

## Active filter solutions in energy systems

Sabir RÜSTEMLİ<sup>1</sup>, Mehmet Sait CENGİZ<sup>2,\*</sup>

<sup>1</sup>Department of Electrical and Electronics Engineering, Faculty of Engineering, Bitlis Eren University, Bitlis, Turkey

<sup>2</sup>Technical Vocational School, Bitlis Eren University, Bitlis, Turkey

Received: 20.02.2014

Accepted/Published Online: 07.08.2014

Printed: 30.11.2015

**Abstract:** Recent developments in power electronics have increased the usage of nonlinear loads in energy systems. With increases in the usage of semiconductor-sourced nonlinear loads, the adverse effects of harmonics-sensitive loads (e.g., protection control circuits and circuit breakers) have also increased. Generally, the negative effects of harmonics in power systems include the following: increased power losses; motor, generator, and transformer overheating; faulty operation of measurement and protection systems; lifetime shortening of electrical components; and parallel and series resonance problems. Therefore, harmonics has become a serious problem in current power electronics systems. However, harmonics can be reduced, particularly through drainage using filters. In this study, some power losses were detected in different facilities in the city of Van, Turkey, on the basis of the variable measurements (e.g., instantaneous electrical values, harmonics, flow, and voltage waveforms) obtained using ZERA MT 310 power analyzers. The harmonics causing these power losses were examined. Some simulation results for active filters were evaluated, and the overall effects of the harmonics are discussed. Shunt active power filter (SAPF) simulation was conducted using Simplorer 6.0, which is known to produce successful results in power electronics simulation applications. SAPF simulation requires the use of measurement points. This utilization of SAPF simulation has demonstrated that voltage drop and power loss in power distribution systems can be reduced. However, it was found that owing to their structure, semiconductor components produce harmonics and consume power.

**Key words:** Power quality, harmonics, active filter, distribution system

### 1. Introduction

Power electronics elements have been used since 1970, particularly as switching elements in control systems in the energy sector. However, these elements can produce harmonics while turning on and off, depending on the switching frequency, which can cause problems in the associated systems [1]. For example, when a linear ohmic load is used stand-alone, it does not draw reactive power; however, when used together with switching elements such as thyristors or triacs, this load draws reactive power and produces effective harmonics [2,3]. Moreover, the use of such switching elements can have adverse effects; in particular, the resulting current and voltage waveforms are periodic, and the sinusoidal form of mains voltage can be broken down [4].

Harmonics can cause losses in terms of operating time in electrically propelled system elements. The following events can occur in such circumstances:

- capacitors in systems break down frequently;

\*Correspondence: [msaitcengiz@gmail.com](mailto:msaitcengiz@gmail.com)

- some breakdowns occur without apparent cause;
- measuring devices in factories do not measure accurately;
- switches that act as connection points for the system deenergize randomly;
- automation systems managed by electronic devices in systems malfunction;
- electronic card faults occur continually;
- neutral cables become overloaded and break down;
- punctures in isolated electrical elements within systems occur repeatedly;
- system machines and transformers break down or operate noisily [5].

All these events can be considered indications of the fact that many harmonics are being produced, thus exceeding operating standards [6]. Harmonic filtration is typically conducted using either passive or active filters [7,8]. Passive filters comprise variable connection types for passive circuit elements; these filters have been used for many years and are still used because they remain economical. By constructing a low-impedance means to allow harmonics to flow through passive filters, the current can pass through the shunt filter instead of returning to the source. Passive LC filters, which can be used to both filter harmonics and to increase the power factor of the load, do have some disadvantages; in particular, they exhibit resonance risk such that harmonics can increase depending on resonance, and they occupy considerable space [9,10].

Therefore, active power filter design and application are becoming increasingly important in industry to ensure suppression of harmonics in order to meet the reactive power demand [11]. Generally, an active power filter can be considered a shunt active power filter (SAPF) [12]. SAPFs are used to suppress flow unbalance, high and low harmonics, neutral flow, and reactive power. Conversely, breakdowns in the network and load such as voltage seesaw, voltage unbalance, and voltage harmonics can be eliminated through serial active filters.

In this study, information regarding harmonics intended for industrial installations has been obtained by conducting measurements using a harmonic analyzer device. Some harmonics exceeding typical standards have been observed, and their SAPF design has been conducted using Simplorer 6.0.

## **2. Harmonics problem**

### **2.1. Harmonic analyzer assemblies**

To operate an electrical power system and the associated electrical devices in an accurate and efficient manner and without problems occurring, it is very important to produce, transmit, and submit voltage in the shape of a sine curve with a 50 Hz frequency. However, because of the side effects caused by network elements and consumers, which vary depending on the system, the sinusoidal waveforms of basic electrical parameters such as flux, current, and voltage can be converted into harmonic, inclusive, and undesirable waveforms that are proportional to multiples of 50 Hz, which can be considered the fundamental frequency [13,14].

In this study, a ZERA MT 310 harmonic analyzer was used. The valid current measuring rate of this device is 1 mA to 12 A, and it has an accuracy rate of 0.1%. This harmonic analyzer can measure in four-, three-, and two-wire circuits. The filters proposed in this study were designed to measure current values between 5 mA and 120 A. The device has an internal memory and can store information for up to 150 measurements, and it also facilitates data management via a computer. Degradation factor measurement, which can simultaneously

investigate active, reactive, and apparent power, can also help determine frequency, phase angle, and power factor. This analyzer can record data up to the 40th harmonic, produce a vector diagram, and transmit the resulting data to a printer.

## 2.2. Passive vs. active filters

Active filters neutralize harmonics spread by load by analyzing the harmonics consumed by load and reinstating the same harmonic current with the appropriate phase. In terms of operation logic, active filters measure the current at the point where the active filter is connected to a circuit. Together with a power electronic circuit, an active filter can produce a harmonic with a sign opposite to that detected by the power electronic circuit and inject this new harmonic into the system.

To remove harmonics, typically passive filters are used for their low cost. Because the values of the elements used in passive filters (i.e. capacitor, coil, and resistance) vary with standard frequency, the performance of filters can decrease during operation. When the nonlinear load increases, the passive filter can become overloaded and damaged; consequently, the probability of occurrence of serial or shunt resonance at different harmonic frequencies between filter elements increases. Because of these negative impacts and improvements in processing semiconductor technology and control systems, active power filters have been developed. Such filters operate by injecting a reverse-phase current produced by a nonlinear load in a power system, ensuring that the amplitude of this current is the same as that of the harmonics of the power system. To achieve this, active power filters use variable control gears to apply a switching element by designating power electronics switching elements and harmonics in the system. In addition to being used to remove harmonics from the system, active power filters are also used to regulate reactive power compensation, voltage and voltage unbalance, neutral current, and mains voltage.

A comparison of active and passive filters (Table 1) shows that active filters surpass passive filters, particularly regarding the following factors [13,14]:

- no overloading risk;
- appropriate for all load types;
- impossible for them to be in resonance with the associated system;
- filters can be expanded practically and easily by increasing nonlinear loads;
- all harmonics selected can subsequently be removed.

SAPFs are typically used for the elimination of current harmonics, for reactive power compensation, and in balancing unbalanced current. As current harmonics are included in the system under consideration, shunt active filters are connected to the load side. To remove harmonics and the reactive components of nonlinear loads, these filters act as sources injecting different compensation currents whose harmonic and reactive components have equal amplitude but a phase difference of  $180^\circ$ . Moreover, these filters are often used as static generators to balance voltage profiles and improve voltage [14,15].

Serial active power filters are fastened to the associated network through a serial transformer before the load. Although serial active power filters exhibit low power quality and superior filtration characteristics, they must be protected from power system abnormalities. Conversely, SAPFs are not affected by power system abnormalities and can conduct harmonic current compensation with these filters, similar to power factor compensation. For these reasons, SAPFs are commonly used.

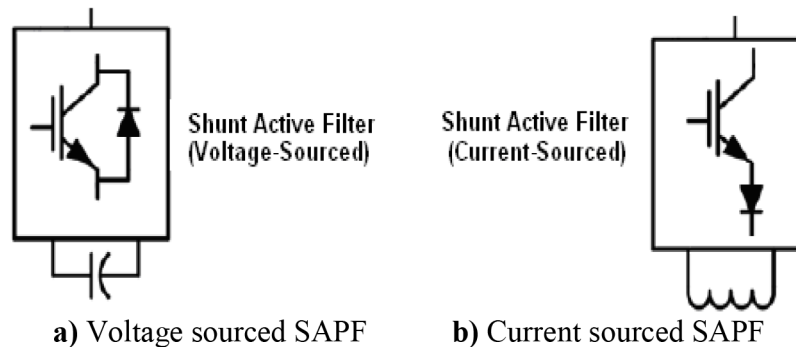
**Table 1.** Comparison of active and passive filters.

Function	Passive filter	Active filter
Harmonic current control	It requires one filter for each harmonic frequency	It is possible to simultaneously control over one harmonic current
Effect of harmonic frequency	Effect of filter decreases	Not affected
Impedance modification effect	Resonance risk is possible	Not affected
Current rise possibility	Overloading and degradation risk is possible	Not affected
Adding new load to the system	Replacement of filter required	Not affected
Frequency change of basic waves in the system	It is not possible to adjust (it can be required to replace filter)	Compatibility is possible with adjustment
Dimensions and weight	It is flexible in terms of harmonic amplitude and degree	Too low
Cost	Installation is low-cost and maintenance is high-cost	Installation is high-cost and no maintenance is required

