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Harmonic Mitigation Study for Large Scale Pump Station

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ABSTRACT
The demand for electrical energy has been rapidly increasing each day due to population growth and industrial development. Electrical energy is one of the fundamental inputs of industrial production, and it must be supplied in a reliable and high-quality manner. Therefore, not only high-power energy generation and consumption activities, but also the quality of the energy itself, have become critically important issues. In particular, harmonics—arising prominently with the rapid advancement of semiconductor technology—are among the most significant parameters of power quality and have adverse effects on power systems. In this study, harmonic problems occurring in a high-power pump station located in Istanbul are examined. First, harmonic distortion levels were analyzed by conducting measurements at various points within the facility, thereby revealing its current power quality condition. Then, based on the measurement results, the facility was modeled in a power system analysis software under the same operating conditions as those present during the real measurements, and the model was validated. Finally, simulations were performed in the ETAP program using passive harmonic filters under different operating scenarios, and the total harmonic distortion levels of current and voltage (THD_I and THD_V) were reduced. By mitigating harmonic-related issues, active power losses in the pump station were decreased, and the power factor was improved.

Keywords **–** harmonic, pump station, case simulation

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I. INTRODUCTION

Electrical energy is one of the most critical infrastructure components today and plays a vital role in ensuring the continuity of high-power pump stations. As the population increases day by day and industrialization accelerates, the rising demand for energy—combined with the limitations of energy production resources and escalating costs—has made not only the quantity of energy but also its quality a significant concern. Consequently, the concept of power quality has gained increasing importance in both academic research and industrial applications [1], [2].

Harmonic distortions are among the most significant factors that determine power quality. Harmonics have become increasingly prominent, particularly due to the widespread use of nonlinear loads and devices containing power-electronics-based semiconductor components [3]. Industrial facilities such as steel plants, arc furnaces, welding machines, frequency converters, inverters, UPS systems, and switched-mode power supplies are all sources of harmonics, and their usage has grown substantially with advancing technology [4], [5].

Although advancements in technology appear beneficial due to increased controllability of power, they also create significant drawbacks for power quality. Harmonics cause distortion in current and voltage waveforms, malfunction of protection devices, equipment failures, transformer overheating, excessive loading of neutral conductors, and increased network losses [6], [7], [8]. In addition to these adverse effects, harmonics also reduce the power factor and pose threats to both operational efficiency and workplace safety [9].

Studies focusing on the detection of harmonic distortions in industrial facilities and the development of solutions for these issues reveal that similar problems occur across various sectors. In the research conducted by Farbis Anthony and colleagues, harmonic distortions generated by adjustable speed drives (VFDs) used to operate submersible electric pumps in an oil field were examined [10]. In the system, where motor power ranged between 800–600 kW, the initial measurements recorded $\%THD_I$ levels of 38–42%, $\%THD_V$ levels of 6–8%, and a power factor of 0.86. These high harmonic levels led to severe power quality problems such as excessive transformer heating, nuisance tripping in protection systems, and failures in neighboring loads. The analysis revealed that the 5th, 7th, 11th, and 13th harmonics were particularly dominant, and a single-tuned passive filter was designed to mitigate their effects. After implementing the filter, $\%THD_I$ was reduced to 6–7%, $\%THD_V$ to 2.5–3%, and the power factor was improved to the range of 0.97–0.99. Similarly, another study carried out in a steel plant containing large motor drives, arc furnaces, and welding machines addressed harmonic distortions caused by nonlinear loads and their impacts [11]. High current harmonics resulted in issues such as cable and transformer overheating, neutral conductor imbalance, and a reduction in power factor. The facility was modeled in the MATLAB/Simulink environment, and passive filter applications were analyzed through simulation. Following implementation, filtering of the 5th and 7th harmonics reduced $\%THD_I$ from 32.8% to 5.2% and $\%THD_V$ from 6.1% to 1.7%, significantly decreasing system losses and waveform distortions. In the study referenced as [12], harmonic distortions caused by heavy nonlinear loads in the chemical industry were examined. Initial measurements recorded a power factor of 0.7, $\%THD_I$ of 30%, and $\%THD_V$ of 11%. After integrating an active harmonic filter into the system, the power factor improved to 0.91, $\%THD_I$ decreased to 6–7%, and $\%THD_V$ to 4–5%, thereby enhancing both the efficiency and stability of the system.

