POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Power quality evaluation of a high-power residential load: An experimental study

Yüksek güçlü bir konut yükünün güç kalitesi değerlendirmesi: Deneysel bir çalışma

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To cite to this article: Bozkurt A. and Yüzer E. Ö., "Power Quality Evaluation of a High-Power Residential Load: An Experimental Study", ***Journal of Polytechnic***, *(*): *, (*).

Bu makaleye şu şekilde atıfta bulunabilirsiniz: Bozkurt A. ve Yüzer E. Ö., "Yüksek Güçlü Bir Konut Yükünün Güç Kalitesi Değerlendirmesi: Deneysel Bir Çalışma", ***Politeknik Dergisi***, *(*): *, (*).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.1636446

Power Quality Evaluation of a High-Power Residential Load: An Experimental Study

Highlights

- *Residential load*
- *Washing machine*
- *Harmonic evaluation*
- *Non-linear loads*
- *Power quality*

Graphical Abstract

In this study, the harmonic effects of three different types of washing machines with high power consumption within residential electrical loads were investigated at different washing temperatures.

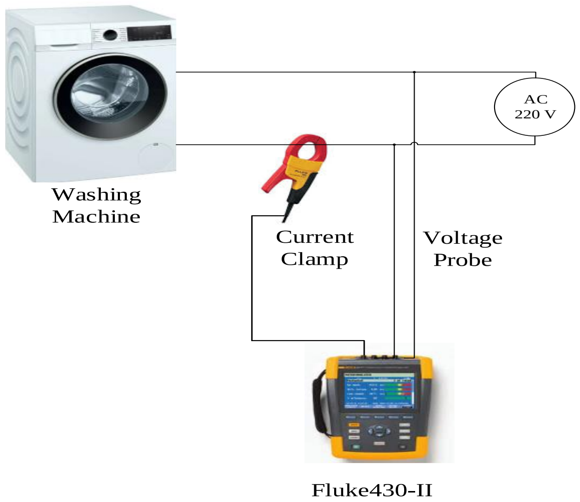

Figure. Measurement setup

Aim

The main objective of this study is to investigate the harmonic characteristics of washing machines under different operating conditions and their impact on power quality terms.

Design & Methodology

In this study, three different types of washing machines manufactured at different times (conventional, dynamic resistor-based, and inverter-based) were examined. The behavior of the washing machines was analyzed at commonly used washing temperatures of 30°C, 40°C, and 60°C throughout the washing program, and harmonic analyses were performed.

Originality

In this study, a comprehensive power quality analysis was conducted based on the investigation of the electrical behavior of washing machines operating at various power levels, temperatures, and programs in a real working environment.

Findings

When examining the THD_I variations of washing machines of types A, B, and C, the highest value was measured during the 40°C washing program. It was observed that as the washing temperature increased, the power factor and cos(φ) values also increased.

Conclusion

In this study, it was observed that as the washing temperature changed, the magnitudes of individual harmonic components varied, and as the washing temperature increased, the power factor and cos(ϕ) values also increased.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Power Quality Evaluation of a High-Power Residential Load: An Experimental

Araştırma Makalesi / Research Article

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(Geliş/Received : 09.02.2025 ; Kabul/Accepted : 16.04.2025 ; Erken Görünüm/Early View : 27.04.2025)

ABSTRACT

The global energy demand is increasing day by day due to factors such as industrialization, technological advancements, and population growth. In order to meet this growing demand, merely exploring new energy sources is not sufficient; issues such as energy efficiency and power quality are also gaining increasing importance. Harmonics, one of the most critical parameters of power quality, refer to the distortions caused by electrical devices in power systems and can directly affect the efficiency and safety of energy systems. Household appliances such as air conditioners, computers, televisions, washing machines, and dishwashers are among the major contributors to harmonic pollution. In this study, the harmonic effects of three different washing machines manufactured in different years were examined. The primary objective of this study is to analyze the impact of washing machines on power quality at different washing temperatures and to compare their harmonic generation levels. Within the scope of the study, harmonics generated during washing cycles at different temperatures (30°C, 60°C, and 90°C) were analyzed in detail for each washing machine. Measurements were conducted using a Fluke 435 power quality analyzer, and the obtained data were processed using MATLAB software for detailed analysis. The measurements revealed that the harmonic levels of washing machines vary depending on the model year, motor type, and washing temperature. It was observed that older models produced lower harmonic levels, whereas modern inverter motor washing machines exhibited higher harmonic levels. Additionally, it was determined that harmonic distortion changes as the washing temperature increases. The results highlight the significance of design modifications aimed at reducing the harmonic generation of electrical household appliances and the importance of techniques that enhance energy efficiency. This study aims to contribute to raising awareness among consumers and engineers regarding power quality and harmonic management, thereby guiding the development of more efficient and environmentally friendly electrical devices.