### 3. Construction of filter

#### 3.1. Features of SAPF

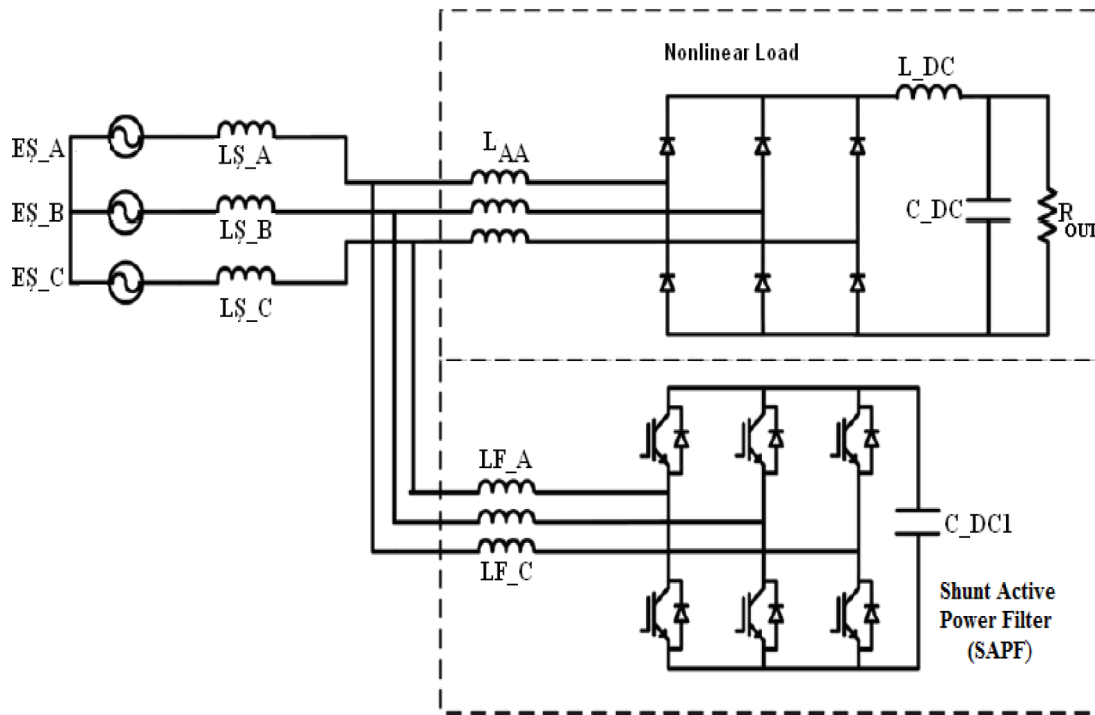
Inverter structures for the SAPF are illustrated in Figure 1. Owing to the nature of the current- and voltage-sourced inverters, insulated gate bipolar transistors (IGBTs) for use in voltage-sourced SAPFs are produced by many semiconductor companies because they exhibit an antishunt diode structure, they can be produced easily, and their losses can be optimized [16]. As the loss of the reactor in the DC linkage of a current-sourced inverter is higher than that of the capacitor in a voltage-sourced inverter, voltage-sourced inverters are used more commonly.



**Figure 1.** Inverter structures for the SAPF: a) voltage-sourced SAPF, b) current-sourced SAPF.

In the technical literature and in industrial settings, the use of SAPFs as linkage-type active filters is most common. Moreover, in terms of linkage type, SAPFs offer a solution for two significant power quality problems: harmonic filtration and reactive power compensation. In these respects, SAPFs are more basic in structure and more stable than serial active filters [17]. The initial cost of a voltage-sourced active power filter is lower than that of a current-sourced filter, which may be an additional reason for the wider adoption of voltage-sourced filters. The most prominent negative features of current-sourced active power filters, particularly in comparison with voltage-sourced filters, include the loss of semiconductor switches and losses due to energy consumed by the reactor used in the DC linkage [18].

Voltage-sourced active power filters with DC capacitors can be wired up to a network through a filter reactor ( $L_f$ ). The voltage-sourced active power filter illustrated in Figure 2 consists of six controlled semiconductor switches and antishunt diodes. The intake filter reactor ( $L_f$ ) used in the active filter intake ensures that the active filter currents can be controlled. Moreover, using both this reactor and the intake capacitor ( $C_f$ ), high-frequency components produced by the inverter can be suppressed.



**Figure 2.** Representations of the SAPF conducting the simulation and the nonlinear load.

### 3.2. SAPF design study

Representations of a SAPF conducting simulation of a nonlinear load are illustrated in Figure 2. A three-phase diode rectifier represents the nonlinear load, and a voltage-sourced shunt three-phase neutral connectionless active filter is connected. In our simulation studies, low voltage levels were selected to govern the SAPF load and the harmonic source connected.

SAPFs are used to eliminate harmonics and compensate for changes in reactive power. In our simulation studies, a diode bridge rectifier (which is used widely in practice) was adopted as the nonlinear load producing harmonic. Components up to the seventh harmonic produced by the designed SAPF and diode bridge rectifier were filtered.

When measuring the load in simulations for the active filter,  $R_{out}$  was provided on the basis of the power values obtained from the measurement points. A capacitor ( $C_{DC1}$ ) connected to the DC side of a voltage-sourced inverter was used as an energy storage element. The coil on the AA side is required to filter the inverter harmonics. A DC line capacitor operating as a DC voltage source for the inverter provided the required compensation current, controlled by power electronics switching elements (i.e. IGBTs). In active power filters, the power source is not typically connected to the DC side of an inverter. Typically, in a voltage-sourced (current-sourced) inverter, a capacitor (coil) is used as the energy storage element.

### 3.2.1. Selection of semiconductors for SAPF inverter circuit

When selecting semiconductors, wavelets caused by switching must be taken into account. For an SAPF inverter, four different types of semiconductor switches are available: MOSFET, GTO, IGBT, and IGCT. Owing to their specific structures, MOSFETs cannot reach the same voltage levels as SAPFs, whereas GTOs are semiconductors composed of outdated technology and exhibit considerable heat loss. In comparison with GTOs, IGCTs are a semiconductor type developed using advanced technology and applied at higher voltage levels and lower switching frequencies. IGBTs are currently being produced in large numbers and developed continuously. In contrast to other semiconductor switches, IGBT switches can be used in inverters owing to their high switching frequency, low losses, and simple driving circuits at middle and high voltages. In other words, IGBTs exhibit very rapid on/off switching and high current strength, making them ideal for use as switching elements.

### 3.2.2. Evaluation criteria for active filter

The total harmonic distortion (THD) for the voltage and current used to limit the harmonic size can be calculated according to Eqs. (1) and (2) [18].

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} (V_n)^2}}{V_1} \quad (1)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} (I_n)^2}}{I_1} \quad (2)$$

In accordance with IEC standards, THD is typically 3% and 6% for voltage and current, respectively [18]. Deviation of the periodical waveform from an exact sine curve is used in determining the THD. Accordingly, THD is zero only for an exact sine waveform with a basic frequency.

SAPFs are not intended to filter all harmonics. Rather, their purpose is to minimize any dominant harmonics exceeding the limiting value to bring them within acceptable levels [19].

## 4. SAPF control methods

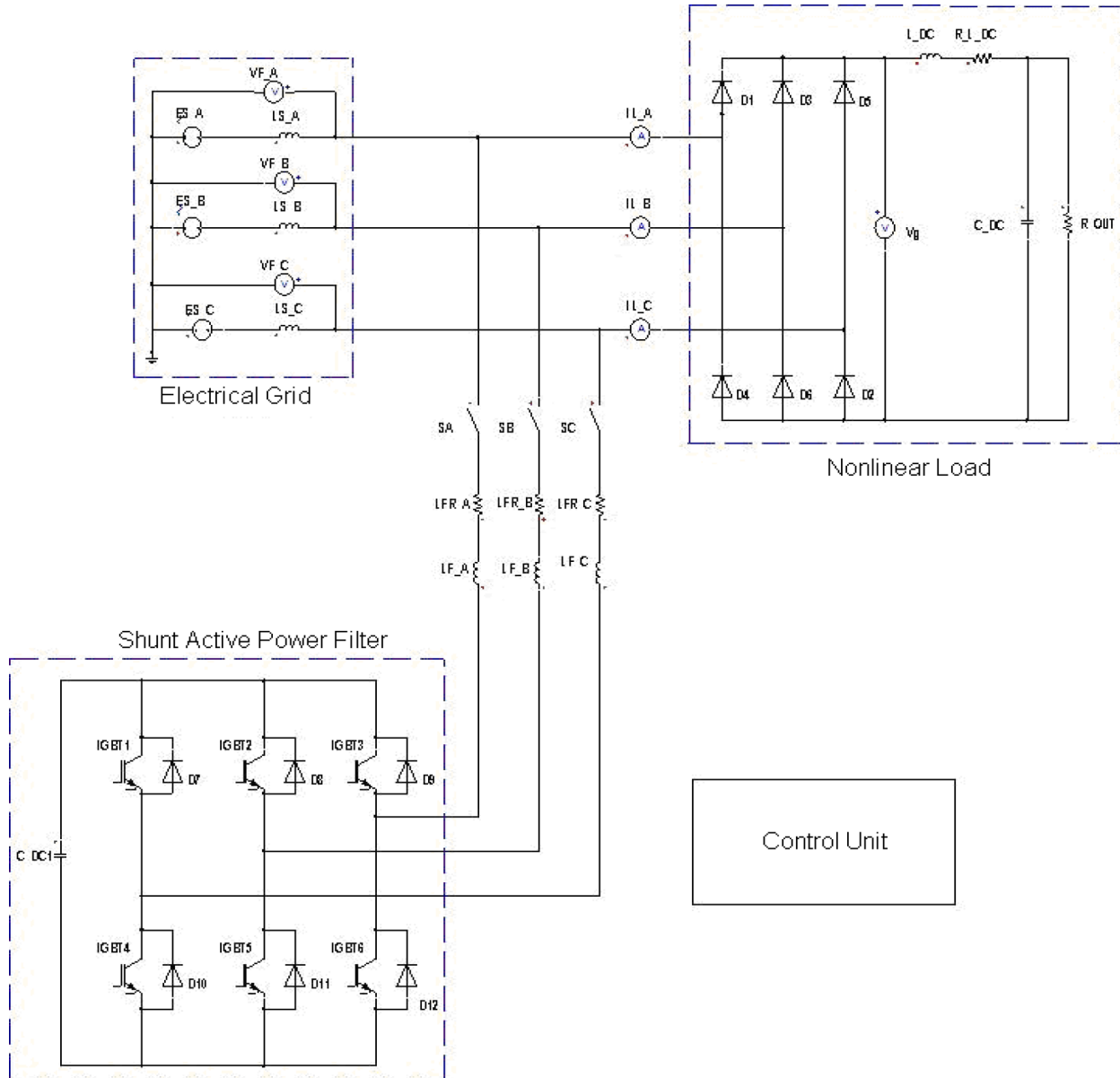
### 4.1. Finding reference current

Because voltage information is not required in the synchronous reference plane (SRP), the SRP method is insensitive to voltage unbalance. Therefore, it is possible to achieve better results with the SRP method. The SRP method is also preferable because it can obtain any harmonic. This method has the following additional advantages: it offers a good level of steady state achievement, i.e. transient response speed and transient response; during these processes, no interaction with voltage occurs, simplifying the removal of selected harmonics; and it does not require memory for performing these processes. The superiority of the SRP method with respect to other controlling methods is summarized in Table 2 [20,21].

### 4.2. Current control method

To obtain ignition signals in voltage-sourced active power filters, the hysteresis band method is typically used for the reference current. After obtaining new reference currents using this method, supervisory regulations or methods of voltage conversion are not required [21–24].

To investigate the SAPF, a simulation circuit was designed using Simplerer 6.0, as illustrated in Figure 3. The values in Table 3 describe the circuit elements used in the SAPF design and indicate the optimum benefits achieved.