Similar power quality issues are also observed in hydraulic systems. In the study referenced as [13], the adverse effects of harmonics generated by motor drives used in water pumping stations on energy efficiency were investigated. Modeling and analysis revealed that passive filters were insufficient; however, with the application of a shunt active power filter (SAPF), %THDI could be reduced from 30% to approximately 3%. This solution reduced system losses, improved the power factor, and minimized waveform distortions. In another related study, El-Arwash, Gafar, and El-Sehiemy examined harmonic problems caused by large motors and pumps in seawater desalination plants [14]. The system contained numerous motor–pump groups, soft starters, UPS units, and frequency converters. Following the implementation of an active filter, the distortion in the 5th harmonic decreased from $\%HD_I$ 12.92 to %0.10. This improvement significantly reduced the overall harmonic content throughout the facility and eliminated power quality issues.

Khaledian, Johnson, and Hemati focused on another critical problem caused by harmonics in motor drive systems: vibration and noise [15]. Investigating a case in which a 12,000-horsepower synchronous motor failed to start when operated through a soft starter, the researchers identified the root cause as harmonic currents generated by the power-electronic components (SCRs) within the soft starter, which produced additional harmonic torques (torque harmonics) on the motor. These additional torques, particularly prominent when the motor speed was in the 1/7 region, reduced the total output torque below the load torque, thereby preventing the motor from starting. In the study, instead of conventional filtering methods, the issue was resolved by developing a startup procedure in which the soft starter's firing angles were gradually increased, resulting in significantly lower harmonic generation. This approach enabled the motor to start smoothly without failure. The study demonstrates that effective harmonic mitigation relies not only on filtering techniques but also on optimizing system design and startup strategies.

The reviewed studies collectively indicate that harmonic distortions caused by nonlinear loads result in similar adverse effects across various sectors—including oil production, steel manufacturing, water treatment, and the chemical industry. However, these studies also demonstrate that appropriately designed active or passive filters can significantly reduce THD levels and improve the power factor.

In this study, a harmonic analysis was conducted on a high-power water pump station located in Istanbul. Measurements were taken at designated points within the facility using a Fluke 435-II power quality analyzer [16], and the current condition of the system was evaluated. Secondly, the facility's operating configuration under real conditions was modeled and simulated using the ETAP (Electrical Transient Analyzer Program) package software, and validation was achieved by obtaining results that closely matched the actual measurements. It was determined that harmonic distortions caused excessive heating in motor and transformer windings, deformation of current and voltage waveforms, malfunctioning of protection relays, increased line losses, and, additionally, a reduction in the power factor. To address all these issues, passive harmonic filters were modeled in ETAP under various scenarios, and simulations were performed. According to the results, the $\%THD_I$ measured at the point of common coupling was reduced by 52.63%, active power losses within the facility were decreased, and the power factor was improved. The findings are presented in detail.

II. THEORETICAL BACKGROUND

2.1. Fundamental Concepts of Harmonics

In electrical power systems, harmonics are sinusoidal waves that occur at integer multiples of the fundamental frequency. These waves arise as a result of connecting nonlinear loads to the network. The instantaneous expressions for voltage and current are given in Equations (1) and (2), respectively.

$$V(t) = \sum_{n=1}^{\infty} V_n(t) = \sum_{n=1}^{\infty} \sqrt{2V_n \sin{(nw1t + \theta_n)}} \quad (1)$$

$$i(t) = \sum_{n=1}^{\infty} i_n(t) = \sum_{n=1}^{\infty} \sqrt{2I_n \sin{(nw1t + \delta_n)}} \quad (2)$$

V_n (Volts) and I_n (Amperes) represent the instantaneous voltage and current of the n^{th} harmonic, respectively. θn (radians) and δn (radians) denote the phase angles of the voltage and current harmonics.

