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Energy efficiency and green transformation: a VFD case study in an industrial facility

Enerji verimliliği ve yeşil dönüşüm: bir sanayi tesisi VFD örneği

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Abstract

In today's world, where competition and change are aggressive and rapid, managing and reducing fixed input costs has become critically important for both the private sector and public institutions. Among these fixed input costs, energy expenses stand out as the most significant and controllable factor. A major portion of energy consumed is attributed to the use of electric motors. These motors, particularly those with high energy consumption, are typically designed to operate at constant speeds and deliver constant output. However, with modern production techniques and practices, many applications now require motors to operate at variable speeds using advanced technological control methods. In this context, Variable Frequency Drives (VFDs), based on power electronics, are used to control motor speed and ensure efficient and economical use of energy and energy resources. By enabling motors to operate more efficiently, VFDs contribute significantly to green transformation in the industrial sector. In addition, they offer several benefits such as extending the service life of motors and electrical cables. However, due to the power electronics components used in their structure, VFDs can cause harmonic distortion. This study aims to demonstrate energy management practices to improve the energy efficiency of induction motors commonly operated with Y-Δ starters in industrial settings and to analyze the effects of harmonic distortion on the power grid. In this context, power consumption, cost analysis and harmonic analysis of different starting methods have been carried out. Furthermore, the energy savings and the level of harmonic distortion resulting from VFD usage have been evaluated and compared with the conventional Y-Δ method. As a result of the study, the payback period was found to be approximately 1.04 years, depending on the motor's operating frequency and duration, and the total harmonic distortion (THD) was observed to increase from an average of around 13% to 30%.

Keywords: Analysis, Energy efficiency, Industrial facility, VFD, Y-Δ Starting method

Öz

Dünya üzerinde rekabetin ve değişimin agresif ve bu denli hızlı olduğu günümüzde, sabit girdi maliyetlerinin yönetilmesi ve düşürülmesi gerek özel sektör gerekse kamu kurumları için hayati öneme sahiptir. Bu sabit girdi maliyetlerinden en yüksek değere sahip ve kontrol edilebilir olanı enerji maliyetidir. Tüketilen enerjinin en büyük kısmı elektrik motoru kullanımından kaynaklanmaktadır. Büyük tüketim değerlerine sahip motorlar sabit bir hızda çalışacak ve sabit bir çıktı sağlayacak şekilde tasarlanmıştır. Ancak modern üretim teknikleri ve uygulamalarıyla birlikte teknolojik kontrol yöntemleri de kullanılan elektrik motorları birçok uygulamada farklı hızlar gerektirir. Bu bağlamda, enerji kaynaklarının ve enerjinin verimli ve tasarruflu kullanılmasını sağlamak üzere, güç elektroniği tabanlı değişken frekanslı sürücüler (VFD), motorların hız kontrolünü sağlamak için kullanılır. VFD'ler yardımıyla motorlar enerjiyi tasarruflu ve verimli kullandığı için sanayide yeşil dönüşüme büyük katkı sağlar. Bunun yanında, motor ve elektrik kabloları kullanım ömrü gibi birçok faydası bulunmaktadır. Ancak yapısında kullanılan güç elektroniği ekipmanları sebebiyle harmonik bozunmaya sebebiyet vermektedir. Bu çalışmada, sanayide yaygın olarak kullanılan yıldız-üçgen (Y-Δ) yol verme ile çalışan asenkron motorların enerji verimliliğini artırmaya yönelik enerji yönetimi uygulamalarını göstermek ve şebeke üzerindeki harmonik bozunmanın etkilerinin analizi amaçlanmaktadır. Bu bağlamda, çalışma kapsamında yol verme yöntemlerinin güç tüketimleri, maliyet analizi ve harmonik analizi yapılmıştır. Ayrıca Y-Δ yol verme metodu ile karşılaştırıldığında VFD kullanımında ne kadar tasarruf elde edilebileceği ve harmonik bozulmanın ne seviyede olacağı ölçülmüştür. Çalışma sonucunda, motorun çalışma frekansına ve süresine bağlı amortisman süresi yaklaşık 1,04 yıl bulunmuş ve toplam harmonik bozunumun (THD) ise ortalama %13' lerden % 30' lara çıktığı belirlenmiştir.

Anahtar kelimeler: *Analiz, Enerji verimliliği, Sanayi tesisi, VFD, Y-Δ yol verme*

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1. Introduction

The global population is increasing day by day and consequently, energy consumption is also rising. In parallel, as the industrial sector has expanded, humanity has shifted from a minimal consumption mindset to a consumption-oriented approach. This shift underscores the growing importance of energy savings and controllability. Global energy consumption is projected to increase by 33% from 2010 to 2030. Figure 1 illustrates the trend in worldwide marketed energy consumption from 1980 to 2030 (Beaulac et al., 2021).