Keywords: Residential load, washing machine, harmonic evaluation, non-linear loads, power quality.

Yüksek Güçlü Bir Konut Yükünün Güç Kalitesi Değerlendirmesi: Deneysel Bir Çalışma

ÖZ

Dünyadaki enerji talebi, sanayileşme, teknolojik gelişmeler ve nüfus artışı gibi faktörler nedeniyle her geçen gün artmaktadır. Bu artan talebi karşılamak için yalnızca yeni enerji kaynaklarının araştırılması yeterli olmamakta, aynı zamanda enerji verimliliği ve güç kalitesi gibi konular da giderek önem kazanmaktadır. Güç kalitesinin en kritik parametrelerinden biri olan harmonikler, elektrikli cihazların enerji sistemlerinde oluşturduğu bozulmaları ifade eder ve enerji sisteminin verimli ve güvenli çalışmasını doğrudan etkileyebilir. Evlerde yaygın olarak kullanılan klima, bilgisayar, televizyon, çamaşır makinesi ve bulaşık makinesi gibi cihazlar da harmonik kirliliğine katkıda bulunan önemli kaynaklar arasında yer almaktadır. Bu çalışmada, farklı yıllarda üretilmiş üç farklı çamaşır makinesinin harmonik etkileri incelenmiştir. Çalışmanın temel amacı, çamaşır makinelerinin farklı yıkama sıcaklıklarında güç kalitesi üzerindeki etkilerini ortaya koyarak harmonik üretim seviyelerini karşılaştırmaktır. Çalışma kapsamında, her bir çamaşır makinesi için farklı sıcaklıklarda (30°C, 60°C ve 90°C) gerçekleştirilen yıkama döngülerinde oluşan harmonikler detaylı olarak analiz edilmiştir. Ölçümler, Fluke 435 güç kalitesi analizörü kullanılarak alınmış ve elde edilen veriler MATLAB yazılımı yardımıyla işlenerek detaylı analizler gerçekleştirilmiştir. Yapılan ölçümler sonucunda, çamaşır makinelerinin harmonik seviyelerinin model yılına, motor tipine ve yıkama sıcaklığına bağlı olarak değiştiği gözlemlenmiştir. Eski model makinelerin daha düşük harmonik ürettiği, ancak modern inverter motorlu çamaşır makinelerinin daha yüksek harmonik seviyelerine sahip olduğu tespit edilmiştir. Ayrıca, yıkama sıcaklığı arttıkça harmonik bozulmanın da değiştiği belirlenmiştir. Elde edilen sonuçlar, elektrikli ev aletlerinin harmonik üretimini azaltmaya yönelik tasarım değişikliklerinin ve enerji verimliliğini artıran tekniklerin önemini vurgulamaktadır. Bu çalışma, tüketicilerin ve mühendislerin güç kalitesi ve harmonik yönetimi konusunda bilinçlenmesine katkı sağlayarak daha verimli ve çevre dostu elektrikli cihazların geliştirilmesine ışık tutmayı amaçlamaktadır.

Anahtar Kelimeler: Konut yükü, çamaşır makinesi, harmonik değerlendirme, doğrusal olmayan yükler, güç kalitesi.

1. INTRODUCTION

1.1. Motivation

The number of people without access to electricity is decreasing every day, and with the increasing number of electricity-powered devices in developing countries, power quality issues arise [1,2]. Due to various factors affecting the power quality of connected loads, deviations from ideal sinusoidal waveforms occur, making it impractical to maintain a perfect sinusoidal waveform in real-world applications [3]. Changes in

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power quality not only cause damage to devices or reduce their lifespan but also increase consumers' energy costs. Furthermore, it gives rise to hazardous situations for electrical devices such as voltage drops/surges, momentary interruptions, noise, and the formation of harmonics. Therefore, power quality is one of the most important requirements for the healthy operation and longevity of household electrical appliances [4-6].