The expressions for active and reactive power in the presence of harmonics are given in Equations (3) and (4).

$$P = \sum_{n=1}^{\infty} V_n I_n cosn(\theta - \delta) \quad (3)$$

$$Q = \sum_{n=1}^{\infty} V_n I_n sin(\theta - \delta) \quad (4)$$

The root-mean-square (RMS) values of current and voltage are given in Equations (5) and (6), respectively.

$$\mathrm{I} = \sqrt{\sum_{n=1}^{\infty} {I_n}^2} \quad (5)$$

$$\mathrm{V} = \sqrt{\sum_{n=1}^{\infty} {V_n}^2} \quad (6)$$

The fundamental quantities used to determine harmonic limits are defined as total harmonic distortion (THD) in the relevant standards and regulations [33]. The %THD values of voltage and current waveforms containing harmonic components are expressed by Equations (7) and (8).

$$\%\mathrm{THD_V} = \frac{\sqrt{\sum_{i=2}^{n} Vi^2}}{V_1} \quad (7)$$

$$\%\mathrm{THD_I} = \frac{\sqrt{\sum_{i=2}^{n} Ii^2}}{I_1} \quad (8)$$

The total active power loss in a system, incorporating the effects of both the fundamental component and the harmonic components, is given in Equation (9).

$$P_{loss} = \sum_{h=1}^{\infty} 3{I_h}^2 . R_h \quad (9)$$

Here, I_h represents the RMS value of the h^{th} harmonic current (A), and R_h denotes the resistance corresponding to the h^{th} harmonic component (Ω).

III. SYSTEM DESCRIPTION

In this study, a high-power pump station located in Istanbul is examined. The reduced single-line diagram of the facility at the time the measurements were taken is shown in Figure 1. As illustrated, two transformers rated at 10 MVA and 12.5 MVA convert the 34.5 kV supply voltage from the grid down to 6.3 kV. Fixed capacitor banks are installed at the outputs of these transformers. The capacitor bank connected to Measurement Point 2 has a nominal rating of 3×279 kVAR, while the capacitor bank connected to Measurement Point 3 has a nominal rating of 3×200 kVAR. These capacitor banks are switched on or off depending on the reactive power compensation requirements. Measurement Points 5 and 7 supply large high-power electric motors operating at 6.3 kV. At Measurement Point 7, there are two identical 2000 kW motor–pump units and one 6.3 kV/0.4 kV, 250 kVA auxiliary transformer. At Measurement Point 5, there is one 800 kW and one 350 kW motor–pump unit, as well as a 6.3 kV/0.4 kV, 400 kVA auxiliary transformer and a fixed capacitor bank rated at 3×117 kVAR. At Measurement Point 6, a 6.3 kV/0.4 kV MVA transformer supplies the facility's low-voltage power distribution center.

The measurement points used for the analyses were identified and are shown in the simplified one-line diagram in Figure 1. These points represent critical locations within the facility, and detailed measurement results obtained with the Fluke 435-II are presented in Table 1. Based on the collected results, the facility was modeled and validated in the power system analysis software using real operational data. Subsequently, simulations were performed under various scenarios, and the outcomes were evaluated accordingly.