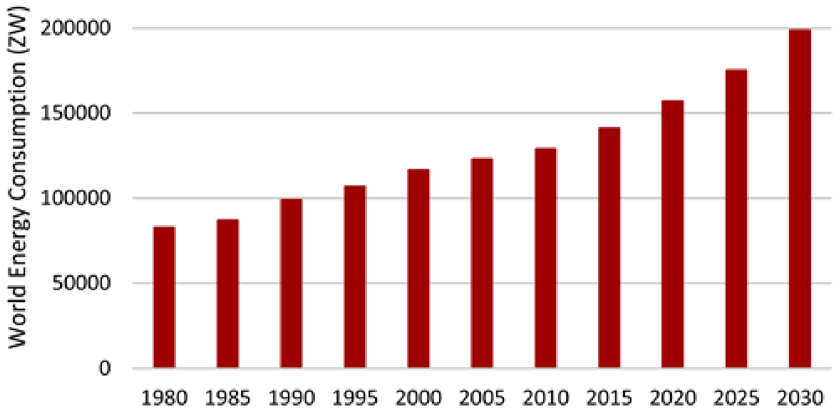

Figure 1. Trends in worldwide marketed energy consumption

As shown in Figure 1, total global energy consumption rose from 82.919 ZW in 1980 to 116.614 ZW in 2000 and it is projected to reach 198,654 ZW by 2030 (Beaulac et al., 2021). Meanwhile, many countries worldwide are striving to reduce carbon emissions, setting continuous new targets. The long-term goal of the European Union (EU) is to achieve zero emissions by 2050 (Almeida et al., 2017). Although new technologies and high-efficiency machines are increasingly used in industry today, they require substantial investment and financial resources.

The Asynchronous Motor is a widely used electrical machine due to its reliability, efficiency, economic structure and adaptable response. However, many factories in the industrial sector operate with machines that have diminished efficiency. By implementing low-cost retrofits, these machines can be converted into processes that allow for years of continued use, achieving performance close to that of new machines. In industrial automation, electric vehicle technology, or any electromechanical system, the use of motors operating at a fixed power frequency often results in significant energy losses. To obtain the desired torque-speed response Variable Speed Drives (VSDs) are required (Harsha et al., 2020). Variable Frequency Drives (VFDs) are a type of drive that uses power electronics components to control motor speed by adjusting the frequency of the motor's input power.

Compared to other speed control methods such as VSDs and adjustable speed drives, VFDs extend equipment lifespan by adjusting motor speed to meet load requirements (Saidur et al., 2012). However, due to the power electronics components in their structure, VFDs introduce harmonic currents, which are considered unwanted distortions that negatively affect power system infrastructure and loads. These harmonics can lead to heat buildup, reduced equipment lifespan and equipment failures (Wallace, 2021). Eslami et al. have noted that in sectors such as renewable energy and others that increasingly use VFDs due to advancements in power electronics, it may be beneficial to employ artificial intelligence, widely used in recent years, to predict harmonic levels based on harmonic measurement data. Additionally, active filters could be used to minimize harmonics effectively (Eslami et al., 2022).

In this study, numerous literature sources that model and examine the effects of energy savings and harmonics with VFD usage in various machines have been reviewed. For example, Schibuola et al. monitored the climate control system of a historic library in Venice over a one-year period. They observed that the Heating Ventilating and Air Conditioning (HVAC) system controlled by a VFD achieved 38.9% annual savings compared to fixed pump flow and fan coil operation. This study highlighted the advantages of using VFDs in historic buildings with limited physical intervention (Schibuola et al., 2018). In a study by Akhan, fan and pump circuits in an energy efficiency laboratory were tested with two different VFDs and evaluations were made regarding energy efficiency. By using variable speeds, it was found that efficiency levels could reach up to 60% for fans and pumps (Akhan, 2022). De Almeida et al. investigated the efficiency impact of VFD technology in the transition process of inefficient electric motors to new high-efficiency motors to meet the zero-carbon target for the electric motor market by 2050, as outlined in the Paris Climate Agreement. It was projected that if a global shift to high-efficiency motors is achieved and motor speeds are controlled with new technologies, over 1.000 TWh of energy savings could be realized annually (Almeida et al., 2023). Wibowo et al. developed a VFD simulation circuit using Matlab Simulink to enhance the efficiency of an inefficient fan system in a power plant in Indonesia. Results obtained from the simulation indicated that the investment could achieve payback within approximately 6.5 months (Wibowo et al., 2021). In a study conducted by Riungu and Moses in Kenya, it was determined that replacing the Y-Δ start method with a VFD in 75 kW fan motors reduced the payback period to less than 3 months (Riungu & Moses, 2022). In the study conducted by Kapp et al. in the United States, an inductive analysis was carried out based on the operating data of industrial motors with VFDs used for various purposes. The study focused on the economic, environmental, and engineering aspects of VFD usage (Kapp et al., 2024).

Öztürk et al. demonstrated that by adjusting the speeds of 36 fan motors used in the HVAC system of a textile factory with VFDs, approximately 50% energy savings could be achieved (Ozturk et al., 2020). Sadek et al. showed that in a petroleum processing facility in Egypt, the payback period for VFD implementation on variable-speed fan and pump motors was less than one year, while for a compressor motor operating at a fixed frequency, the payback period was calculated to be 6.2 years. Their study indicated that after applying VFDs to all equipment, an annual energy saving of 7.204 MWh was realized, but in some cases, the cost could not be recovered within a short time frame (Sadek et al., 2023). Fauzi et al. monitored a fan motor connected to a steam boiler for 341 days using a VFD. It was found that when the boiler operated at 30%, 50%, and 80% capacities, energy savings of 90%, 61.10%, and 42.64%, respectively, were achieved. The study emphasized that the application of VFDs in similar operational contexts not only provides significant energy savings but also reduces wear and mechanical stress on the system. (Fauzi et al., 2024). Mokhtar and Nasooti designed a holistic program considering cement production facilities in various regions of Iran, demonstrating that investments in efficient fans equipped with VFDs could be recouped in approximately 2.5 years across the entire facility. The study also examined harmonic distortions caused by VFDs (Mokhtar & Nasooti, 2020). Wallace's research investigated the harmonics generated by VFD usage in ventilation, fan and pump applications, along with filtering methods, providing various solutions. They noted that there is no single solution method for harmonics, but that the correct solution can be determined after a thorough examination of the system (Wallace, 2021). In a study by Turinno and Facta conducted in the steel industry in Indonesia, the power quality was monitored after VFD conversion in a dust collection unit. It was observed that when the VFD operated at low frequency, the current harmonic increased to 45% and exceeded the 12% limit; however, when the machine operated near the fundamental frequency, the current harmonic fell below the threshold and did not pose a problem, while the voltage harmonic remained below the 5% limit in both cases (Turinno & Facta, 2024). Krishnasamy and Ashok investigated the reduction of harmonic distortion in induction motors driven by VFDs in a wheat flour mill using an artificial neural network (ANN) based hybrid power filter. The results demonstrated that the proposed filter reduced total harmonic distortion (THD) to 1.4% and contributed to energy savings (Krishnasamy & Ashok, 2022).