Today, most household electrical appliances require good power quality throughout their operation. According to the EN 50160 standard, the user has the right to receive high power quality energy from the grid [7]. The EN 50160 standard specifies that under normal load conditions, the supply voltage should be limited within ±10% of the nominal voltage, and the nominal frequency should be limited within ±1% [8].

In recent times, electrical devices used in homes and workplaces contain more electronic hardware due to technological advancements. Ensuring power quality and reliability is particularly crucial in power electronics circuits due to the challenges associated with the design, assembly, and post-production testing of complex systems [9]. Due to reasons arising from the structures of these devices, energy quality is affected and deteriorated [10]. Years ago, the impact of electrical devices on the fundamental frequency was significantly lower. However, new electrical devices with efficient power electronics-based hardware, commonly referred to as non-linear loads, increase energy efficiency. However, by altering the current and voltage ratio, they contribute to the degradation of power quality [11].

Most important power quality parameter in a power system is to have current and voltage waveforms resembling a pure sine wave and, consequently, have a frequency of 50 Hz. Today, power electronics circuits inject harmonic currents and voltages into the electrical power grid [12]. However, due to the operation of power electronic components and connected electrical devices such as electric motors, as well as non-linear loads in the electric power system, the current and voltage relationship cannot be linear. As a result, current and voltage waveforms will be distorted in a form different from a sinusoidal shape. Thus, harmonics will appear in the power system. In this case, linear devices connected to the power system can be exposed to harmonic effects. The presence of harmonics causes distortion in voltage and current waveforms, leading to increased heating of devices, increased losses, and consequently a decrease in efficiency [13-15]. Therefore, it is necessary to reduce or eliminate harmonics in the power system. To address this issue, international standards such as IEC 61000 and IEEE 519, define the maximum permissible limits for harmonic distortion levels [16-18].

Air conditioners, water heaters, washing machines, and refrigerators, which are commonly used in daily life, are among the non-linear loads. These devices are prone to disturbances such as voltage sag, voltage swell, and harmonic effects, making them less resilient against power quality issues [19,20]. Furthermore, due to these issues, these devices will overheat and have a shorter lifespan due to voltage or frequency fluctuations [21].

1.2. Literature Overview

Measurements of harmonics in electrical household appliances have been conducted in the literature, and the problems have been identified in various studies. The impact of this situation on power systems has also been investigated. Rahman et al. determined the optimal switching positions to assess and manage voltage level changes for different electrical devices, including washing machines [22]. Torres et al. have developed a new model for the potential power quality assessment of large-scale electric vehicle integration into the distribution network [23].

Rawa et al. conducted experimental measurements to accurately model and measure the harmonics injected by loads, emphasizing the need for proper modeling to precisely measure the harmonics generated by TV, refrigerator, and washing machine [24]. Çiçek et al. performed a comprehensive harmonic analysis by measuring the fundamental electrical quantities of non-linear loads generated by the existing electrical appliances in a smart home laboratory [25]. In their study, Niitso et al. determined that there is a significant harmonic distortion in residential load current and voltage while evaluating the current distortion caused by domestic and electric vehicle loads in residential distribution grids [26]. Djordjevic et al. conducted research on device load monitoring based on harmonic analysis focusing on fluorescent lamps, PC, and monitor devices [27]. Kit et al. presented a new study that examines measurement results and harmonic analysis of modern household appliances under various voltage distortions [28]. Farooq et al. evaluated the harmonic distortion caused by various non-linear residential loads in distribution systems in their research study [29]. Nikum et al. indicated that the total harmonic distortion current component was measured to determine the level of harmonic distortion in household appliances such as laptops, power banks, mobile chargers, and LED. They found that the power bank had the highest THD_I value [30]. Nassif et al., have created a database by comparing the harmonic effects and phase angles of many electrical appliances used in household settings, including washing machines [31].

Power electronic devices play a vital role in most industrial, commercial, and residential applications. However, the nonlinearity of these power electronic switches can lead to power quality issues [32]. Washing machines, being equipped with both an electric motor and power electronic components, fall into the category of non-linear loads. As a result, it generates harmonic currents due to the electric motor, and the electronic circuit components produce harmonics during periodic current switching. This results in voltage drops, additional losses, and malfunctions of protection devices in the electrical grid to which the washing machine is connected [16,33]. Furthermore, it has been observed that due to voltage fluctuations, the power consumption of these devices with electric motors can increase by up to 10%, resulting in increased energy cost [34]. Harmonic analysis is important in terms of addressing these issues and designing filter circuits.