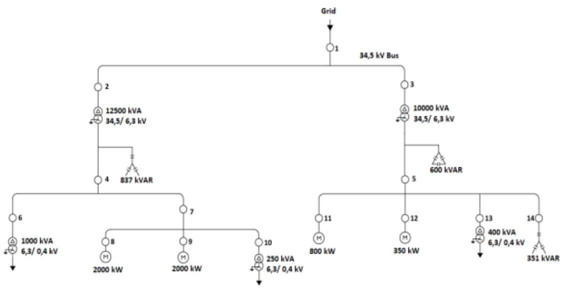

Figure 1. Reduced Single-Line Diagram

The harmonic spectrum clearly shows that the total harmonic distortion is predominantly caused by the 5_{th} and 7_{th} order harmonics. Therefore, a cost-effective tuned passive filter was selected to eliminate these dominant harmonics from the system.

IV. MODELLING AND ANALYSIS STUDIES

ETAP software was used for the modeling and analysis studies. All electrical equipment in the facility—including electric motors, capacitors, transformers, cables, and circuit breakers—was entered into the program according to their actual nameplate values, with the aim of obtaining simulation results that closely match the real measurement data. The scenarios created in the program were intended to evaluate and improve the existing condition of the facility.

4.1 Case Study

The scenarios considered in the modeling and analysis studies are as follows:

Case 1: Modeling and analysis of the existing condition and validation of model accuracy

Case 2: Modeling and analysis of harmonic-filtered compensation instead of fixed capacitors connected to measurement points 2 and 3

Case 3: Modeling and analysis of keeping the filtered capacitor at measurement point 2 active, deactivating the filtered capacitor at measurement point 3, and adding harmonic-filtered compensation instead of the fixed capacitor at measurement point

When the existing condition (Case 1) was modeled and analyzed, the results were found to be very close to the actual measurements. Based on the results obtained from Case 1, the electrical parameters of the filters to be used in Case 2 and Case 3 were also determined. During the filtering process, single-tuned passive filters were employed with the aim of reducing the 5_{th} and 7_{th} harmonics, thereby lowering the overall harmonic distortion in the system and improving operational efficiency. While analyzing Case 1, the existing reactive power demand of the system was calculated, and the filter capacities for compensation in the other scenarios were determined accordingly.

4.2. Simulation Results

In this study, a screenshot of the model created in the software used for modeling three different cases is shown in Figure 4. The modeled compensation units and harmonic filters were included or excluded from the simulations according to the scenarios by switching them within the model. For the evaluations, measurement point 2 connected to the 12.5 MVA transformer, measurement point 3 connected to the 10 MVA transformer, and measurement point 1 at the facility's point of common coupling with the grid were selected as critical areas. For each case, key data at these designated measurement points were analyzed and presented in tables.

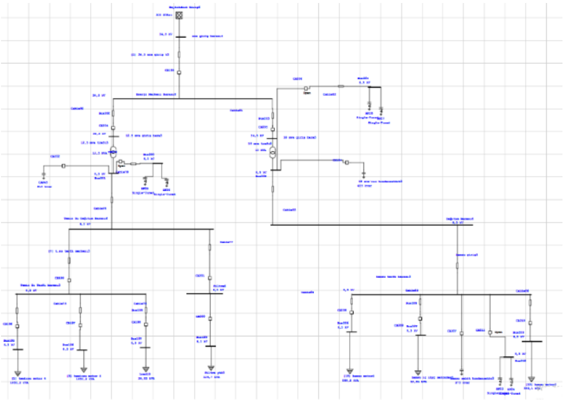

Figure 4: Screenshot of the Water Treatment Plant Model

4.2.1. Case 1

In this scenario, the system's operation was modeled to exactly replicate real operating conditions. The primary objective was to validate the closeness of the simulation results to the actual measurements. Accordingly, all fixed capacitors in the system were activated during the simulation, as they were at the time of the measurements. The resulting measurement data are presented in the table below.