With the widespread understanding of energy efficiency and the continuous search for efficiency points by technical teams, methods have been sought to achieve the same level of productivity without compromising quality in production processes. In this context, VFDs technology has emerged as a significant innovation, especially in industrial applications. VFDs allow for optimization of energy consumption by controlling motor speed, which provides a significant advantage in improving energy efficiency (URL-1; URL-2).

In earlier times, VFDs were not as advanced and expensive, which led to the preference for Y-Δ starting methods in many production lines. The Y-Δ starting method, commonly used in large motors, helps reduce the high inrush currents at startup, but it has limitations in terms of energy efficiency. Over time, as technology advanced, VFDs became more affordable and efficient. As a result, retrofitting older machines with VFDs is now possible. With this transformation, machines can operate more efficiently, reducing the kWh per produced unit. However, it is important to recognize that harmonic effects on the electrical grid will occur once this transformation is implemented, and thus, harmonic filtering measures should be considered (URL-1; URL-2).

The importance of VFD technology lies not only in its ability to improve energy efficiency and reduce energy consumption but also in the precise control it offers over systems. Particularly in industrial applications that require speed control, VFDs enable machines to operate more efficiently, reducing operational costs and minimizing environmental impact. This technology supports the long-term sustainability of industrial systems and allows for better management of energy consumption (URL-1).

The scientific aim of this study is to investigate the effects of VFD implementation on energy efficiency, power quality, and economic performance in an industrial fan motor system under real operating conditions. The core subject of the research is to conduct comparative measurements between the conventional star-delta (Y-Δ) starting method and a VFD-controlled system in terms of key parameters such as active and reactive power consumption, THD and payback period. This study expands the existing research in the field of industrial energy management through a field application conducted in an electrostatic powder coating facility. Going beyond the simulation-based analyses commonly found in the literature, it provides practical contributions based on real production data. Additionally, by considering the trade-off between energy savings and harmonic distortion, the study identifies the technical and economic conditions under which VFD retrofitting can be effectively implemented. The main contributions of this study can be summarized as follows:

- A practical implementation and verification of a well-known phenomenon related to [topic, e.g., energy efficiency with VFDs] has been conducted under real industrial conditions.
- Unlike many theoretical studies, this work provides experimental validation and field data from an actual industrial setup.
- The study demonstrates measurable energy savings and operational improvements, contributing to the growing body of research on sustainable industrial practices.

The organization of the paper is as follows: In Section 2, the materials and methods related to the transition from Y-Δ starting to VFD in a factory engaged in electrostatic powder coating production are discussed. Section 3 presents the power analysis, harmonic analysis and economic analysis conducted based on the data obtained from the experimental study. Finally, the planned projects for future periods are discussed.

2. Materials and methods

2.1. Asynchronous motor

Walter Bailey's invention in 1879 is considered the first primitive induction motor. The first practical motors designed using rotating magnetic fields were invented by Nikola Tesla and Galileo Ferraris through two separate works (Aydın, 2014). Asynchronous motors are used at points requiring motion in industrial systems and in the majority of electrical household appliances. Numerous auxiliary equipment, such as condensation pumps, circulation pumps, induced draft fans, forced draft fans, primary air fans and secondary air fans, are driven by high-voltage induction motors, meaning they are motor systems (Shuping et al., 2012). Figure 2 illustrates the structure of the asynchronous motor in detail (D'Urso et al., 2021).

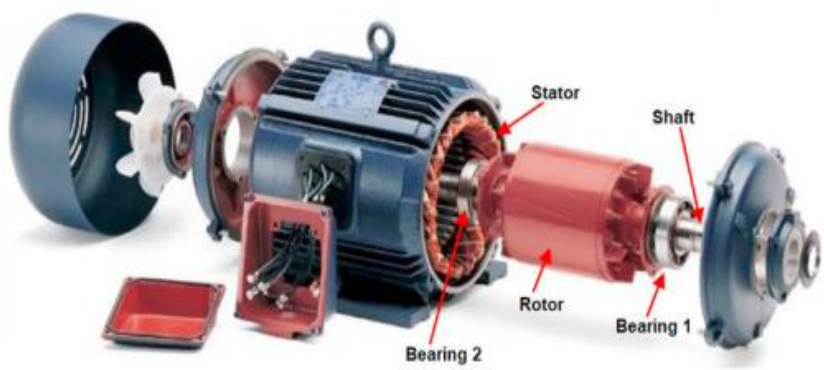

Figure 2. Structure of the Asynchronous Motor

Asynchronous motors are widely used due to their simple structure, reliability, high efficiency, low cost and ease of maintenance (Hannan et al., 2018). However, asynchronous motors consume excessive currents at the moment of startup due to their inertia. Consequently, various motor starting methods have been developed and implemented over time to meet different operational needs. Some of these methods are listed below.