A washing machine consists primarily of an electric motor and a heating resistor. The electric motor can be in three different operating modes:

- Off status
- Low-speed operation mode (washing)
- High-speed operation mode (spinning)

These three operating modes are not evenly distributed throughout a normal washing cycle. Therefore, obtaining harmonic characteristics for such machines is not easy. Because it is heavily dependent on the operating mode as well as the stage of the operating cycle [35]. Therefore, in order to develop effective methods for minimizing high harmonics in washing machines, it is important to identify the problems caused by high harmonics in a consumer network.

There are a limited number of studies in the literature that specifically investigate the harmonic characteristics of washing machines. However, washing machines, which have an important position among essential household appliances, account for approximately 10% of electricity consumption in developed countries. In this context, both having an electronic control board and an electric motor contribute to power quality issues. A study was conducted to determine the power consumption of the washing machine at different spin speeds, investigating the dependency of energy output on the machine's rotation speed [36]. In this context, the harmonic effects during start-up and operation are important and depend on the power of the electric motor and the operating mode. Jacobs et al., investigated the power consumption of a washing machine and analyzed the behavior of the motor during the washing cycle in a real home working environment [37]. Olhovskiy et al., analyzed the high harmonic currents generated by a washing machine operated on a 220 V. mains voltage [38]. Similarly, Descheemaeker et al. tested the current and harmonic variations in the performance of a washing machine based on voltage fluctuations on a 230 V. grid. They have also investigated the load shift compatibility of the machine [39].

In this study, measurements and analyses were conducted on three different washing machines that vary in terms of production year and applied technology. A comprehensive harmonic analysis was performed by measuring the fundamental electrical parameters of washing machines with different power levels while operating under various temperature and program settings. The study is based on measurements carried out under real operating conditions, and the obtained results were thoroughly analyzed and evaluated.

In this study, a comprehensive harmonic analysis is conducted based on the measurement of fundamental electrical quantities during the operation of different washing machines with varying electrical powers, temperatures, and programs. The analysis is performed to understand the electrical behavior of the machines. Results are analyzed using real measurements taken in an actual working environment.

This article is organized into four different sections. Section 2 presents a detailed description of the methodology used in the study. Section 3 presents the analysis results obtained in the study. Lastly, Section 4 presents the discussions of the obtained results and our final conclusions.

2. METHODOLOGY

The main objective of this study is to investigate the harmonic characteristics of washing machines under different operating conditions and their impact on power quality terms. The experimental setup with appropriate circuit connections for measurements is shown in Figure 1.

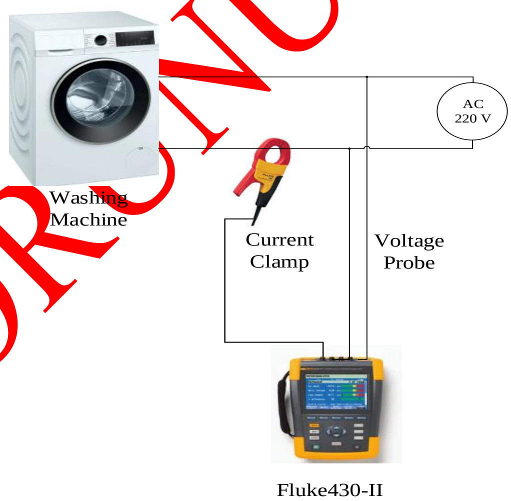

Figure 1. Measurement setup

Three different types of washing machines produced at different times (namely conventional, dynamic resistor-based, and inverter-based) are examined in this study. Power quality measurements are conducted using the Fluke 435 Power Quality Analyzer for different operating temperatures. The data obtained during the experimental study was transferred from the Fluke device to a computer for further analysis.

Comprehensive harmonic analyses are conducted by extensively measuring the electrical quantities of the washing machine. The measurements are performed during the washing machine's commonly used washing temperatures of 30°C, 40°C, and 60°C, as well as throughout the duration of the washing program.

