Implementing a Demand Side Management Strategy for Harmonics Mitigation in a Smart Home using Real Measurements of Household Appliances

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Abstract: Significant developments on semiconductor technology have captured the electronic industry and paved the way for dominating household appliances market. Typical loads in this market generally have nonlinear voltage-current characteristics. Therefore, highly-integrated power-electronic based electrical equipment in the demand side has caused harmonic pollution, which is one of the most important power quality problems in distribution system operation. To address this issue, there have been significantly great attempts to keep Total Harmonic Distortion (THD) and Total Demand Distortion (TDD) levels within International standard limits defined by IEEE 519 and IEC 61000. On the other hand, load shifting has recently drawn special attention of power grid planners to improve system performance substantially in the smart grid paradigm. In this study, the real harmonic measurements of residential appliances (both linear and nonlinear) are carried out in the Smart Home Laboratory in Yildiz Technical University, Istanbul, Turkey. Different load profiles are then created with a high accuracy based on the measured voltage and current, active, reactive and apparent power. Also, three case studies are considered to investigate the impacts of load shifting strategies on power quality requirements in terms of satisfying the relevant standards. As a result, it is shown that the TDD value decreases below nearly 8% limitation by mitigating the harmonic distortion and the TDD index, which indicates the harmonic distortion effect on the system regarding the desired standard limits of IEEE.

Keywords—Harmonic current; harmonic distortion; load shifting; smart home; total demand distortion.

1. Introduction

The pure sinusoidal waveforms of current and voltage are of great interest to power system community since the power system equipment is designed to operate with fundamental power frequency. There might be, however, odd and even harmonics in power system due to the connection of nonlinear loads such as power electronic components, static VAR compensators, converters and arc furnaces. The harmonic distortion caused by many nonlinear loads in power grid may lead to unfavourable problems for both power systems and consumers [1]. Regarding the power system, the decrease in power quality might result in overloading of transformers, rotating equipment, neutral conductors, and failed capacitor banks, and even might affect the reliability and efficiency of the system [3]. As for the consumers, lower power quality might further increase the economic losses.

It is crucial to avoid the mentioned effects of harmonics in power system on both connection points and other loads. To address this problem, the international standards define the maximum permissible limits for harmonic distortion levels [4].

The power system operators improve their operational strategies based on either IEEE Std 519 or IEC Std 61000 standards. As an example, total harmonic distortion (THD) value is set as 5% in the low voltage system according to IEEE Std 519-2014 while the current distortion limits related to total demand distortion (TDD) should conform to the limits indicated in Table 1 [5].

In the literature, there are several implementations for mitigating the effects of harmonics. Among these, line reactors, phase shifting transformers, K-Factor transformers, low-pass active, passive and hybrid harmonic filters have provided satisfying results. In particular, the interest for active filters has increased compared to passive filters due to the increasing prevalence of IGBTs [6], [7]. However, the abovementioned techniques are generally very costly.

Table 1. Current Distortion Limits for Rated Voltages between 120 V to 69,000 V According to the IEEE Std 519-2014 [8].

I_{sc}/I_L	**Total demand distortion TDD (%)**
<20	5.0
20<50	8.0
50<100	12.0
100<1000	15.0
>1000	20.0

I_{SC} = maximum short-circuit current at point of common coupling

I_L= maximum load current (only fundamental frequency components)

In order to deal with such operational problems in power systems, there has been a strong trend towards incorporating demand side management (DSM) into power system operation in the last few decades. Among the sub-programs of DSM such as load shifting, peak clipping, strategic growth and valley filling, which are generally used for different objectives, load shifting may be evaluated as one of the most promising solution in terms of reducing harmonic distortions and keeping the indices between standard values. It enables to reduce the stress on the utility grid by shifting the flexible loads from peak periods to off-peak periods without need of extra installation cost [9]. Besides, this strategy helps to decrease line losses, and power quality requirements can be also satisfied thanks to the information transactions by digital monitoring technology, i.e., an improvement in THD and TDD values may be achieved by changing the usage period of residential loads with load shifting approach.