- Direct-on-line (DOL) starting can be used. In this case, speed adjustment is not possible.
- Y-Δ starting or soft starting methods can be used, which are suitable for limiting the starting current.
- It can be powered by a VFD for speed control, suitable for both scalar and vector control. With this method, the motor can be operated in a frequency range of 0-60 Hz on a 50 Hz grid.

2.2. Experimental study

The high current drawn by asynchronous motors at startup can lead to many adverse effects, especially in high-power motors. To minimize these effects, it is essential to start the motor with low voltage and Y-Δ starting is a method used for this purpose. In Y-Δ starting, the control circuit prepared with contactors applies phase-neutral voltage to the motor terminals until the inertia moment is exceeded. After the motor starts, phase-phase voltage is applied to the terminals, allowing the motor to operate without being exposed to excessive currents. The aim of this study is to investigate the energy efficiency and energy quality of the starting method used for fans in a powder coating production facility. In this context, energy savings and energy quality were evaluated when a 37 kW fan motor driven by Y-Δ starting was operated using a VFD in an electrostatic powder coating production facility located in the organized industrial zone. The technical specifications of the 37 kW three-phase fan motor used in the study are provided in Table 1. Upon examining Table 1, it can be observed that there are significant current differences between the Y and Δ conditions for a fixed power value at different voltage levels.

Table 1. Technical specifications of the 37 kW three-phase fan motor

Voltage (V)	**Frequency** (Hz)	**Power** (kW)	**RPM** (rpm/minute)	**Current** (A)	**Power Factor** (cos φ)
690 Y	50	37	2950	37.31	0.90
400 Δ	50	37	2950	64.36	0.90
660 Y	50	37	2945	38.79	0.91
380 Δ	50	37	2945	67.37	0.91
415 Δ	50	37	2960	62.66	0.89

The selected VFD for use in this study is a product designed for industrial systems, used in various machine sections of our factory with different kW ratings and has a low failure rate. Considering the operating costs, the chosen VFD should have a minimum failure rate and a wide service network. The technical specifications of the VFD used for starting the motor are also provided in Table 2.

Table 2. VFD technical specifications

Voltage	**Phase**	**Power**	**Brake – Safe Stop**	**RFI Filter**
380 - 480 VAC	Three phase	45 kW / 60 HP	No brake cutter	RFI Class A1/B (C1)

In this study, a 37 kW three-phase fan motor was driven by a 45 kW heavy-duty inverter, taking into account heavy operating conditions. Raw data were collected firsthand using a Chauvin Arnoux C.A.8331 power analyzer. Both driving methods of the installed fan in the facility were measured with the same analyzer to minimize the possibility of measurement error. Secondary data were obtained through literature review and engineering expertise. All data obtained from the study were evaluated using qualitative and quantitative data analysis methods. Qualitative analysis helps to understand the reasons and processes behind decision-making, while quantitative analysis facilitates the scientific investigation of quantitative characteristics, measurements and their relationships. The measurements taken using the power analyzer are visually represented in Figure 3.

Figure 3. Measurement conducted with a power analyzer

The existing Y-Δ circuit, consisting of three contactors as seen in Figure 3, operates the 37 kW fan motor on a 6 days 24 hours production basis. The factory has five different production lines where these fans are utilized. During production, the machine parts need to be cleaned during color changes. Having the ability to adjust the fan speed during this cleaning process provides numerous advantages to the operator. The ability to vary the fan speed allows the operator to achieve different particle sizes according to the product type, offering a comfortable working range. Additionally, variable frequency operation enables energy savings as well. Considering all these advantages, this experimental study was conducted to quantitatively determine the savings achieved through an engineering approach.

2.3. Application circuit

Electrostatic powder paint is produced from raw materials that have undergone two processes (extruder and micronizer) and is ready for use. The fan component relevant to our application is located in the micronizer process. In this study, the Y-Δ circuit controlling the fan motor within the micronizer's control panel has been removed. Since the VFD occupies more space than the Y-Δ circuit, a new panel has been prepared outside to accommodate it. Figure 4 illustrates the panel featuring the Y-Δ starting circuit (a) and the VFD circuit (b).