The washing program durations are selected to be very close to each other for each temperature. During the study, measurements are conducted for commonly used power quality parameters such as Total Harmonic Distortion of Current (THD_I), Power Factor (PF), and Cos(ϕ) values. The measurement results are analyzed using MATLAB 2022b software. The characteristics of the washing machines used in the experimental study are given in Table 1.

Table 1. Technical specifications of the washing machines

Washing Machine	**V_{nom}** (V)	**P** (W)	**P_{max}** (W)	**Spin Speed** (rpm)	**Load Capacity** (kg)
Type A	220-240	3000	3300	850	6
Type B	220-240	2000	2350	1000	7
Type C	220-240	2000	2300	1400	9

Washing machine A operates with a conventional resistive heating element, washing machine B uses a dynamic resistive heating system, and washing machine C is equipped with an inverter-driven motor and heating system.

Total Harmonic Distortion (THD) is an important parameter that quantifies the amount of distortion present in a real waveform and represents the impact of harmonics on system disturbances. It is well known that with increasing harmonic orders, the magnitude of voltage and current tends to decrease, and after a certain value, it can be neglected. THD_I is shown in Eq. 1 [40].

$$THD_I = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + \cdots + I_n^2}}{I_1} \quad (1)$$

Here, I_n represents the current value at the n-th harmonic order, and I_1 represents the value of the current at the fundamental frequency.

In calculating the power factor, Eq. 2 is used. Having a power factor close to 1 indicates that the power quality is high.

$$PF = \frac{P}{S} \quad (2)$$

The P (kW) in Eq. 2 represents the active power, while S (kVA) represents the apparent power, which are obtained using Eq. 3 and Eq. 4 respectively.

$$P = V_n * I_n * \cos(\varphi_n - \delta_n) \quad (3)$$

$$S = V_{rms} * I_{rms} \quad (4)$$

Here, V_n represents the voltage value at the nth harmonic order, ϕ_n and δ_n represent the phase angles of the n-th order current and voltage harmonics respectively, V_{rms} and I_{rms} represent the rms values of the current and voltage. The rms values are given by Eq. 5 and Eq. 6 respectively.

The analyses are performed using data collected at intervals of 3 seconds. The data presented in the tables and figures represent the average values of the measurements taken throughout the measurement period.

$$I_{rms} = \sqrt{I_1^2 + I_2^2 + I_3^2 + \cdots + I_n^2} \quad (5)$$

$$V_{rms} = \sqrt{V_1^2 + V_2^2 + V_3^2 + \cdots + V_n^2} \quad (6)$$

In addition to the total power factor (PF), the displacement factor (DF) was also evaluated in this study. The displacement factor, which represents the phase angle contribution of only the fundamental frequency component (50 Hz), was calculated using the Eq. 7.

$$DF = \cos\varphi \quad (7)$$

Where φ is the phase angle between the fundamental voltage and current components. Unlike the total power factor, DF does not consider harmonic distortion, making it an important indicator of reactive power effects.

3. RESULTS AND DISCUSSION

The operation programs of the machines are recorded by sampling the data every 3 seconds throughout the operating time. Each washing machine exhibits similar power variations for different temperature values. The moments of maximum power consumption vary at different times depending on the washing machine type. The average THDI values of the current drawn from the grid during an average one-hour operating period are given in Table 2.

Table 2. Average THD Values of Current

Degree (°C)	**THD_I** (Type A)	**THD_I** (Type B)	**THD_I** (Type C)
30	6.464828	18.639823	16.92995
40	6.697376	18.789273	**21.51431**
60	**6.375730**	15.569237	18.27195

The time-dependent variation of the active power drawn from the grid by the washing machines for different washing temperatures are shown in Figure 2.