The bi-directional information and communication technologies are the main elements of smart grid applications which enable end-users to change their habits and power consumption profiles [10]. Especially for smart homes, residential appliances can be monitored and scheduled according to the power quality needs of low-voltage distribution system [11]. In order to develop any management strategy on the load pattern of end-users, advanced metering infrastructure (AMI) and smart meters have to be installed on demand side. Thanks to the bi-directional power and information flows, it might be possible to collect the consumption data and report them in an understandable manner from the distribution system operator's perspective. Moreover, the functionalities of smart meters such as measuring power factor, THD, TDD and distorted waveforms have paved the way for achieving higher power quality while implementing these mechanisms. Last but not least, AMI, on the other hand, presents various services such as DSM, disaster prevention and disaster recovery [12], [13].

In the literature, the problems in the power systems caused by the harmonics of household electrical appliances have been examined in various studies. Among them, an approach was proposed in [14] to determine the technical losses in distribution system due to the integrated non-linear devices' harmonic components in a microgrid environment. Appliance models were created based on real measurement data associated with different loading scenarios. In [15], current harmonic measurements and analyses of their components were conducted for some types of loads at high voltage, medium voltage and low voltage, and also harmonic generating sources and relevant standards were discussed in detail. In [16], the impact of new residential appliances on power quality was examined. It was stated that many residential appliances have a non-sinusoidal power converter which increases the harmonic voltage level, and that the total effect depends on the appliance power values and harmonic diversity. In addition, power quality characteristics of different appliances were analysed.

Displacement power factor, transient currents and THD for an India scenario were experimentally examined in [17] where an MFMACE-357 device was used to measure the parameters. From the results obtained in the study, it was concluded that some appliances, such as compact fluorescence, have as high distortion as 32.11% despite drawing a low current.

Current harmonic measurements and analyses of their components were carried out for household appliances in [18]-[22]. Current distortions and voltage disturbances in the grid were investigated in [23] by considering household appliances and electric vehicles. In the study, it was concluded that electric vehicles have great impacts on the results.

Harmonic investigations of residential, commercial and industrial loads were performed in North America through analyses of data collected from various distribution systems and third harmonic was found as the most prominent component [24].

In order to control the harmonic level of network, a method based on harmonic pricing was proposed in [25] with the aim of providing fair harmonic pricing allocation. In this method, the consumers pay a penalty if they do not comply with the specified rules so that the system operator can perform harmonic filter installation.

The benefits of DSM or its sub-branch load shifting have not been considered in references [14]-[25] for the purpose of reducing harmonics. For more detailed information about the most common solution methods and technologies for harmonics, the study in [5], where IEEE and IEC standards are examined, can be referred to. The aim of the study was to ensure that public utilities and stakeholders make the right decision about safe harmonic emission limits by considering the appropriate standards. It was stated that there are generally two solution methods for high voltage and low voltage distribution systems.

Regarding the works aiming at using load shifting strategies in residential premises, a DSM model was developed in [26] for photovoltaics (PV) integrated smart home. In [27], the economic effect of load shifting was investigated by modelling the appliances that are likely to be used in a typical household. An approach for scheduling home loads under uncertainty of consumer behaviour was presented in [28]. Moreover, load shifting was applied in the study to improve consumer habits. The harmonic mitigation, however, was not taken into account in [26]-[28], while DSM or load shifting were involved. The taxonomy of the specialized literature in the proposed research area is presented in Table 2 in order to compare the aforementioned studies comprehensively.

Table 2. *Classification of Specialized Literature in the Proposed Research Area*

Ref.	Demand side management	Analyses of harmonics	TDD%	Measurement of household appliances	Complying with standards
[14]	–	√	–	√	–
[15]	–	√	√	–	√
[16]	–	√	–	√	–
[17]	–	√	–	√	–
[18]	–	√	–	√	–
[19]	–	√	–	√	√
[20]	–	√	–	√	–
[21]	–	√	–	√	–
[22]	–	√	–	√	√
[23]	–	√	–	√	√
[24]	–	√	√	√	–
[25]	–	√	–	–	–
[26]	√	–	–	√	–
[27]	√	–	–	√	–
[28]	√	–	–	–	–
This paper	√	√	√	√	√

In this study, a comprehensive harmonic analysis is conducted by measuring the basic electrical quantities in the existence of nonlinear loads. Based on the real measurements of residential appliances in a Smart Home Laboratory, the load profiles are created for different case studies. In order to cope with the harmonic problem, load shifting strategies are considered and it is aimed to keep TDD values below the determined standard limits.