**Figure 3.** SAPF simulation circuit designed using Simplerer 6.0.

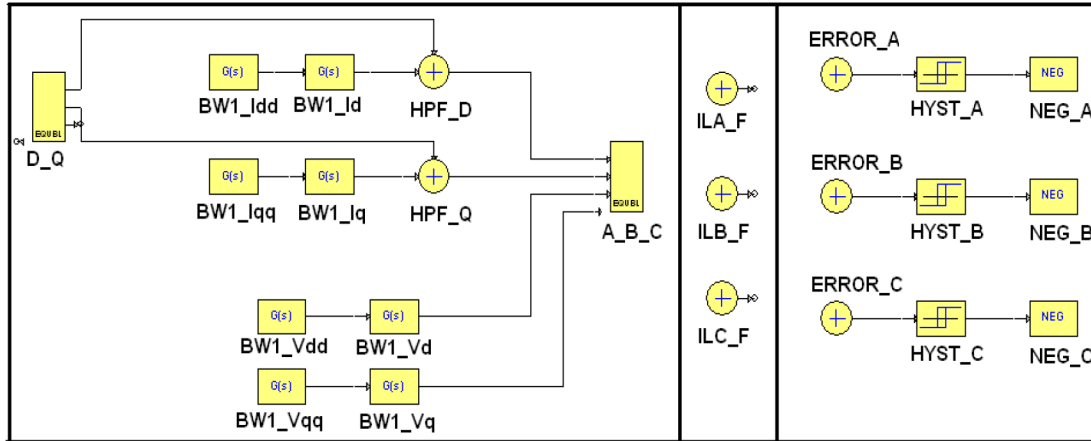
A block diagram illustrating the working logic of the control unit for the SAPF in Figure 3 is presented in Figure 4. From this block diagram, it is clear that AC load currents are subject to Clark–Park transformation, where the currents filtered using high-pass filters are transformed to DC. Voltage blocks are also included in the same control unit. On the basis of these configurations, the inverter reference currents required for the filter currents ( $I_{ah}$ ,  $I_{bh}$ ,  $I_{ch}$ ) were calculated. In the second cell, the obtained currents are compared with the filter currents and placed in hysteresis, whereas the third cell illustrates the hysteresis operation.

**Table 2.** Comparison of reference finding methods.

Reference Method	Filter	Instantaneous reactive power theory of	Synchronous reference plane (SRP)	Discrete fourier transform	Fast fourier transform	Repetitive fourier transform	Kalman
Steady-state performance	Appropriate	Appropriate	Appropriate	Fully appropriate	Fully appropriate	Fully appropriate	Fully appropriate
Transient response time	Not acceptable	Acceptable	Appropriate	Not acceptable	Not acceptable	Acceptable	Acceptable
Transient response performance	Not acceptable	Acceptable	Appropriate	Not acceptable	Not acceptable	Acceptable	Acceptable
Voltage requirement	No	Yes	No	No	No	No	No
Finding selected harmonic	Yes	No	Yes	Yes	Yes	Yes	Yes
Storage requirement	No	No	No	Yes	Yes	Yes	Yes

**Table 3.** Values belonging to circuit elements used in SAPF design and providing optimum benefit.

R Out-A	R Out-B	R Out-C	S A,B,C	LS A,B,C	L DC	R L-DC	C DC	L FR _A,B,C	L F _A,B,C
3.71 Ω	5.28 Ω	2.66 Ω	50 ms	40 μH	200 μH	3 mΩ	60 mF	10 mH	70 μH



**Figure 4.** Block diagram of the control unit for the SAPF.

## 5. Findings

After conducting active filter simulation for the available system, the responses of the system to the filter were inspected individually. This evaluation was conducted using Simpler 6.0.

### 5.1. Distribution systems examples

Here, a single line diagram was considered for active filter simulation, and power values taken from the system at the points where samples A, B, and C were connected were used for calculation and simulation. This was undertaken for the 3rd, 5th, and 7th dominant harmonics.



In the distribution system, we assumed that the loads were distributed equally between three phases. The voltage levels of the sample distribution system, the installed power values, and the line diagram indicating the SAPF connection method are indicated in Figure 5. In the figure, A refers to Van Meat Combination, B refers to the Erciş Sugar Factory, and C refers to Special Hospitals. To obtain the THD rate of the model load determined by calculation based on the active power, the simulation was run without the filter; for each sample, the THD rate was obtained from the simulation circuit. For the available simulation circuit under filter less conditions, THD was 51.35%, 37.32%, and 42.76% for samples A, B, and C, respectively.

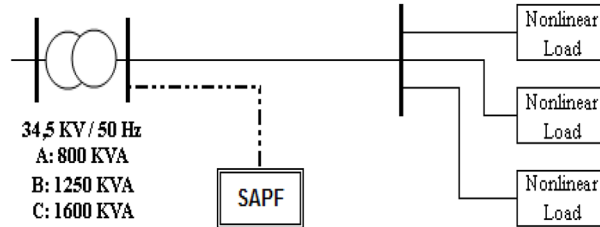


Figure 5. Block diagram of the control unit for the SAPF.

## 5.2. Simulation results

For sample A, the load and filter currents are illustrated in Figures 6 and 7, respectively, whereas the current for the circuit with the active filter after rectification is illustrated in Figure 8. Modification of the voltage obtained after application of the active filter is presented in Figure 9, whereas the active filter output current and output voltage are illustrated in Figure 10.

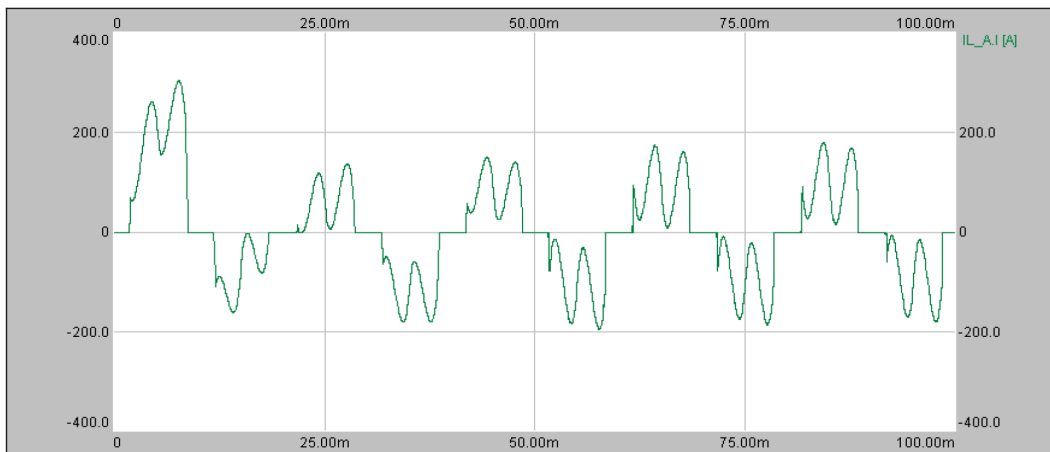
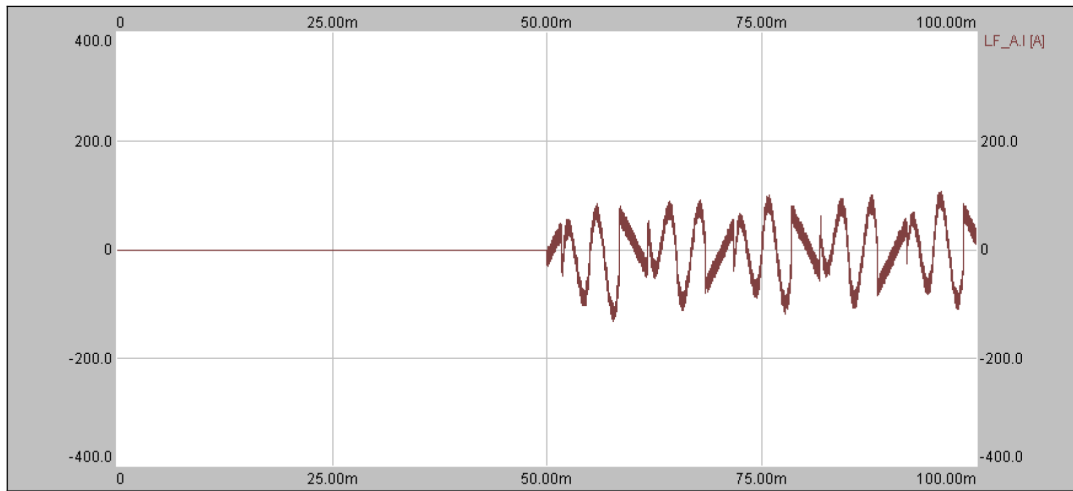


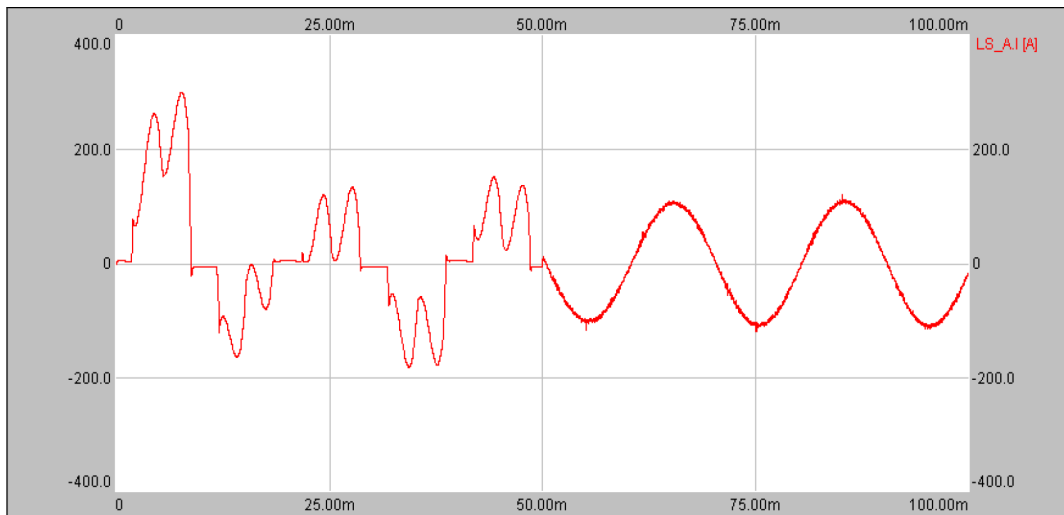
Figure 6. Modification of the load current for sample A (SAPF operates after 50 ms).

The THD rates obtained for simulations without and with a filter for sample A are illustrated in Figures 11 and 12, respectively. The current amplitude spectrum of the system before filtration is indicated in Figure 13, whereas that following application of the filter is shown in Figure 14.