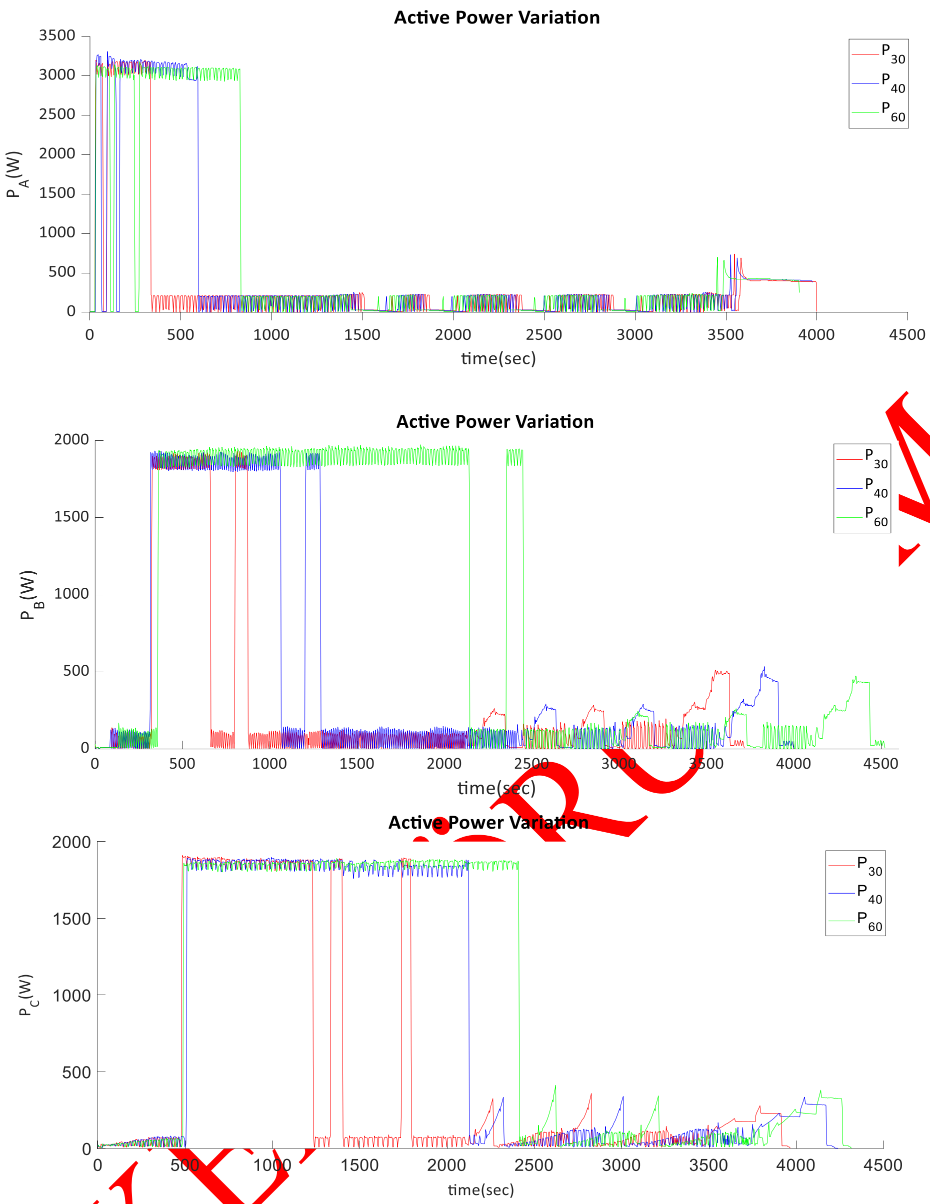

Figure 2. Active power variations of washing machines

When examining the values for Type A, B, and C washing machines, it can be observed that the highest THD_I values occurred during the 40-degree wash cycle. Among the examined devices, the highest THD_I value is calculated to be approximately 21.51% in the Type C device during the 40-degree wash program.

The lowest THD_I value is observed in the Type C washing machine during the 60-degree operating program. The current harmonic spectra for each investigated temperature value of the washing machines are shown in Figure 3.

Type A is a conventional resistive washing machine equipped with a resistance-based heating element and a simple motor control system. In such systems, due to the absence of switching elements and the relatively low presence of nonlinear loads, certain harmonic components, particularly the 3rd and 5th harmonics, become more pronounced.

Type B features dynamic resistance control, which adjusts the resistance value based on load conditions. This system can help smooth the current waveform and reduce the levels of low-frequency harmonics, such as the 3rd harmonic.

Type C utilizes an inverter-controlled motor system, which optimizes motor speed and energy consumption using Pulse Width Modulation (PWM). This modulation technique suppresses low-order harmonics (e.g., the 3rd harmonic) while generating higher-frequency harmonic components.