The major contributions of this study also considering the summarized taxonomy given in Table 2 are as follows:

- The real harmonic measurements of the residential linear and nonlinear appliances in a Smart Home Laboratory are analysed and realistic load profiles are created by avoiding modelling errors.
- Load shifting methods are presented for the purpose of mitigating harmonics and reducing TDD_i value so that it can comply with the relevant standard.

The organization of the paper is prepared as follows: Section 2 gives the mathematical background of the developed architecture with detailed explanations. Section 3 shows the simulation results and analyses. Finally, the conclusions with the possible future studies are discussed in Section 4.

2. Methodology

2.1. An Overview of the Considered Structure

The main objective of the study is to examine the effects of load shifting strategies on TDD values. To this end, first, the comprehensive harmonic analyses were conducted by measuring the electrical quantities of residential appliances in the Smart Home Laboratory at Yildiz Technical University (YTU) Davutpasa Campus, Istanbul, Turkey (Fig. 1). These measurements with a time granularity of 3-seconds pave the way for creating more realistic harmonic behaviours of various equipment and evaluating their characteristics by avoiding modelling errors. Almost all the equipment found in a typical Turkish house is available in this laboratory as indicated in Table 3.

The power quality measurement of the appliances was experimentally conducted using a Fluke 435 analyser. The setup was managed for every equipment in order to measure the current and voltage harmonics (up to 50th) with their phase angles, active, reactive, apparent powers as well as power factor and frequency. The distortion problem was investigated by importing data from Fluke to a computer system. Thanks to the capability of the related device, measurements were carried out in 3-seconds scale. The variation of harmonic spectrum in different ranges is out of scope in this proposed architecture.

Fig. 1 The inside view of smart home laboratory [29].

Table 3. Electrical appliances in Smart Home Laboratory.

Appliance	Rated Power (kW)	Appliance	Rated Power (kW)
Refrigerator	0.150	Hair straightener	0.055
Iron	2.4	Oven	2.05
Toaster	0.708	Dishwasher	1.7
Kettle	2	Microwave oven	1.18
Hair dryer	1.536	Printer	0.02
LCD-TV	0.09	Air conditioner	1.14
PC desktop	0.05	Washing machine	1.8
PC monitor	0.03	Vacuum cleaner	1.9
LED Lighting	0.035	Laptop	0.03

2.2. Mathematical Background

The instantaneous value of voltage and current can be formulated as follows [30]:

$$v(t) = \sum_{n=1}^{\infty} v_n(t) = \sum_{n=1}^{\infty} \sqrt{2} V_n \sin(n\omega_1 t + \theta_n) \tag{1}$$

$$i(t) = \sum_{n=1}^{\infty} i_n(t) = \sum_{n=1}^{\infty} \sqrt{2} I_n \sin(n\omega_1 t + \delta_n) \tag{2}$$

where v_n and i_n are the instantaneous harmonic voltage and current of the order n, respectively in which DC component is neglected for simplicity. V_n and I_n express the actual values of harmonic order n. Also, ω_1 states the angular frequency of fundamental frequency. Lastly, the phase angles of voltage and current harmonics of the orders n are θ_n and δ_n, respectively.

The related current and voltage r.m.s. values of an AC source procuring nonlinear harmonic generating components are formulated as follows [31]:

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T v^2(t)dt} = \sqrt{V_1^2 + V_2^2 + V_3^2 + V_4^2 \dots\dots V_n^2} \tag{3}$$

$$I_{rms} = \sqrt{\frac{1}{T}\int_0^T i^2(t)dt} = \sqrt{I_1^2 + I_2^2 + I_3^2 + I_4^2 \dots\dots I_n^2} \tag{4}$$

From fundamental order to higher order harmonic contents are indicated as $V_1, V_2, V_3 \dots\dots V_n$ in Eq. (3) while current values are stated as $I_1, I_2, I_3 \dots\dots I_n$ in Eq. (4).