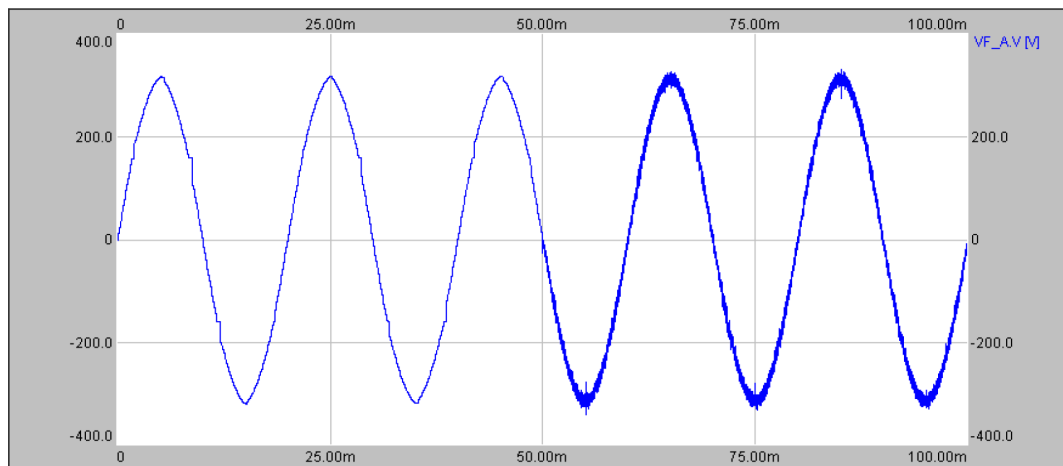
For sample B, the load and filter currents are illustrated in Figures 15 and 16, respectively, whereas the current for the circuit with the active filter after rectification is presented in Figure 17. Modification of the voltage obtained following application of the active filter is illustrated in Figure 18, and the corresponding output current and output voltage are shown in Figure 19.



**Figure 7.** Filter current distributed to the system by the SAPF for sample A (operates for 50 ms).



**Figure 8.** Circuit current while the SAPF operates for sample A (SAPF operates after 50 ms).



**Figure 9.** Voltage modification while the SAPF operates for sample A (operates after 50 ms).

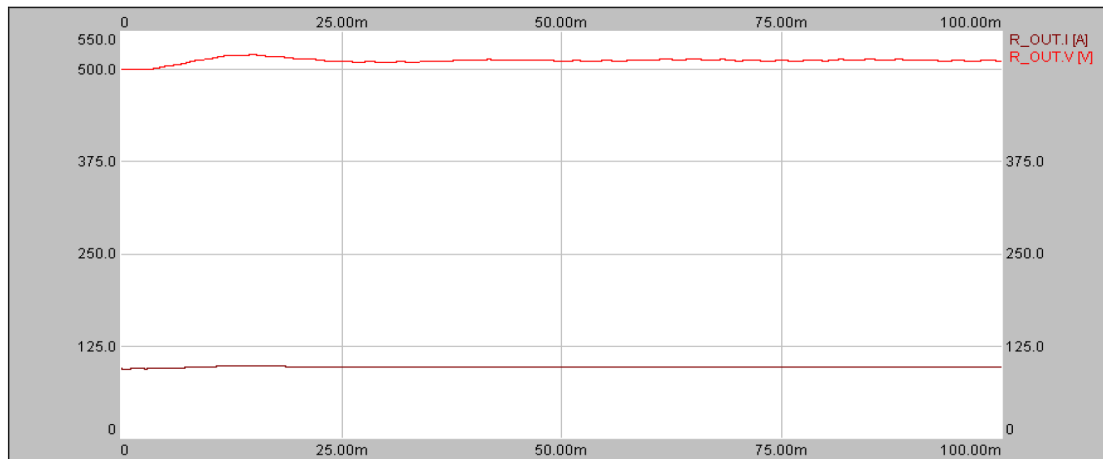


Figure 10. Output current and output voltage while the SAPF operates for sample A.

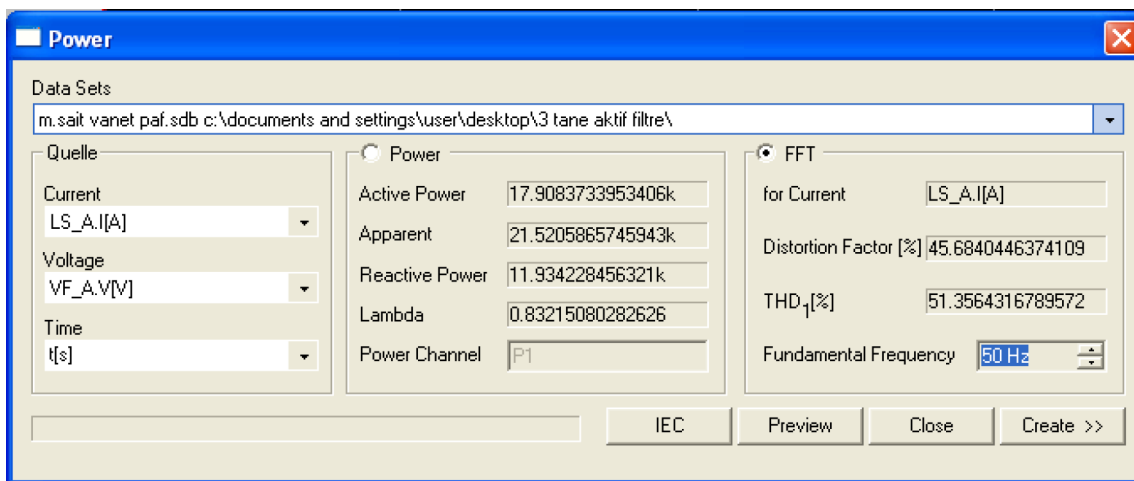


Figure 11. THD of the system before filtration for sample A.

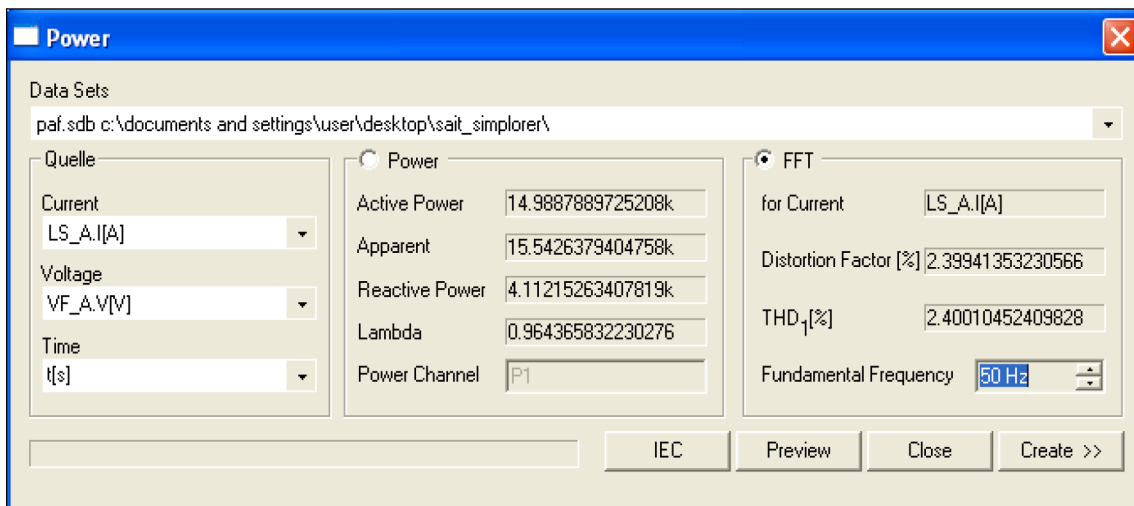
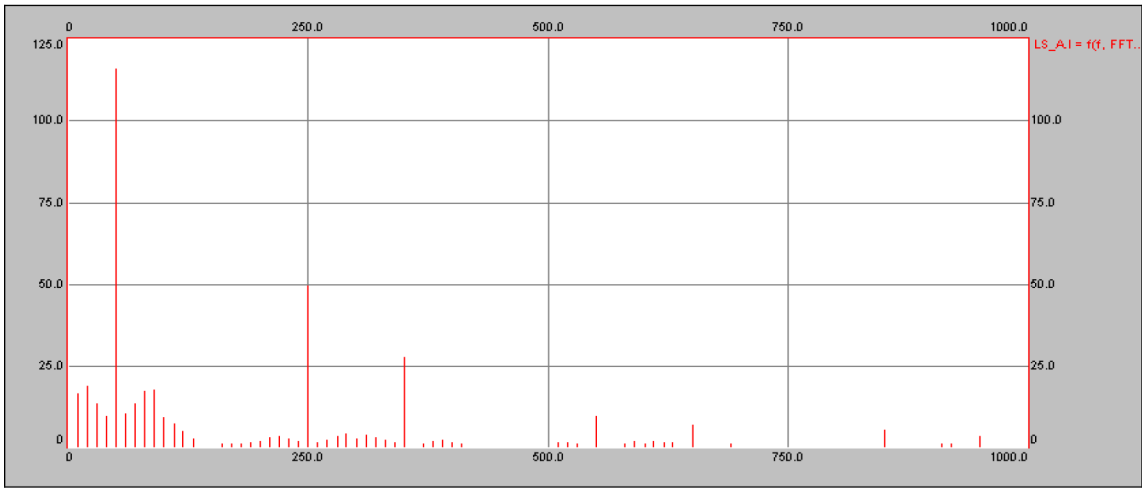
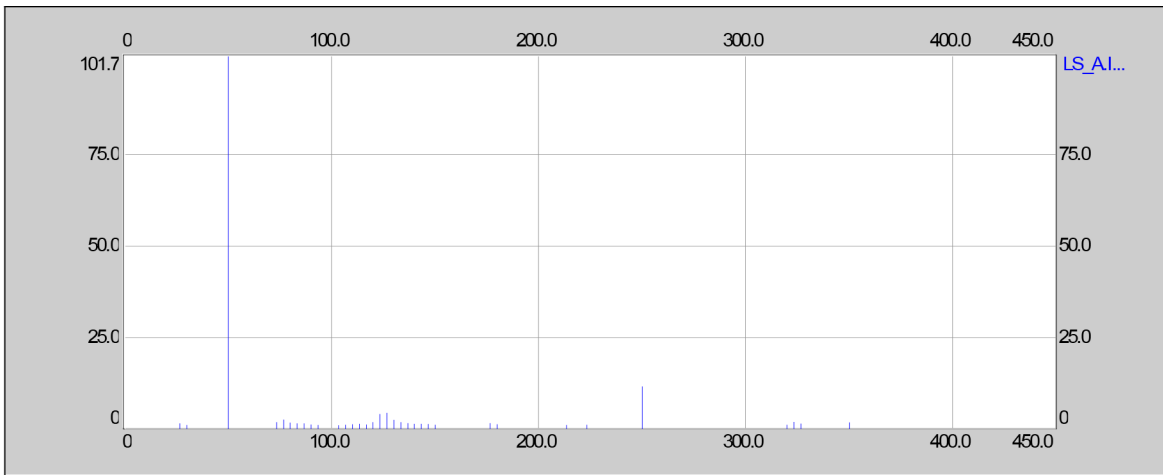