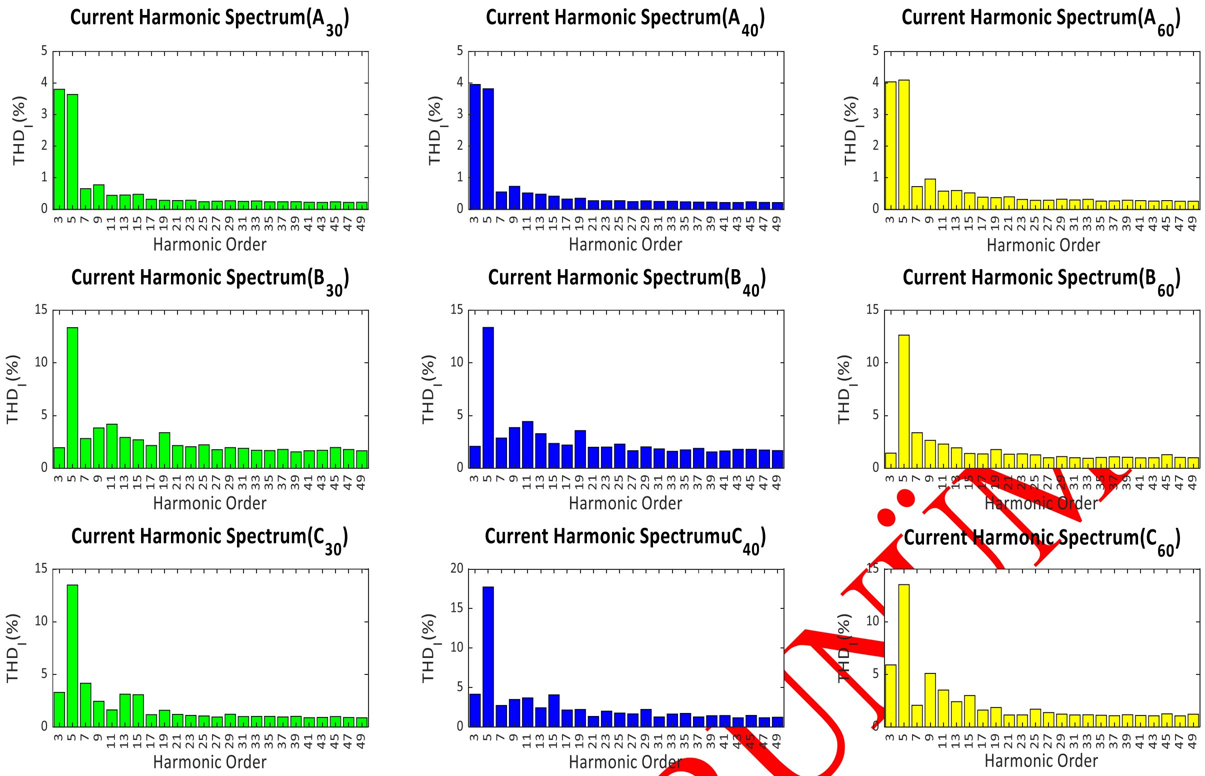

Figure 3. Harmonic spectrum of washing machines

It is clearly observed in Figure 3 that there are variations in the magnitudes of individual harmonic components as the washing temperatures change. When examining the harmonic spectra for each operating temperature of Type A machine, it is observed that the 3rd and 5th current harmonic components are more dominant compared to the other current harmonic components.

When examining the harmonic spectra for each operating temperature of Type B and Type C machines, it is observed that the 5th current harmonic component is more dominant compared to the other current harmonic components, and it is around 14%.

Since Type A has a simple resistive system, the 3rd and 5th harmonic components are more pronounced, whereas in Type B, dynamic resistance adjustments, and in Type C, inverter-controlled drives lead to the attenuation of these harmonic components.

Due to the harmonic currents drawn by the examined three types of washing machines, the power factor and cos(φ) values differ from each other. The average values of power factor and cos(φ) measured during the operation of the washing machines are given in Table 3.

Table 3. Average Power Factor and Cos (φ) Values

Degree (°C)	Type A		Type B		Type C	
	PF	**Cos *φ***	**PF**	**Cos *φ***	**PF**	**Cos *φ***
30	0.6962	0.7284	0.4277	0.4870	0.6949	0.9370
40	0.7104	0.7297	0.4944	0.5477	0.7777	0.9483
60	0.7243	0.7458	0.6356	0.6752	0.7951	0.9503

Upon examining all measurement values, it can be observed that as the washing temperature of the washing machines increases, there is an increase in the power factor and Cos(φ) values. In particular, it is clearly seen that the Cos(φ) value of the C type washing machine is close to 1 for all temperature values.