For the purpose of calculating the active power consumption of harmonic generating loads, Eq. (1) and Eq. (2) should be multiplied with as follows [31]:

$$P = \sum_{n=1}^{\infty} V_n I_n \cos(\theta_n - \delta_n) = \sum_{n=1}^{\infty} P_n \tag{5}$$

It is worth noting that multiplying current and voltage at different frequencies does not contribute to both active and reactive power as stated in Eq. (5), i.e., the orders having the same frequency are to be used for determining the amount of power consumption. Similarly, reactive power consumption of the harmonic generating sources can be expressed by Eq. (6) as follows [31]:

$$Q = \sum_{n=1}^{\infty} V_n I_n \sin(\theta_n - \delta_n) = \sum_{n=1}^{\infty} Q_n \tag{6}$$

Multiplication of (3) and (4) results in finding apparent power consisting of active, reactive and distortion power as given in Eq. (7).

$$S = V_{rms} \cdot I_{rms}{}^{*} \tag{7}$$

In addition to Eq. (7), apparent power can also be calculated as follows [32]:

$$S^2 = P^2 + Q^2 + D^2 \tag{8}$$

where D expresses distortion power, which is actually a kind of reactive power and assumed to be zero in linear circuits. The other important parameter is power factor, which is the indicator of how electrical energy is used efficiently.

The main formula for calculating power factor is stated in Eq. (9). A power factor close to 1 indicates that the overall power quality can be evaluated as high.

On the other hand, a low power factor means that system is operated in a low efficient fashion due to supplying the same amount of demand with higher power injection from grid side. In this respect, improving the power factor plays an important role in terms of boosting the system efficiency and reducing the cost of electricity consumption [33], [34].

$$DPF = \frac{P}{S} = \frac{P_1}{V_{rms} \cdot I_{rms}{}^{*}} \tag{9}$$

In addition, THD is one of the most widely used metrics in harmonic analysis of power systems, which estimates the harmonic pollution on the related bus [13]. In fact, it is necessary to evaluate the square root of the sum of the squares of the voltages and currents for all the components; however, the harmonics are considered by IEEE up to the 50^{th} component, and therefore the calculations were conducted up to these components in this study. It is well known that the magnitude of voltage and current tends to decrease with increasing harmonic orders and can be neglected after a certain value. The following formulations are given in Eq. (10) and (11) for voltage and current, respectively.

$$THD_v = \sqrt{\left(\sum_{n>1}^{n_{max}} V_n^2\right)} \Big/ V_1 = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 \ldots\ldots . V_n^2}}{V_1} \tag{10}$$

$$THD_i = \sqrt{\left(\sum_{n>1}^{n_{max}} I_n^2\right)} \Big/ I_1 = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 \ldots\ldots . I_n^2}}{I_1} \tag{11}$$

The ratio between the total r.m.s. values of current harmonic components and the maximum load current (I_L) gives the TDD value as stated in Eq. (12) [35]. It should be highlighted that TDD is also utilized for calculating distorted current waveforms in especially practical implementations even more than THD_i [36].

$$TDD_i = \sqrt{\left(\sum_{n>1}^{n_{max}} I_n^2\right)} \Big/ I_L = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 \ldots\ldots I_n^2}}{I_L} \tag{12}$$

In order to determine the related I_L, the currents are constantly measured in 3-seconds intervals from point of common coupling (PCC) and then the average points are used in the formulation in 15 to 30 minutes basis according to the IEEE 519 standard [13].

3. Results and Analyses

In order to validate the effectiveness of the load shifting strategies on harmonic mitigation, three different case studies are considered. In the first case, which is called the Base Case, the harmonic producing appliances are considered to work together especially in the peak periods. In the second and third cases, load consumption changes at the end user side are carried out to investigate their impacts on the power quality improvements. In other words, the working period of some of the harmonic generating appliances is shifted to different times. The operating intervals of the appliances for each case study are given in Table 4.

It is important to indicate that the operating time of each appliance for different cases is determined as same for making realistic assumptions. In the case studies, each load profile is created using the abovementioned residential appliances in the smart home. The total demand power curves of Base Case, Case 2 and Case 3 are shown in Figs. 2, 3 and 4, respectively. The peak load exceeds 2.5 kW for Base Case, which is also the highest loading condition in three cases.