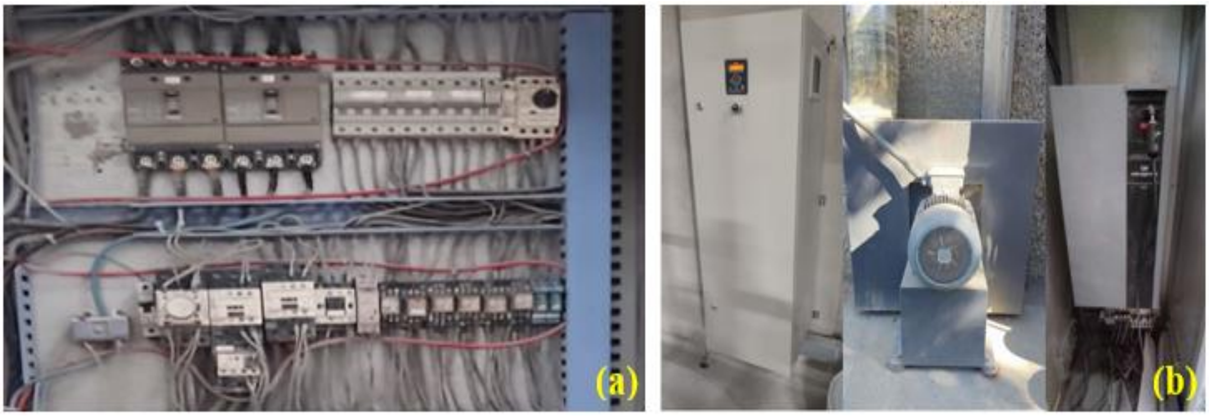

Figure 4. (a) Panel containing the Y-Δ starting circuit; (b) panel containing the VFD circuit

Measurements and monitoring were conducted for the 37 kW fan motor using two different starting methods. In the first method, the Y-Δ starting method currently used in the production line was examined, while in the second method, the fan's operation after being converted to a VFD was analyzed. The investigations were carried out during production, ensuring that there was no degradation in product quality. This approach allowed for the attainment of accurate data free from modeling errors. The results of the investigations highlighted both the advantages and disadvantages of each method through numerical data.

The Y-Δ operating condition depicted in Figure 4 (a), located in the micronizer panel, was recorded using an analyzer at one-minute intervals over a period of one week. Following this, the VFD panel shown in Figure 4

(b) was activated and the system's values were measured over another week at a frequency of 50 Hz. At this stage of the study, data for both starting methods were obtained at the same frequency. Subsequently, utilizing the capabilities provided by the driver, the fan motor was operated within a frequency range of 45-55 Hz on a 50 Hz grid and measurement data were recorded via the power analyzer. The objective of collecting data at different frequency ranges was to enable a better interpretation of energy consumption and harmonic analysis results.

3. Results and discussion

3.1. Power analysis

Power analysis is fundamentally conducted to compare the power consumption of different starting methods. In this study, various scenarios related to power analysis have been compared using the obtained data, leading to enlightening results. Currently, a 37 kW three-phase fan motor is operated using the Y-Δ starting method; this study aims to minimize energy consumption by controlling the motor speed through frequency modulation and to observe its effects on the grid. In this context, the analyzer was first connected to the machine operating under the Y-Δ method to examine the power consumption and harmonic levels of the motor currently in use. The evaluations of the findings obtained from this examination are discussed below.

3.1.1. Power analysis at base frequency (50 Hz)

At the base frequency (50 Hz), a power difference of approximately 0.44 kW is observed between the VFD and the Y-Δ starting method based on the active power values obtained. In the first case, the motor draws an average active power of 18.89 kW; however, in the second case, when operated in VFD mode, the average total motor power is observed to be 19.43 kW. The active powers are balanced with each other. The comparison of active power between Y-Δ starting and VFD at the base frequency is presented in Figure 5.

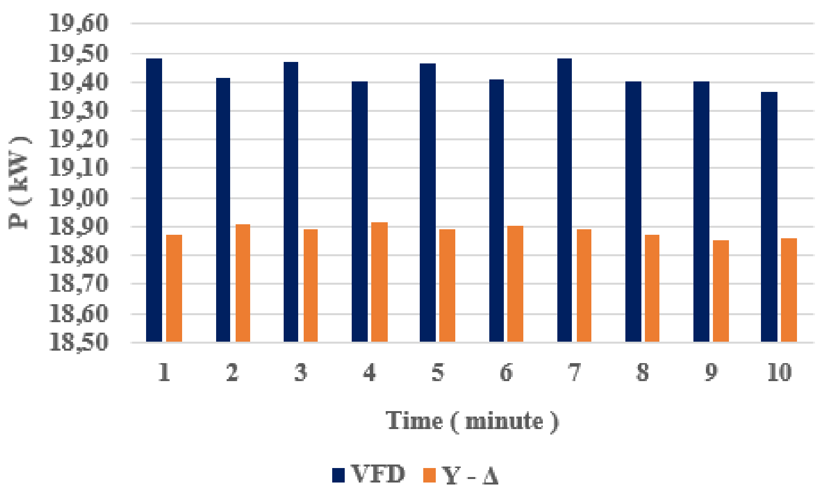

Figure 5. Graph comparing active power between Y-Δ starting and VFD at the base frequency

At the base frequency, there is a power difference of approximately 12.6 kVAR between VFD and Y-Δ starting based on the reactive power values obtained. In the first case, the motor draws an average of 13.84 kVAR of reactive power, while in the second case, when the motor is operated in VFD mode, the total motor power is observed to be an average of 1.24 kVAR. Thus, a significant difference in reactive power is noted between the first and second cases. The graph comparing reactive power between Y-Δ starting and VFD at the base frequency is shown in Figure 6.

