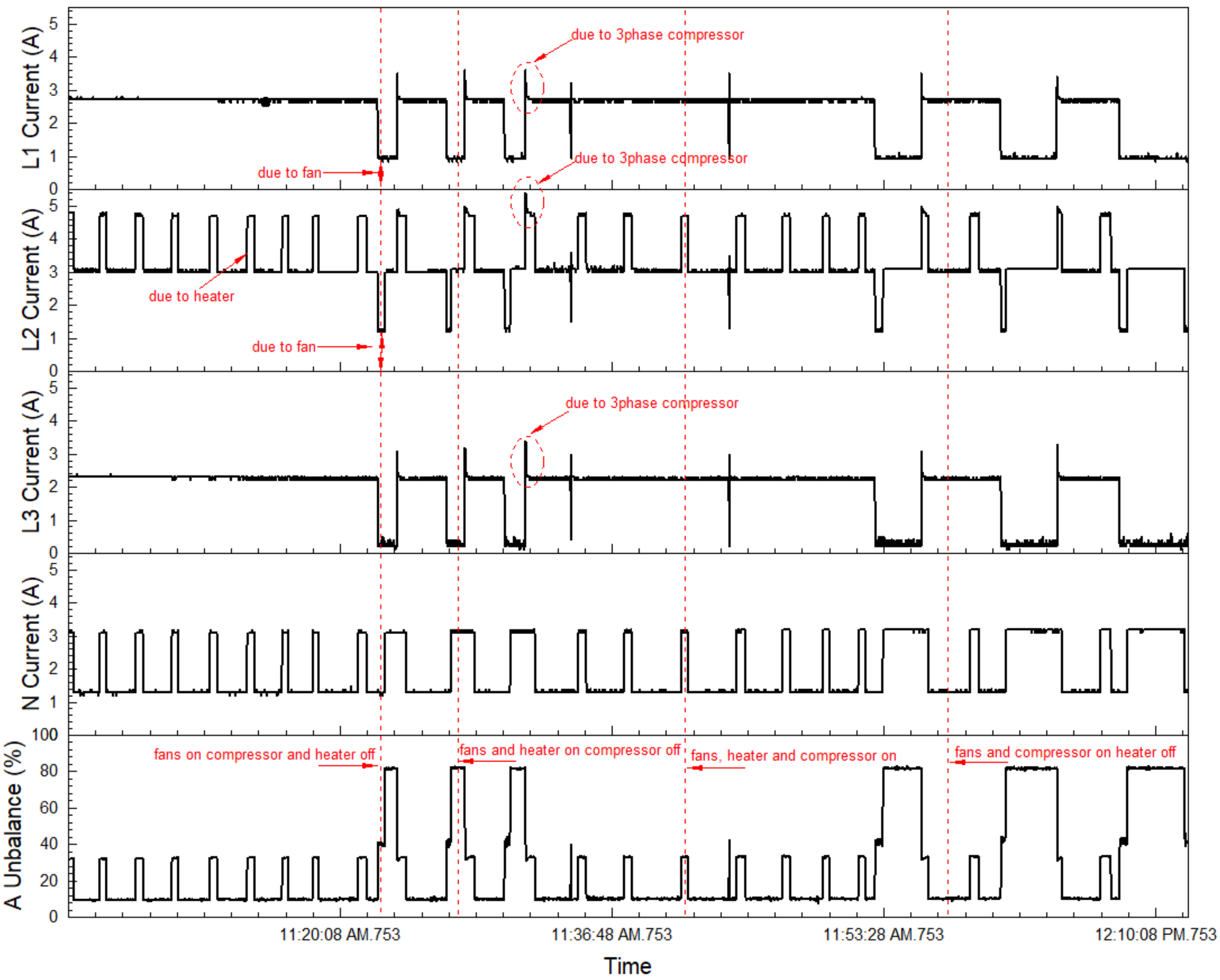

Figure 8. Time-dependent current for each of the three phases and the neutral line, along with the graph showing current imbalance in the system.

3. RESULTS AND RECOMMENDATIONS

This study provides significant insights into the impact of HPD systems on power quality of the grid. The low power factors of the system's fan and compressor units result in supplying unnecessary reactive power to the electrical grid, negatively affecting power quality. In the case of the HPD system's 1530 W active power consumption, there is a reactive power consumption of around 1600 VAR. Over the course of the study (69 minutes, from 11:03 to 12:12), the HPD system consumed 1181 Wh of active energy, 1529 VARh of reactive energy, and 2121 VAh of apparent energy. It is evident that almost twice the amount of active power, which is the useful power, is drawn from the grid, contributing to grid pollution and energy losses. Additionally, this situation leads to harmonic generation and adverse effects on other devices. Current imbalances were found to be between 8% and 80%, often exceeding the 20% limit set by regulations. The detected current imbalance in three-phase systems leads to unnecessary current flow through the neutral line, resulting in energy losses. The problem of high current draw during the initial start-up of the compressor also causes momentary high demands on the grid. These findings point to important steps that can be taken to mitigate the impact of HPD systems on power quality of the grid. Integration of the device after power factor correction can reduce the amount of reactive power, thereby enhancing power quality. Additionally, direct control of fans or the use of low-harmonic-producing drives can minimize harmonic distortions on the grid. Distributing single-phase equipment evenly in three-phase systems can address the current imbalance issue. Finally, integrating an appropriate system to softly start the compressor can resolve the issue of high current draw during initial start-up. Implementing these recommendations can make HPD systems a more sustainable option in terms of power quality and contribute to grid stability, providing a reliable source of electricity for industrial processes and residential users. While the identified issues are specific to the HPD system in use, the general findings and solutions are applicable to various electrical equipment.

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Sunay Türkdoğan: Orginized the work done, analyzed the results and wrote the manuscript.

Mehmet Direk: Performed the experiments and wrote the manuscript.

Cüneyt Tunçkal: Analyzed the results and wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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