Table 2: Comparison of Case 1 Simulation Results with Actual Measurements

Measurement Points	S (kVA)		Cosφ		Power Factor		THD_I (%)		THD_V (%)	
	Simulation	Actual Measurement	Simulation	Actual Measurement	Simulation	Actual Measurement	Simulation	Actual Measurement	Simulation	Actual Measurement
1	4542,753576	4574,5	0,9993	1	0,997681	0,9966	5,7	5,8683	2,01	1,7855
2	3377,178645	3487,5	0,9987	1	0,997611	0,9982	4,67	4,44	2,01	1,7994
3	1219,370697	1181	0,962	0,9902	0,957489	0,9796	9,53	9,7922	2,01	1,7833

As shown in Table 2, the error between the modeled and simulated results and the actual measurement data in this scenario is low. It is known that the facility experiences issues caused by harmonics, and the measurement results are consistent with the simulation. Furthermore, the modeling results indicate that the active power loss in the system is 16,293.58 watts.

4.2.2. Case 2

In this scenario, the system was modeled using single-tuned filter compensation instead of conventional compensation. Based on previous measurement results, the 5_{th} and 7_{th} harmonics were identified as dominant in the system. Additionally, the reactive power requirement of the system was determined from the results obtained in Case 1. Using this information, passive filter designs were carried out, and modeling and analysis were performed. For connection at measurement point 2, two 300 kVAR passive filters were designed. The filter used to eliminate the 5_{th} harmonic has a capacitance of 24.06 µF, an inductance of 16.84 mH, an internal resistance of 0.378 Ω, and a quality factor (Q) of 70. The filter for the 7_{th} harmonic has a capacitance of 24.06 µF, an inductance of 8.59 mH, an internal resistance of 0.27 Ω, and a Q factor of 70.For measurement point 3, two 40 kVAR passive filters were added to the system. The filter for eliminating the 5_{th} harmonic has a capacitance of 3.208 µF, an inductance of 126.36 mH, an internal resistance of 2.835 Ω, and a Q factor of 70. The filter for the 7_{th} harmonic has a capacitance of 3.208 µF, an inductance of 64.46 mH, an internal resistance of 2.025 Ω, and a Q factor of 70.

The passive harmonic filters were designed, modeled in package software, and simulations were conducted. The resulting data are presented in the table below.

Table 3: Case 2 Measurement Results

Measurement Points	S (kVA)	Cosφ	Power Factor	THD_I (%)	THD_V (%)
1	4542,75358	0,9999	0,99951	2,8	1,86
2	3383,155953	0,9999	0,99954	2,68	1,86
3	1159,59762	1	0,99851	5,47	1,86

According to Table 3, as a result of the implemented measures, the $\%THD_I$ at the main incoming point of the system, measurement point 1, decreased to 2.8%, representing an approximate reduction of 50.88%. In addition to the current, the voltage harmonic distortion (%THD_V) decreased to 1.86%, corresponding to a 7.46% reduction. Improvements in the power factor are also observed in the table. Moreover, as a positive effect of the filters, the total active power loss in the system decreased to 16,280.92 watts.

4.2.3. Case 3

In this scenario, the passive filter connected to measurement point 2 was kept active, while the filter compensation unit at measurement point 3 was deactivated. Instead, a single-tuned harmonic filter was designed to replace the fixed capacitor at measurement point 14. Single-tuned filters were designed to eliminate the dominant 5_{th} and 7_{th} harmonic components identified in the system. Based on the measurement results at the existing bus, the reactive power requirement of the system was determined. Using this information, the passive filter design was implemented in the software. Two 120 kVAR passive filters were designed for connection at measurement point 14. The filter used to eliminate the 5_{th} harmonic has a capacitance of 9.624 μF, an inductance of 42.11 mH, an internal resistance of 0.945 Ω, and a Q factor of 70. The filter for the 7_{th} harmonic has a capacitance of 9.624 μF, an inductance of 21.48 mH, an internal resistance of 0.675 Ω, and a Q factor of 70.

The designs were modeled, simulations were performed, and the resulting data are presented in the table below.