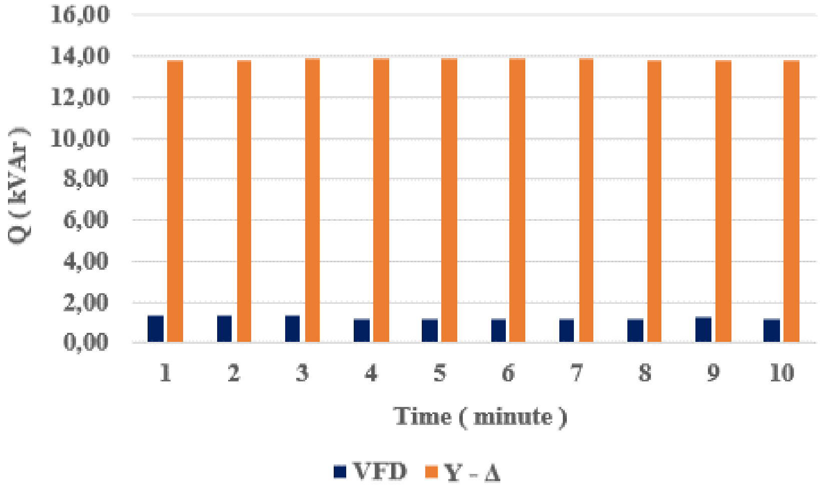

Figure 6. Graph comparing reactive power between Y-Δ starting and VFD at the base frequency

At the base frequency, there is a power difference of approximately 2.98 kVA between VFD and Y-Δ starting based on the apparent power values obtained. In the first case, the motor draws an average apparent power of 23.64 kVA, whereas in the second case, when the motor operates in VFD mode, the average total apparent power observed is 20.66 kVA. The graph comparing the apparent power between Y-Δ starting and VFD at the base frequency can be found in Figure 7.

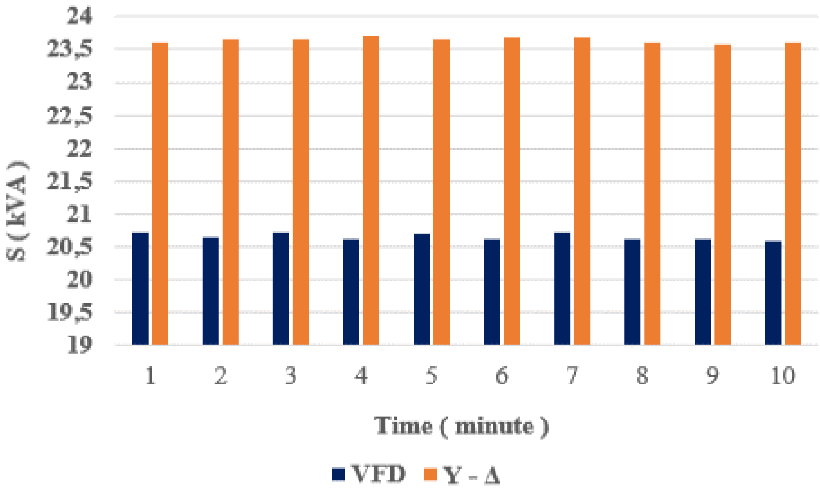

Figure 7. Comparison of apparent power between Y-Δ starting and VFD at the base frequency

When Figure 5, Figure 6 and Figure 7 are evaluated together, it is observed that as a result of the application of starting methods, the active powers are similar, there is a slight difference in apparent powers, but there are significant differences in reactive power.

3.1.2. Power analysis in vfd starting

In this section, the VFD's capability to operate at different frequencies has been utilized and power values have been obtained within a frequency range of ± 5 Hz around the fundamental frequency. Figure 8 illustrates the variation of active power values obtained in the VFD mode within the frequency range of 45-55 Hz. It has been observed that active power values increase steadily with frequency changes, reaching 15.1 kW at a frequency of 45 Hz and 25.3 kW at a frequency of 55 Hz. The average active power value measured at the fundamental frequency is approximately 19 kW. In general, it can be stated that for processes requiring variable speeds but operating continuously at the fundamental frequency, the VFD is highly efficient and practical.

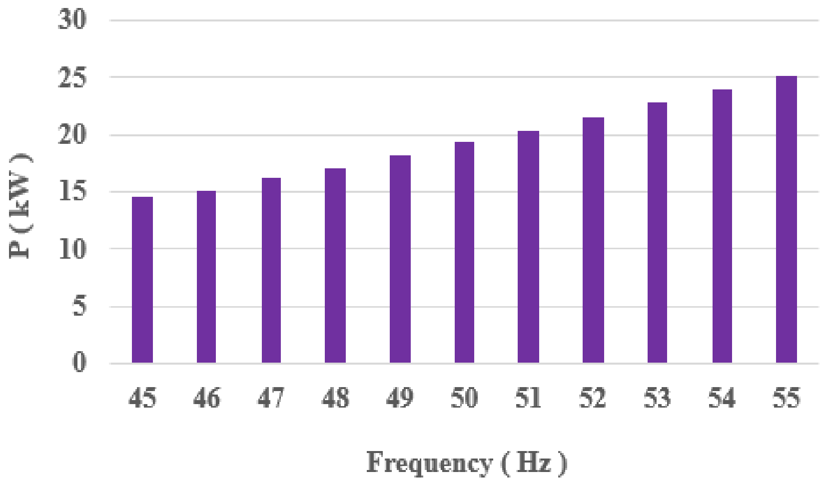

Figure 8. Active power comparison graph in VFD mode at 45-55 Hz

3.2. Harmonic analysis

In this study, current harmonics up to the 50th order have been examined. Since even harmonics do not have a significant impact, only odd harmonics have been considered. The data was recorded with a precision of one minute over a period of one week. The graphs showing the measured values of the harmonics generated during the operation of the Y-Δ starting method and the VFD are presented in Figures 9 and 10, respectively.