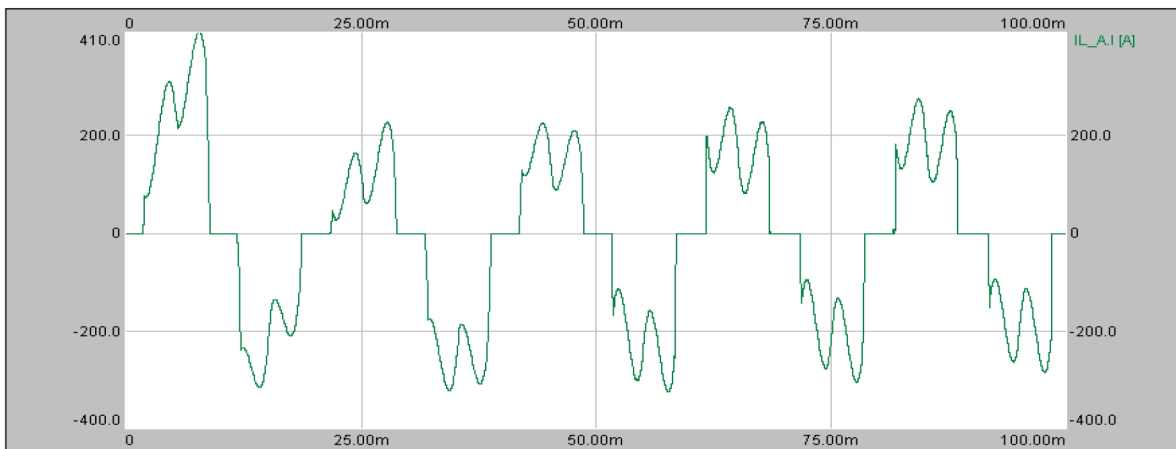
Figure 12. THD calculated while the SAPF operates for sample A (filter operates for 0 ms).



**Figure 13.** Current amplitude spectrum of the system before filtration for sample A.



**Figure 14.** Current amplitude spectrum while the SAPF operates for sample A (filter operates for 0 ms).



**Figure 15.** Modification of the load current for sample B (SAPF operates after 50 ms).

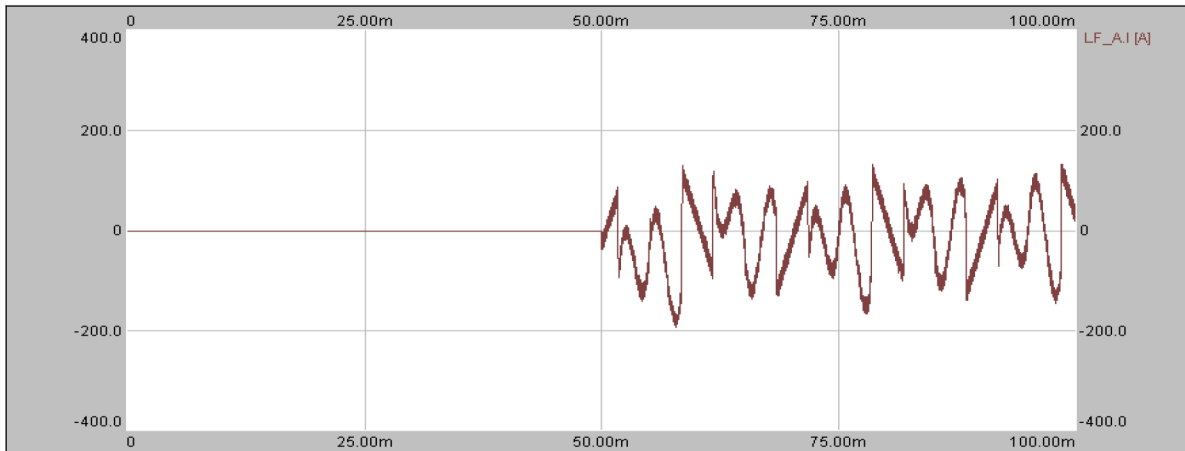


Figure 16. Filter current distributed to the system by the SAPF for sample B (SAPF operates for 50 ms).

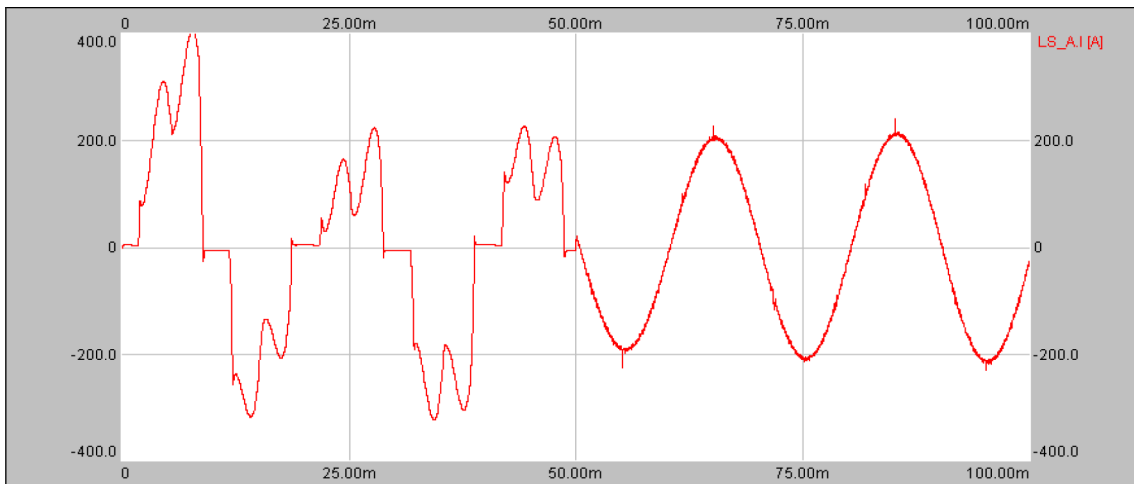


Figure 17. Circuit current while the SAPF operates for sample B (SAPF operates after 50 ms).

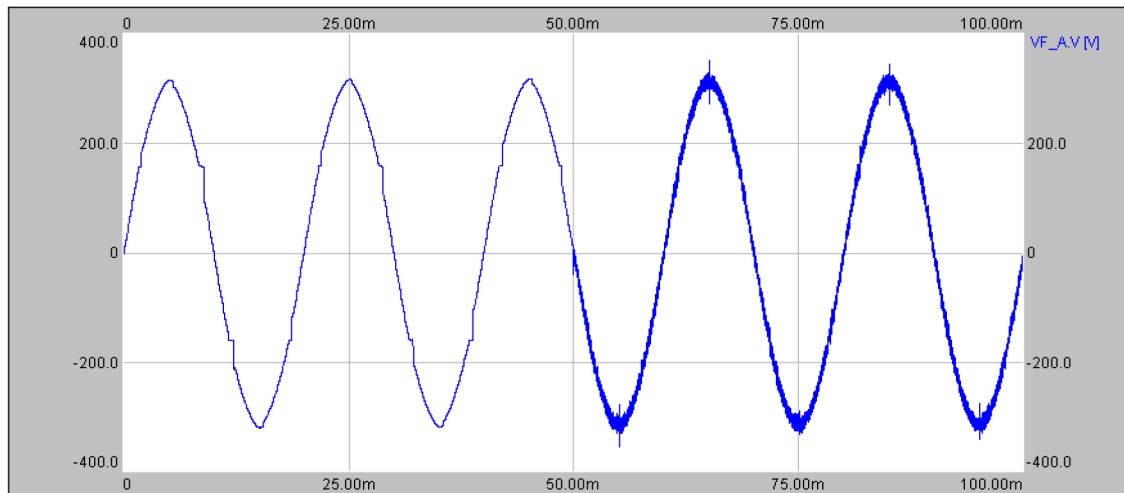


Figure 18. Voltage modification while the SAPF operates for sample B (SAPF operates after 50 ms).

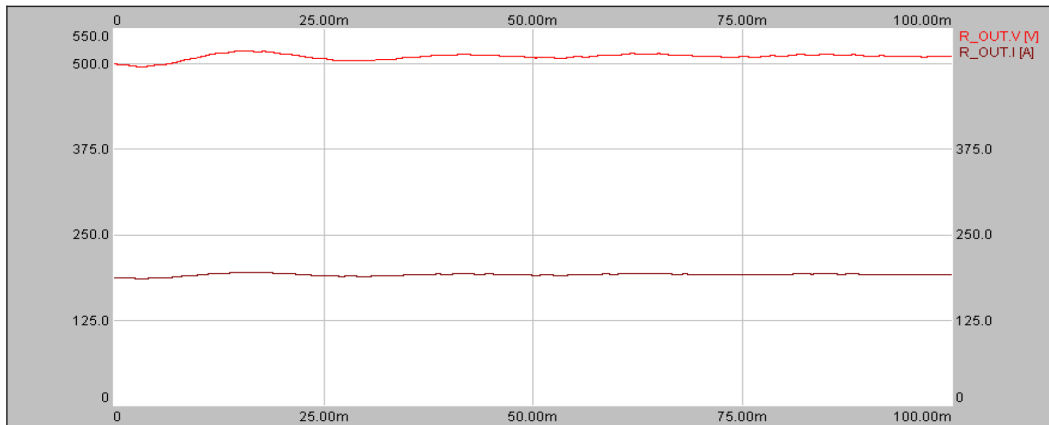


Figure 19. Output current and output voltage while the SAPF operates for sample B.

The THD rates obtained for sample B for simulations without and with the filter are illustrated in Figures 20 and 21, respectively. The current amplitude spectra of the system before and after filtration are presented in Figures 22 and 23, respectively.