In Case 2 and Case 3, it can be stated that the load profile is at a better level in terms of peak load. In each case study, the total amount of consumed energy is equal due to the same operation periods of the appliances.

The percentage of current harmonics of the air conditioner, washing machine, refrigerator, TV, PC desktop, laptop, LED armature and dishwasher in the smart home is given in Figs. 5-13. It should be recalled that the harmonic components were examined up to the 50th order. The component 1 is the base component and the even harmonics were neglected in this study due to their low values, i.e., they are not as dominant as odd harmonics in the household appliances.

Table 4. The operating periods of each electrical appliance in the smart home for three case studies.

Appliance	Operating Interval for Each Case Studies		
	Base Case	Case 2	Case 3
Hair dryer	07:05-07:10, 07:13-07:17, 22:27-22:32	07:05-07:10, 07:13-07:17, 22:27-22:32	07:05-07:10, 07:13-07:17, 22:27-22:32
Kettle	07:05-07:13, 21:25-21:33	07:05-07:13, 21:25-21:33	07:05-07:13, 21:25-21:33
Air conditioner	12:00-15:00, 16:00-20:00	11:00-14:00, 14:30-18:30	11:00-14:00, 14:30-18:30
LCD-TV	11:00-12:00, 17:00-22:00	11:00-12:00, 17:00-22:00	11:00-12:00, 17:00-22:00
Refrigerator	00:00-24:00	00:00-24:00	00:00-24:00
Iron	13:00-13:57	11:00-11:57	13:00-13:57
Toaster	07:11-07:21	07:11-07:21	07:11-07:21
PC desktop	19:15-20:45	19:00-20:30	19:00-20:30
PC monitor	19:15-20:45	19:00-20:30	19:00-20:30
LED Lighting	20:00-24:00	20:00-24:00	20:00-24:00
Hair straightener	07:17-07:22	07:17-07:22	07:17-07:22
Oven	17:00-17:45	11:00-11:45	18:00-18:45
Dishwasher	19:17-20:37	21:00-22:20	21:00-22:20
Microwave oven	18:23-18:28	18:47-18:52	18:47-18:52
Printer	20:28-20:31	20:28-20:31	20:28-20:31
Vacuum cleaner	11:00-11:08, 11:09-11:08, 11:09-11:18, 11:19-11:25, 11:26-11:42	14:00-14:08, 14:09-14:08, 14:09-14:18, 14:19-14:25, 14:26-14:42	11:00-11:08, 11:09-11:08, 11:09-11:18, 11:19-11:25, 11:26-11:42
Washing machine	19:35-21:04	09:00-10:29	09:00-10:29
Laptop	19:15-20:45	19:00-20:30	19:00-20:30

The components of the current harmonics for the air conditioner were given in Fig. 5. The most dominant harmonics for air conditioning unit are 3rd and 5th components. The components were found to be negligible especially after 17th component.

The percentages of current harmonics for the washing machine were shown in Fig. 6. Especially, the 3rd and 5th harmonic components were found to be quite high where the percentage of the 3rd harmonic component is 45%. Furthermore, it is noted that the 11th harmonic component has a value higher than 7th and 9th components.