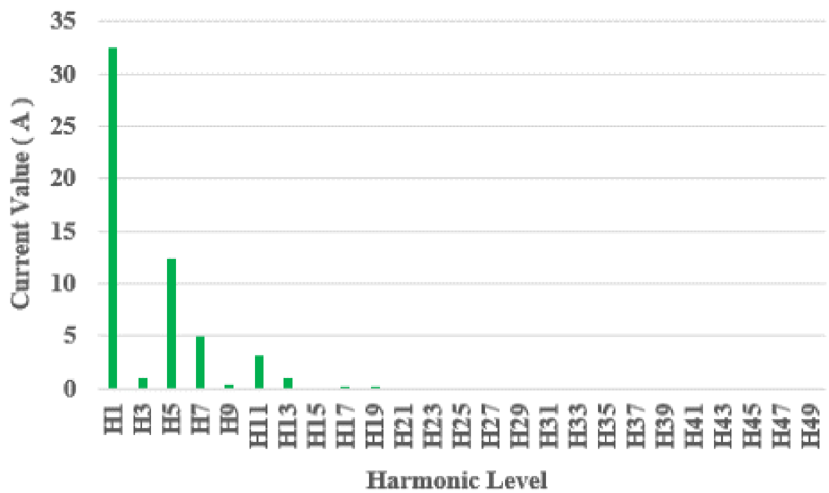

Figure 9. Harmonic current values generated during Y-Δ starting method

In the case of Y-Δ starting method, the following values were measured for the odd harmonics up to the 11th harmonic: 32.43 A, 1 A, 12.37 A, 5.02 A, 0.35 A, 3.07 A and 0.93 A respectively. It was observed that current levels at harmonic frequencies beyond these were either zero or close to zero. However, in cases where the fan motor was operated using a VFD, the current for the 3rd, 5th, 7th, 11th, 13th, 17th, 19th, 23rd, 25th and 29th harmonics was found to increase. In the case where the fan motor was driven by a VFD, the highest current value, similar to that observed during Y-Δ starting, was recorded as 24.94 A at the 5th harmonic. Additionally, it is notable that high current values were also present in other odd harmonics.

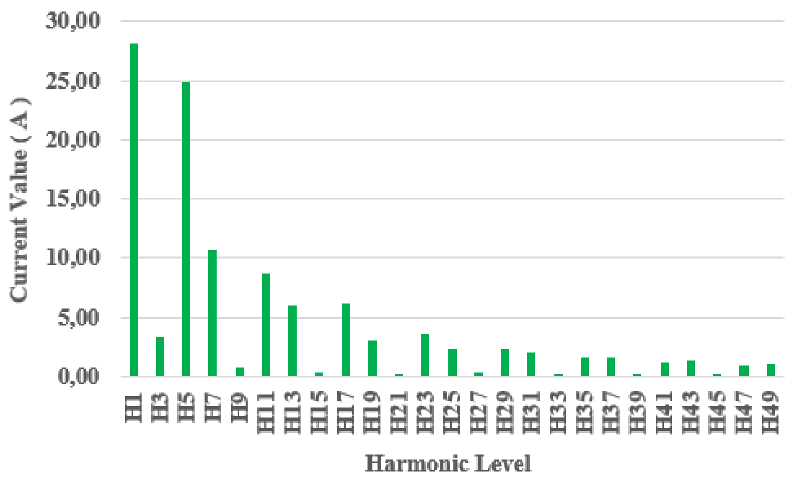

Figure 10. Harmonic current values generated during VFD operation

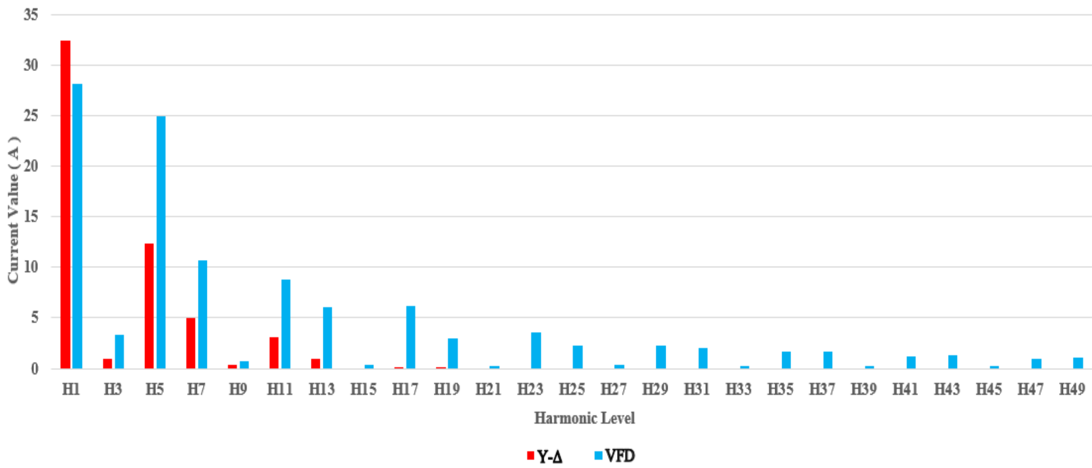

Figure 11. Comparison of harmonic current values in Y-Δ starting and VFD operation conditions

When comparing the current values generated during the VFD operation of the fan motor with those during the Y-Δ starting method, as shown in Figure 11, it can be observed that the harmonic currents in the VFD operation condition are higher for all odd harmonics except for H1. This situation arises due to the power electronics components present in the VFD structure.