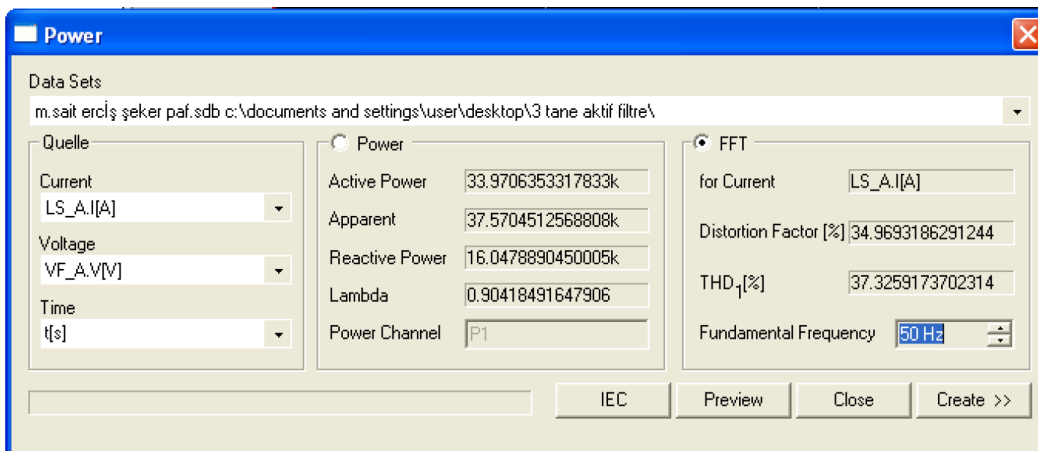


Figure 20. THD of the system before filtration for sample B.

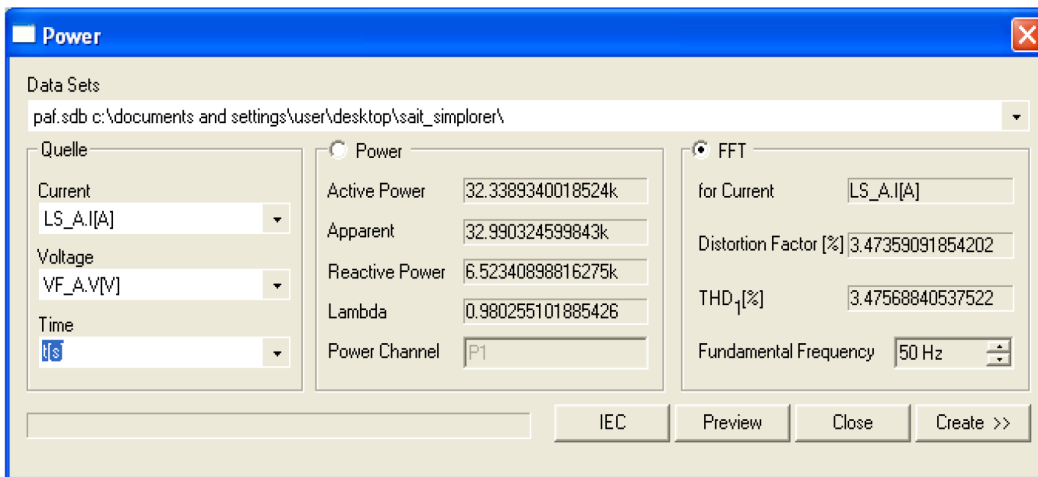
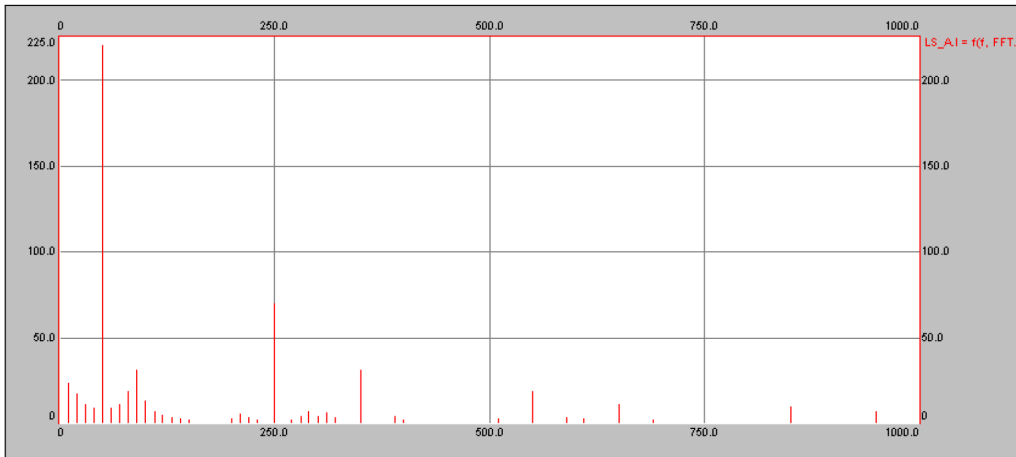
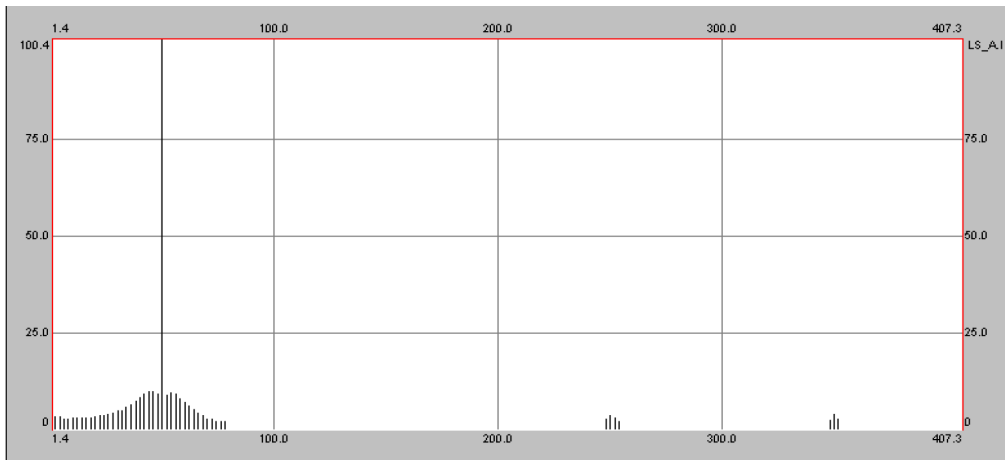


Figure 21. THD calculated while the SAPF operates for sample B (filter operates for 0 ms).

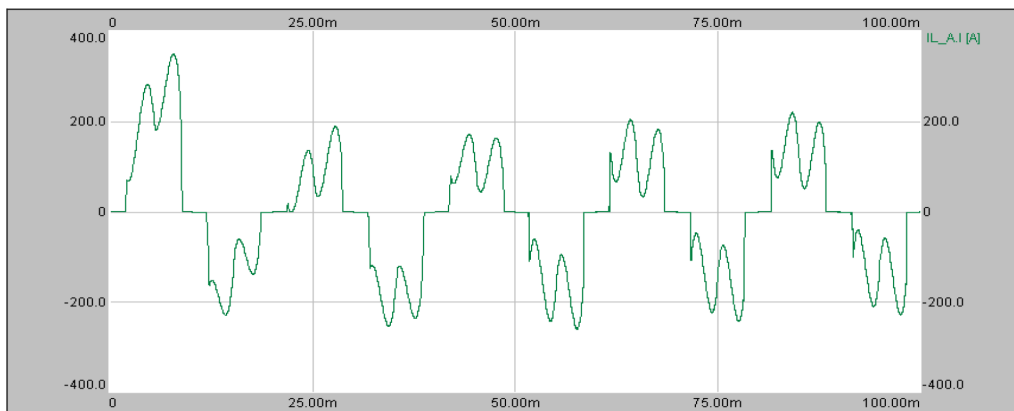


**Figure 22.** Current amplitude spectrum of the system before filtration for sample B.



**Figure 23.** Current amplitude spectrum while the SAPF operates for sample B (filter operates for 0 ms).

For sample C, the load and filter currents are illustrated in Figures 24 and 25, respectively, whereas the current of the circuit with the active filter after rectification is shown in Figure 26. Modification of the voltage obtained by application of the active filter is shown in Figure 27, with the corresponding output current and output voltage illustrated in Figure 28.



**Figure 24.** Modification of the load current for sample B (SAPF operates after 50 ms).

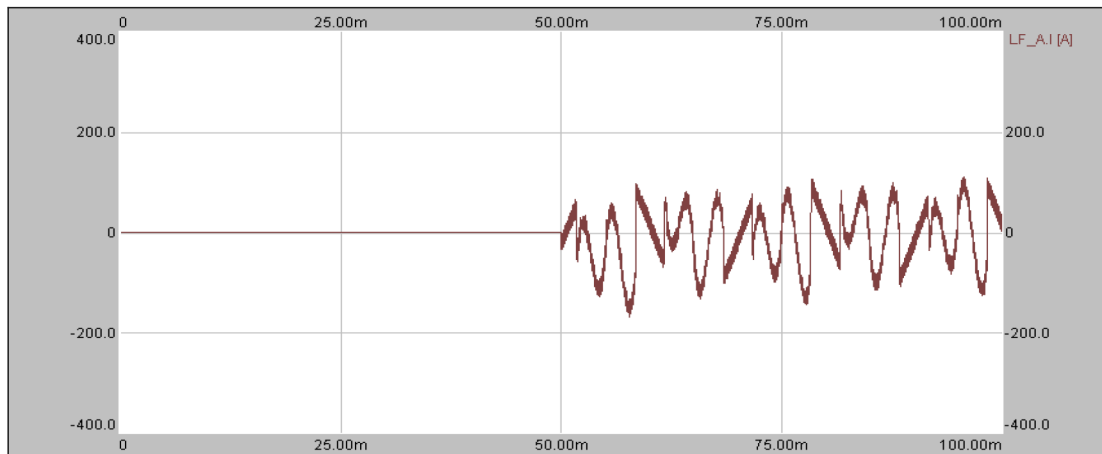


Figure 25. Filter current distributed to the system by the SAPF for sample B (SAPF operates for 50 ms).

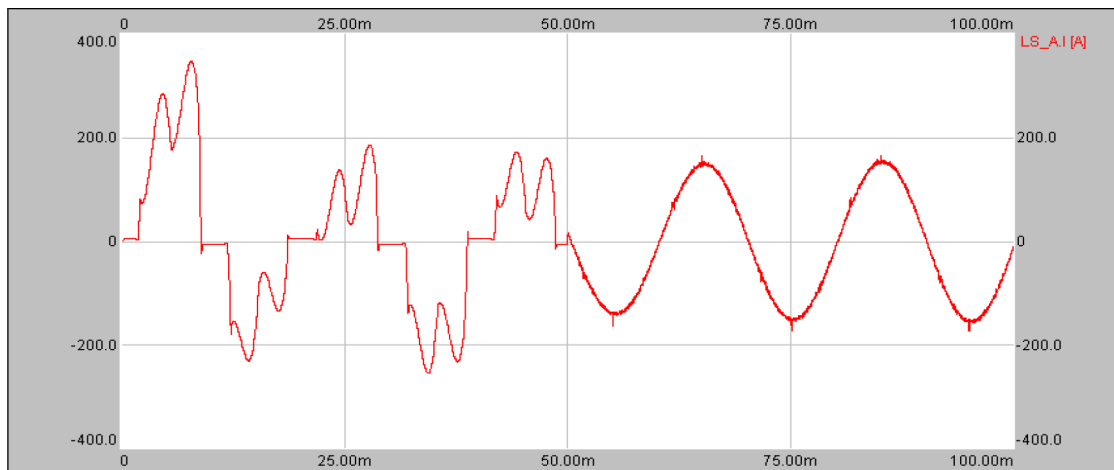


Figure 26. Circuit current while the SAPF operates for sample B (SAPF operates after 50 ms).