When examining the THD_I variations of A, B, and C types of washing machines, it is observed that the highest values occur during the 40º washing program. Therefore, the THD_I variations during the 40º washing program for all devices are shown in Figure 4.

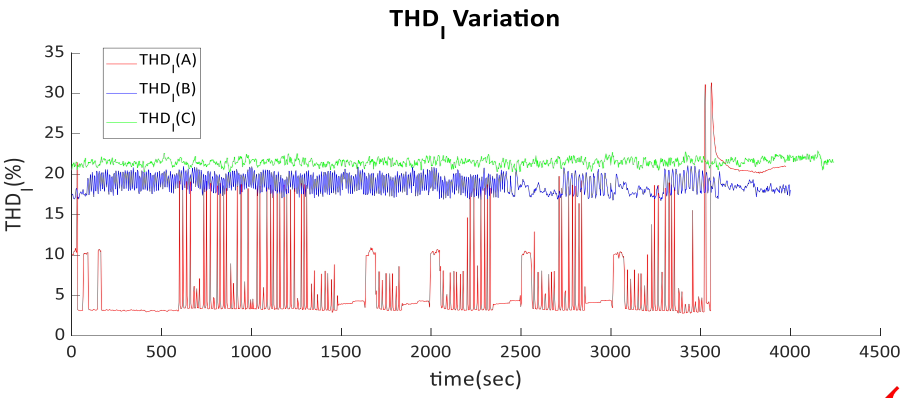

Figure 4. THD_I Changes in 40 °C washing program

4. CONCLUSION

Power quality is one of the most important parameters that ensure the smooth operation and efficient use of electrical appliances in homes. Deviation from standard power quality can lead to a range of issues, including higher energy and maintenance costs, equipment instability, and device damage. Washing machines consist of an electric motor and an electronic control board that determines the operating sequence of the motor. Therefore, they are devices with non-linear load characteristics that negatively affect power quality. In this study, a comprehensive harmonic analysis of washing machines, which have significant power consumption among household appliances, is conducted under different operating conditions. The obtained results have been evaluated from different perspectives. The real measurements of harmonic components of devices operating under actual operating conditions have been performed using a power analyzer. The current harmonics, active and apparent powers, power factor, and frequency are measured. According to the measurements, the highest THD_I value, 21.51%, is obtained with the C-type washing machine at a temperature of 40 degrees Celsius. In addition, the A-type washing machine has shown similar THD_I values across all three temperature conditions, and the lowest THD_I value of 6.37% was measured. It would not be wrong to associate this situation primarily with the spin speed and power of the washing machine. In this context, it is known that washing machines contribute to harmonic distortion during their operation, and harmonic filters can be used to reduce the harmonics generated by washing machines and limit their effects on the power grid within the limits of international standards.

Although the A-type washing machine has the lowest THD_I value among the examined washing machines, its THD_I value varies continuously during operation. On the other hand, the THD_I variations of B and C type washing mchines remain close to a constant value throughout the operation.

This study provides an in-depth analysis of the harmonic effects of different types of washing machines under real operating conditions. The findings highlight the impact of washing machine technology on power quality and emphasize the need for harmonic mitigation strategies.

The originality of this research lies in its detailed evaluation of everyday appliances through experimental data collection and analysis. It offers insight into how different operational modes of washing machines affect harmonic emissions and the relationship between active, apparent power, and power factor under harmonic conditions. These findings can serve as a practical guide for manufacturers in designing devices with lower harmonic impacts and in implementing effective filtering strategies.

Future studies can explore the implementation of active and passive harmonic filters to minimize the power quality disturbances caused by household appliances. Additionally, extending the research to other nonlinear residential loads, such as refrigerators, air conditioners, and dishwashers, could provide a more comprehensive understanding of power quality challenges in residential electrical networks. Furthermore, investigating the long-term effects of harmonic distortion on household appliances and electrical infrastructure could offer valuable insights for manufacturers and grid operators.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require the permission of the ethics committee and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Altuğ BOZKURT: Supervision, resources, writing-review and editing.

Erşan Ömer YÜZER: Conceptualization, methodology, software, validation, formal analysis, ınvestigation, resources, writing-original draft, visualization.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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