Table 4: Case 3 Measurement Results

Meusurement Points	S (kVA)	Cos φ	Power Factor	THD_I (%)	THD_V (%)
1	4542,753576	1	0,999742	2,27	1,82
2	3382,175612	0,9999	0,999544	2,67	1,82
3	1159,261606	0,9981	0,997731	2,72	1,82

According to Table 4, as a result of the implemented measures, the %THD_I at the main incoming point of the system, measurement point 1, decreased to 2.27%, representing a reduction of approximately 60.18% compared to Case 1 and 18.93% compared to Case 2. The voltage harmonic distortion (%THD_V) decreased to 1.86%, corresponding to reductions of 9.45% and 2.15% compared to Case 1 and Case 2, respectively. In addition to mitigating harmonic distortion, the system's power factor has moved closer to unity. Furthermore, the total active power loss in the system with the filters is 16,271.57 watts.

4.2.4. Assessment

Significant problems caused by harmonics occur in high-power pump stations. These issues not only increase losses and reduce energy efficiency in the facility but also damage electrical equipment within the system. In this study, the existing system was modeled in software to eliminate the harmful harmonics, and solutions were explored through various scenarios. According to the prepared scenarios, the %THD_I, %THD_V, and total active power losses at the critical measurement points are presented in the table.

Table 5: Comparison of Scenarios

	Case 1		Case 2		Case 3	
Meusurement Points	THD_I (%)	THD_V (%)	THD_I (%)	THD_V (%)	THD_I (%)	THD_V (%)
1	5,7	2,01	2,8	1,86	2,27	1,82
2	4,67	2,01	2,68	1,86	2,67	1,82
3	9,53	2,01	5,47	1,86	2,72	1,82
P_{loss}	16,293.58 W		16,280.92 W		16,271.57 W	

According to Table 5, one of the positive effects of eliminating harmonics is the reduction of losses. Case 1 confirms the accuracy of the modeled system by closely matching the actual measurement values. Based on this established model, the scenarios were applied. In Case 2 and Case 3, harmonics were significantly reduced, and total active power losses also decreased. Case 3 represents the most efficient scenario, with $\%THD_I$ reductions of 60.18% at measurement point 1, 42.81% at measurement point 2, and 71.46% at measurement point 3 compared to Case 1, while $\%THD_V$ reductions were 9.45% across all points. In the scenarios using harmonic filters (Case 2 and Case 3), the RMS values of currents decreased, leading to reductions in copper losses in cables, transformer losses, and motor losses, which are reflected in the results presented in the table.

V. CONCLUSION

Harmonics are among the most important power quality parameters and, if not mitigated, can cause serious problems in electrical installations. High-power pump stations contain numerous electrical devices, some of which generate harmonics, while others may be damaged due to the harmonics present in the system. The main problems caused by harmonics include overheating of transformer and motor windings, distortion of voltage and current waveforms, malfunctioning of protective equipment, increased losses due to higher current RMS values, and damage to capacitors caused by resonance effects.

In this study, a high-power pump station was examined to analyze the effects of harmonic mitigation on $\%THD_I$, $\%THD_V$, power factor and system losses. First, the actual measurements of the system were evaluated to identify existing problems. Subsequently, the system was modeled using the collected data and measurement results. During modeling, the actual operating conditions were first replicated in the software, and a low error margin between the simulation results and the real measurements was confirmed. Then, the model was simulated under different scenarios to explore solutions for harmonic issues. As a result, in Case 2, $\%THD_I$ and $\%THD_V$ at measurement point 1, the main incoming bus of the facility, decreased by 50.88% and 7.46%, respectively. In Case 3 at the same measurement point, $\%THD_I$ decreased by 60.18% and $\%THD_V$ by 9.45%. In both cases, the power factor at point 1 improved from 0.997 to 0.999. After harmonics were mitigated, a reduction in total active power losses within the system was also observed.

This study demonstrates that high-power pump stations can experience problems caused by harmonics. Through various modeling and analyses, these issues can be addressed and resolved with appropriate designs. In future studies, more detailed analyses for high-power pump stations are planned.

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