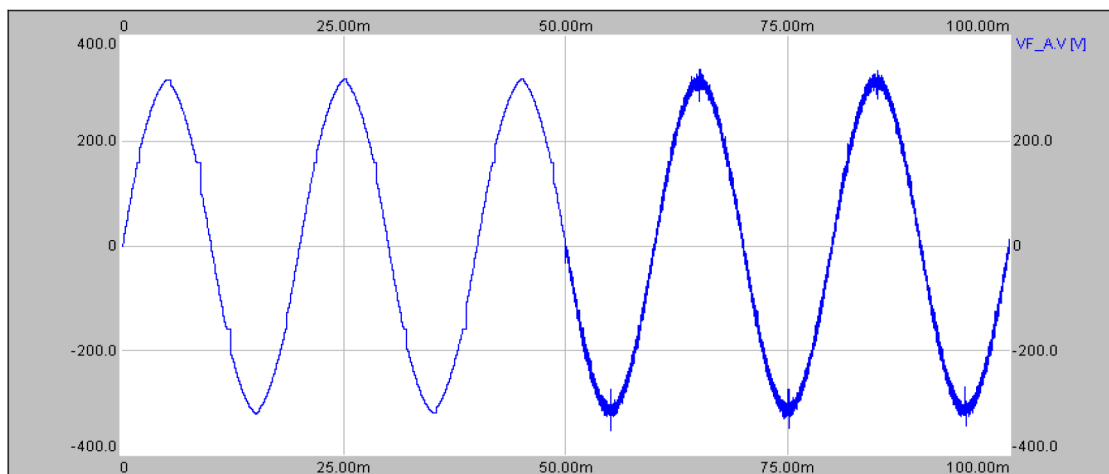


Figure 27. Voltage modification while the SAPF operates for sample C (SAPF operates after 50 ms).



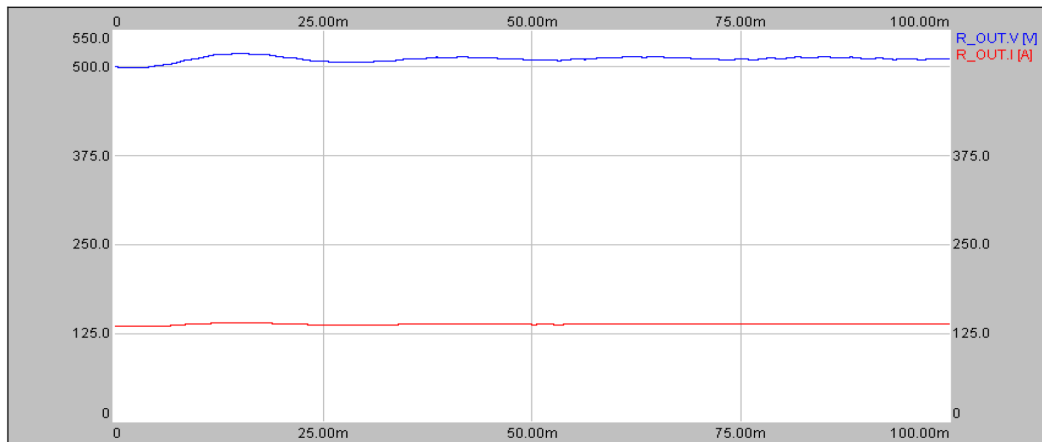


Figure 28. Output current and output voltage while the SAPF operates for sample C.

The THD rates obtained for sample C for simulations without and with the filter are shown in Figures 29 and 30, respectively. The current amplitude spectra of the system before and after filtration are shown in Figures 31 and 32, respectively.

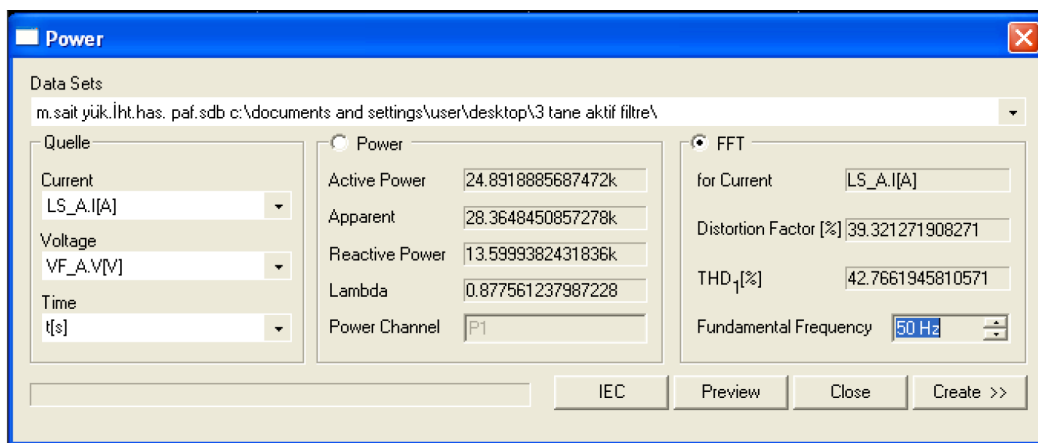


Figure 29. THD of the system before filtration for sample C.

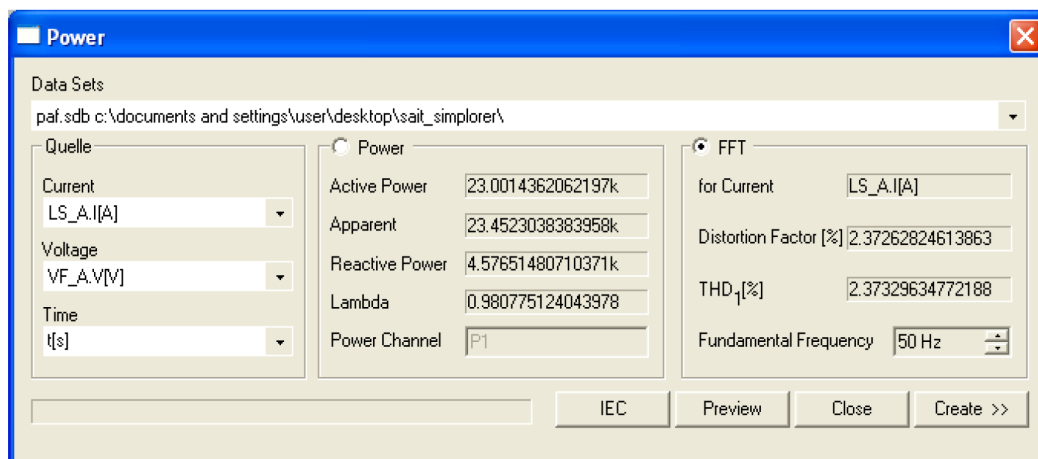
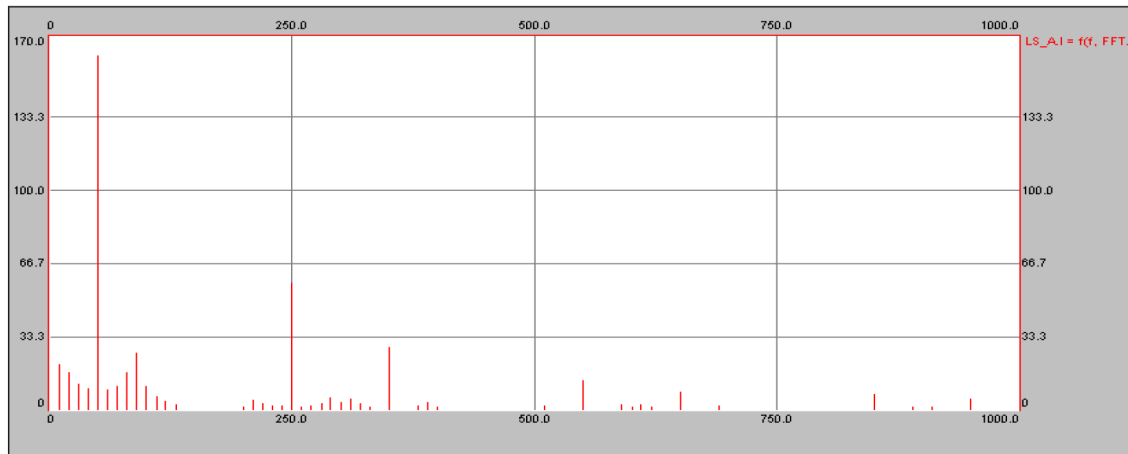
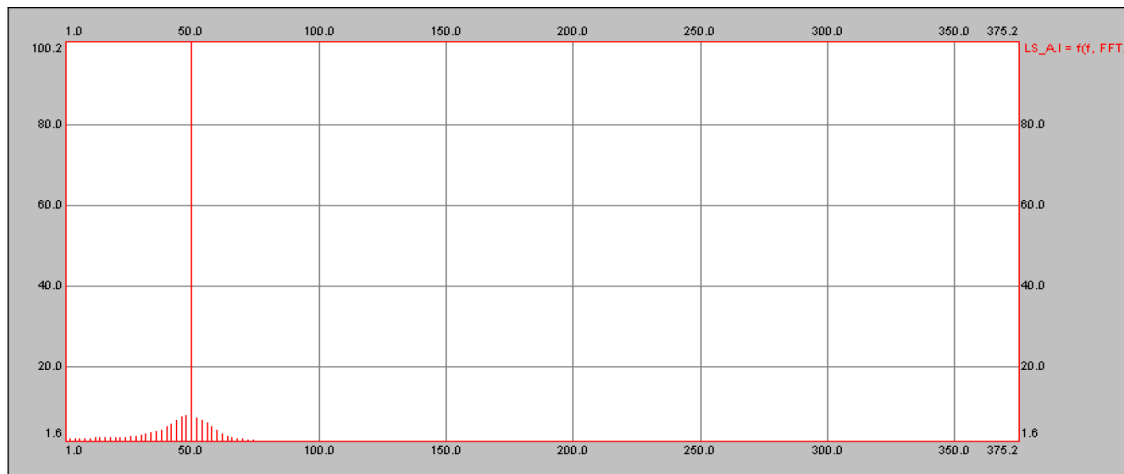


Figure 30. THD calculated while the SAPF operates for sample C (filter operates for 0 ms).