3.3. Economic analysis

Based on the results obtained in this study, the economic analysis of operating a 37 kW three-phase fan motor in an electrostatic powder coating production facility using a VFD drive circuit has been evaluated. Since the payback period for such a system is very short, a simple economic analysis has been conducted without considering interest rates and inflation.

Annual Energy Savings (kWh) = Annual Motor Operating Percentage × (PY-Δ − PVFD) × 24 (hours/day) × Number of Working Days per Week × Number of Working Weeks per Year

Total Savings (TRY) = Annual Energy Savings (kWh) × Unit Energy Cost (₺ /kWh)

Payback Period (Years) = Investment Cost (₺) / Total Savings (₺)

The payback period was calculated by multiplying the annual energy savings achieved through the use of VFD with the unit energy cost to determine the total savings, which was then divided by the investment cost.

The economic analysis results, taking into account different operating rates of the motor, are presented in Table 3.

Table 3. Economic Analysis

Annual Operating Rate (%)	Y-Δ / VFD (kWh)	Hour	Day	Week	Annual Energy Savings (kWh)	Project Cost (₺)	Unit Energy Cost (₺ /kWh)	Total Amount of Savings (₺)	Payback Period (Year)
70	18,9/15	24	6	52	20.442	56.676	2,66	54.375	1,04
80	18,9/15	24	6	52	23.362	56.677	2,66	62.142	0,91
90	18,9/15	24	6	52	26.282	56.677	2,66	69.910	0,81
100	18,9/15	24	6	52	29.203	56.677	2,66	77.7679	0,73

In the current situation, the energy consumption during the Y-Δ starting method has been calculated to be an average of 18.9 kWh. In contrast, when operating with a VFD, taking energy savings into account, it has been measured that production occurs at an adequate quality with an energy consumption of 15 kWh at a frequency of 45 Hz. In this context, the power consumption difference between Y-Δ and VFD operation has been determined to be 3.9 kWh. The facility operates six days a week, 24 hours a day throughout the year. The total production hours and the payback periods of the investment have been calculated based on occupancy rates ranging from 70% to 100%. The project cost has been realized at 56.677 ₺, excluding taxes, while the unit energy price at the time of operation is 2.66 kWh/₺, net of taxes. Considering that the fan motor operates at a 70% occupancy rate even under the worst conditions, the payback period for the investment has been calculated to be 1.04 years.

4. Discussion and conclusions

In this study, the analysis of data obtained from driving an asynchronous motor with frequency control revealed significant advantages for energy consumption optimization and process condition adjustments in systems operating at varying speed ranges. Calculations show that the Variable Frequency Drive (VFD) used for the fan motor can save 20.442 MWh of energy annually, even with a 30% loss time. Additionally, it is estimated that the system has prevented 10.57 tons of carbon emissions, which contributes to avoiding future carbon taxes and environmental damage. The investment is observed to pay for itself in just 1.04 years, even at the lowest efficiency. Compared to similar studies that report energy savings in the range of 10 to 30 percent, the results obtained in this study, which indicate savings exceeding 28 percent, align with the upper limit of this spectrum and confirm the practical applicability of VFD integration in industrial environments. From a theoretical perspective, the study contributes by validating energy efficiency models using real-world operational data. From a practical standpoint, it offers a useful reference for engineers and facility managers who are planning to implement energy-efficient motor control systems. However, it has been noted that the THD increased from 13.81% to 32.77% when the fan motor operates with VFD compared to the Y-Δ starting method. The increase in harmonic currents resulting from the use of VFDs should be considered not only for their immediate impact but also for their long-term implications. Elevated harmonic levels can lead to excessive heating, reduced efficiency, and premature aging of electrical components such as transformers, cables, and other infrastructure. These effects may compromise system reliability and result in increased maintenance requirements and operational costs. In this regard, the implementation of harmonic filters, whether passive or active, represents an effective solution to minimize harmonic distortion and ensure the stable and efficient operation of the electrical system.

The data used in this study were obtained under specific industrial conditions, which may not fully reflect all operational environments. Therefore, the applicability of the results may vary across different industries or system configurations. Although the proposed model has been shown to provide energy savings, factors such as the system’s long-term performance, maintenance requirements, and component wear have not been examined in depth. Furthermore, the study was limited to a single motor type, and additional research is needed to evaluate the applicability of the model to other motor types or more complex systems.

Based on these results, it has been concluded that VFD conversion is not only suitable for fan motors but also for other types of motors, according to the benefit-cost analysis, thus potentially improving operational efficiency in industrial applications. Moreover, the methodologies proposed in this study provide a practical roadmap for future energy efficiency projects.

Future research could focus on applying similar VFD-based efficiency analyses to other types of motor-driven systems within the same facility or across different industries. In particular, motors operating under variable load conditions such as pumps or compressors can be prioritized. Additionally, the impact of harmonics on the power quality can be examined in greater detail, and advanced filtering technologies or multi-level inverter systems could be studied to reduce THD levels more effectively. Long-term performance monitoring and the integration of energy management systems may also offer new perspectives on sustainable industrial practices.

Author contribution

MG: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Resources, Writing. EOY: Supervision, the preparation of the manuscript, interpretation of the results, and revised the draft. AB: Supervision, the preparation of the manuscript, interpretation of the results, and revised the draft.

Declaration of ethical code

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

Conflicts of interest

The authors declare that they have no conflict of interest.

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