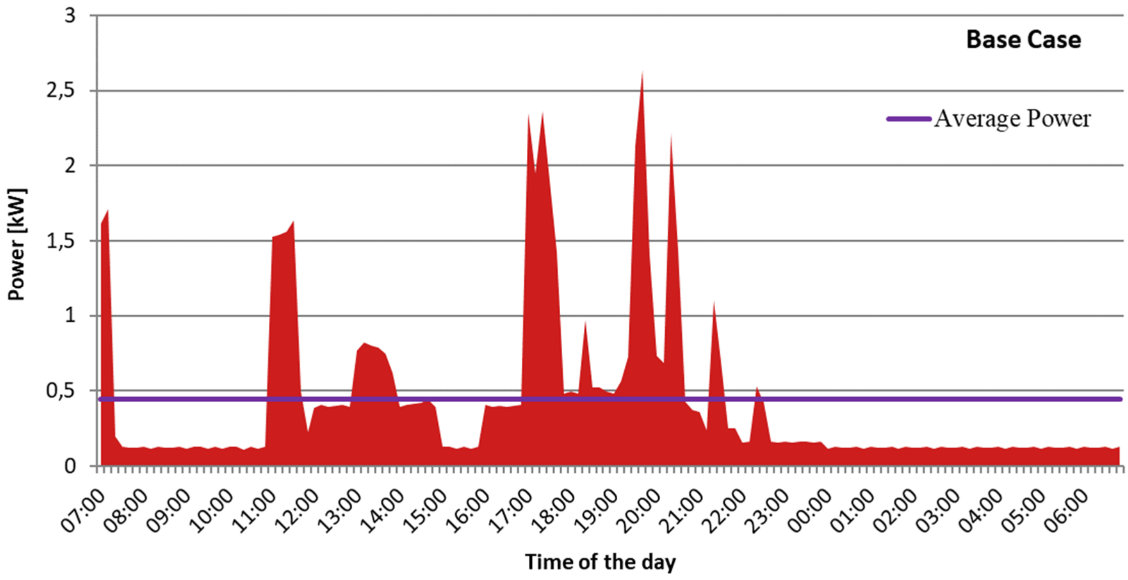

Fig. 2 *Total active power demand curve of Base Case.*

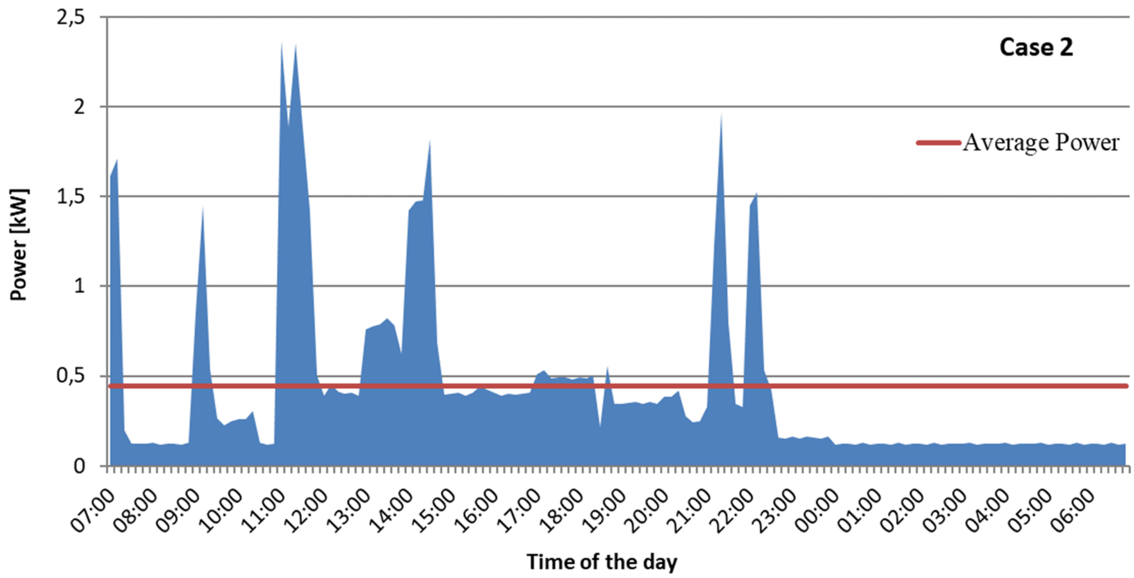

Fig. 3 *Total active power demand curve of Case 2.*

Figure 7 shows the values of the current harmonic components of the refrigerator. Considering that the refrigerator works all day, the harmonic components become more important. Interestingly, the 5^{th} component is the most dominant component for this appliance. The current harmonic components of the TV, which is 42” and LCD, are given in Fig. 8. The most dominant harmonic component is the 3^{rd} component, and the 5^{th} and 7^{th} harmonic components are also relatively high. The current harmonic components of the monitor can be seen in Fig. 9. It can be seen that the monitor has the highest harmonic distortion among these household appliances and THD_i is measured as 133.891% for this appliance.