**Figure 31.** Current amplitude spectrum of the system before filtration for sample C.



**Figure 32.** Current amplitude spectrum while the SAPF operates for sample C (filter operates for 0 ms).

## 6. Discussion

During the project design process and the preparation of technical specifications, it is a legal obligation to ensure that parameters values such as current, voltage, and THD and similar harmonics are written on the labels of devices. When selecting devices, producers will be particularly sensitive in their consideration of harmonics.

Measurement should be undertaken frequently at facilities that produce large quantities of harmonics. Moreover, producers who continue to select devices with high harmonic values will be penalized with increased energy costs; this measure is intended to deter producers from increasing harmonics.

In automation system design, which typically involves constructing systems that allow power quality to be observed, large power consumers (e.g., factories, hospitals) that carry nonlinear loads should be inspected regarding their harmonics. Such inspections will allow preventative measures to be implemented.

Despite their good filtration performance, active filters require high initial costs. Nevertheless, this is their only major negative setback, and they offer many advantages as follows: they are effective for several harmonic levels in the system, they do not achieve resonance with the associated systems, and they can adjust reactive power and reduce voltage.

Nonlinear loads in a given system should be gathered at central points where possible when large quantities of harmonics are observed, as in this study. This will reduce the number of filters required, thereby minimizing the initial cost.

Evidently, the production of harmonics in quantities exceeding the specified limits by some consumers can damage the interests of other consumers. Accordingly, we can predict that consumers and companies may encounter difficulties in their relationships. If such harmonic pollution were to occur, particularly in cases where active filters were not operated to mitigate the pollution, companies may be forced to pay compensation.

In our study, owing to recent developments in semiconductor technology, simulation of a filtration technique, which we think can successfully eliminate harmonics, has been conducted using the SAPF Simplorer 6.0.

On the basis of measurements, we showed that voltage harmonics are below the specified tolerance limits; however, the current harmonics were found to exceed the tolerance limits. Because nonlinear loads are included in the simulated system without daily control measures, no measures have been implemented to mitigate the effects of the resulting harmonics. Consequently, each load with aliasing strains the system and shortens the life span of related electrical devices.

Investigation of active filters using traditional analysis methods is expensive. Herein, simulation was achieved using Simplorer 6.0, thus reducing cost, time, and labor requirements. Moreover, in the event of modification of an electrical system under consideration, the system response can also be investigated by modifying the simulation.

From the simulation results for current, the THD rate for sample A was found to be 51.35% (Figure 18) without the filter; when the active filter was operational, the THD rate decreased to 2.4% (Figure 21). Similar decreases were observed for sample B (37.32% to 3.47%) and sample C (42.76% to 2.37%). Thus, the operation of the active filter has reduced the THD rates to below standard harmonic levels. Moreover, the system's current and voltage exhibited a form similar to the sine waveform.

On the basis of the results for the designed shunt active filter, it is clear that no phase shifting occurred in any of the samples, and the amplitude values of all the samples were maintained successfully.

Because semiconductor switches were used in the simulation, ripples are apparent in the resulting voltage and current sinusoidal waveforms. For all three samples, the active filters combined with IGBT switching elements acted as shunt active filters to regulate the systems and produce harmonics such that they did not have a negative effect on the basic sine waveforms. Such conditions can cause voltage losses. For example, for sample A, the output voltage and current were 538.8 V and 102 A, respectively, before application of the filter. Conversely, the active filter output voltage and current were approximately 520 V and 102 A, respectively (Figure 10). Thus, evidently, the semiconductor switching elements of the shunt active filters caused voltage drop.

Ripples are apparent in the sine forms of the voltage and current waveforms obtained following activation of the IGBT semiconductor switches. When the inductance of the filter output is optimized, these ripples will decrease. Simultaneously, together with the selection of the optimum inductance value, the ripples in walking parts will be minimized (Figure 9). The ripples on the sine troughs and peaks can be attributed to the effects of the IGBT semiconductor elements on the circuit (Figure 8).

## 7. Conclusions

According to the results of the SAPF simulation, harmonics have been decreased and the current waveforms have become similar to sinusoidal waveforms. The power flow is illustrated in Figures 8, 17, and 26. Moreover, we can see that the voltage waveforms approach the ideal sine waveform in Figures 9, 18, and 27.

Owing to harmonic effects, the output voltage and current were found to be unstable for the unfiltered conditions. The output voltage varied in the range 500–540 V for the unfiltered conditions, but remained stable at 520 V when the SAPF was in use. Changes in voltage are apparent in Figures 10, 19, and 28, and the observed decreases in the number of voltage change points and the increasing stability of the voltage indicate that harmonics have been removed from the system.

Theoretically calculated values of voltage and power could not be measured at the output. This was because although the IGBTs remove harmonics from the system, they also produce harmonics and consume power. Ripples in the voltage and current waveforms were observed after the triggering of the IGBTs; these ripples entered the system as harmonics and consumed power.

Simulation was performed using Simpler 6.0, resulting in savings in cost, time, and labor requirements. The filter's system response can be changed by modifying the simulation conditions.

In our study, the SAPF simulation circuit components were determined by trial and error. However, in future studies, intelligent optimization techniques can be used to determine the optimum circuit components.

In addition, removal of the ripples that occur during the triggering of the semiconductor IGBTs used inside the SAPF circuit, depending on their current direction, should be investigated in future studies. In this manner, the effects of harmonics on the system can be minimized.

The proposed SAPF can lock the harmonic load currents or unbalanced nonlinear load currents internally, such that the supply side always delivers three-phase balanced sinusoidal currents with unity power factor under all conditions.

The simulation results under various system operating conditions have verified the design concept of the proposed SAPF to be highly effective and robust. Moreover, the simulation and test results were utilized to verify the performance of the single-phase shunt active filter for three-phase four-wire distribution systems. The efficiency increased with application of the filter, while the load current harmonics and reactive current components disappeared. With balanced sinusoidal networks, the power factor provides a current draw. Even in cases of transient supply, current stability can be maintained.

## References

- [1] Varschavsky A, Dixon J. Cascaded nine-level inverter for hybrid-series active power filter, using industrial controller. *IEEE T Ind Appl* 2010; 57: 761–767.
- [2] He Y, Liu J, Tang J, Wang Z, Zou Y. Deadbeat control with a repetitive predictor for three-level active filters. *Journal Power Electron* 2011; 2: 583–590.
- [3] Uyyuru KR, Mishra MK, Ghosh A. An optimization-based algorithm for shunt active filter under distorted supply voltages. *IEEE T Power Electro* 2009; 24: 223–232.
- [4] Geethalakshmi B, Kavitha M. Comparison of reference current extraction methods for shunt active power filters. *International Journal of Computer and Electrical Engineering* 2011; 3: 23–32.
- [5] Odavic M, Biagini V, Zanchetta P, Sumner M, Degano M. One sample-period-ahead predictive current control for high-performance active shunt power filters. *IET Power Electronics* 2011; 4: 414–423.
- [6] Montero MIM, Cadaval ER, Gonzalez FB. Comparison of control strategies for shunt active power filters in three-phase four-wire systems. *IEEE T Power Electr* 2007; 22: 229–236.
- [7] Cengiz MS, Rustemli S, Almali MN. The advantages of the applicability of new generation sectionalisers and reclosers over the pole. *Przeglad Elektrotechniczny* 2013; 89: 155–159.
- [8] Dumitrescu AM. Current controllers design using Naslin polynomial method for APF. *Rev Roum Sci Techn Électrotech. et Énerg* 2009; 5: 115–124.

- [9] Salmeron P, Litran SP. Improvement of the electric power quality using series active and shunt passive filters. *IEEE T Power Deliver* 2010; 25: 1058–1067.
- [10] Gonzalez SA, Garcia-Retegui R, Benedetti M. Harmonic computation technique suitable for active power filters. *IEEE T Ind Electron* 2007; 54: 2791–2796.
- [11] Freijedo F, Gandoy JD, Lopez O, Comesana, PF, Penalver CM. A signal-processing adaptive algorithm for selective current harmonic cancellation in active power filters. *IEEE T Ind Electron* 2009; 56: 2829–2840.
- [12] Ribeiro A, Azevedo C, Sousa R. A robust adaptive control strategy of active power filters for power-factor correction, harmonic compensation, and balancing of nonlinear loads. *IEEE T Power Electr* 2012; 27: 718–730.
- [13] Buso S, Malesani L, Matavelli P. Comparison of current control techniques for active filters applications. *IEEE T Ind Electron* 1998; 45: 722–729.
- [14] Lascu C, Asiminoaei L, Boldea I, Blaabjerg F. Frequency response analysis of current controllers for selective harmonic compensation in active power filters. *IEEE T Ind Electron* 2009; 56: 337–347.
- [15] Bhattacharya A, Chakraborty C, Bhattacharya S. Shunt compensation. *IEEE Ind Electron Mag* 2009; 3: 38–49.
- [16] Terciyanlı A, Ermis M, Cadirci I. A selective harmonic amplification method for reduction of KVA rating of current source converters in shunt active power filters. *IEEE T Power Deliver* 2001; 26: 65–78.
- [17] Asiminoaei L, Blaabjerg F, Hansen S, Thogersen P. Adaptive compensation of reactive power with shunt active power filters. *IEEE T Ind Appl* 2008; 44: 867–877.
- [18] Kocabaş I, Çadircı I. DSP based implementation of a 10 kVA voltage source active power filter. MSc, Hacettepe University, Ankara, Turkey, 2008.
- [19] Avcı T, Çadircı I. Comparison of various control techniques for a current source active power filter. MSc, Hacettepe University, Ankara, Turkey, 2008.
- [20] Bojoi R. I, Griva G, Bostan V, Guerriero M, Farina F, Profumo F. Current control strategy for power conditioners using sinusoidal signal integrators in synchronous reference frame. *IEEE T Power Electron* 2005; 20: 1402–1412.
- [21] Matavelli P. A closed-loop selective harmonic compensation for active filters. *IEEE T Ind Appl* 2001; 37: 81–89.
- [22] Newman MJ, Zmood DN, Holmes DG. Stationary frame harmonic reference generation for active filter systems. *IEEE T Ind Appl* 2002; 38: 1591–1599.
- [23] Cengiz MS. Smart meter and cost experiment. *Przeglad Elektrotechniczny* 2013; 89: 206–209.
- [24] Yuan X, Merk W, Allmeling J. Stationary-frame generalized integrators for current control of active power filters with zero steady-state error for current harmonics of concern under unbalanced and distorted operating conditions. *IEEE T Ind Appl* 2002; 38: 523–532.