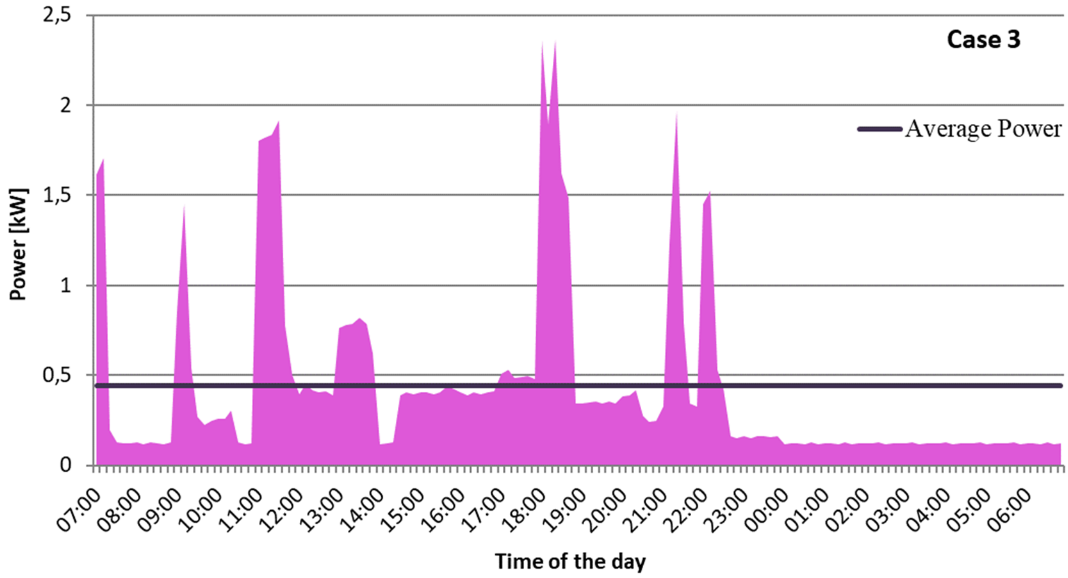

***Fig. 4** Total active power demand curve of Case 3.*

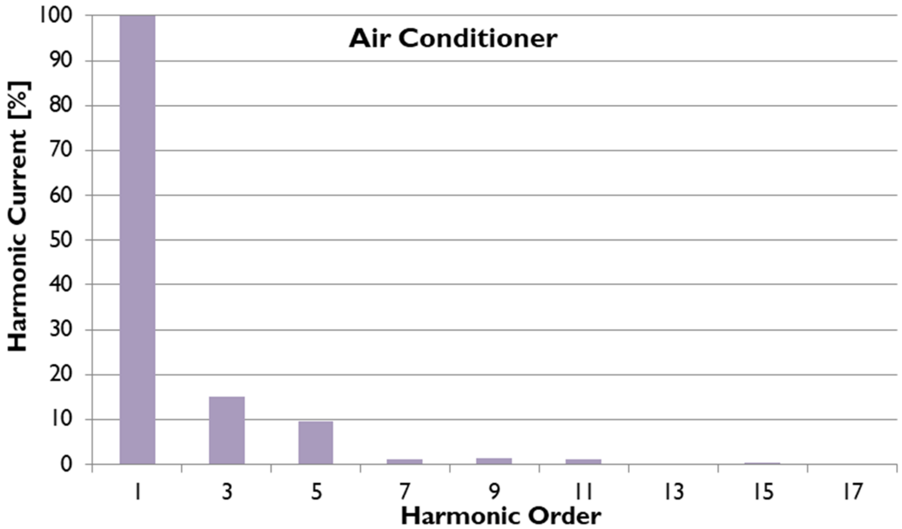

***Fig. 5** Current spectrum of the air conditioner.*

The current harmonic components of the PC desktop are given in Fig. 10. It is seen that the 3rd harmonic, which is close to 30% of first harmonic component value, is the highest component. Other components are also quite high. The current harmonic components for the laptop are given in Fig. 11. Similar to the desktop PC, the 3rd harmonic component with a value of approximately 42% is the highest component.

The current harmonic components of the armature, which is a 9W LED bulb, are given in Fig. 12. LED bulbs consist of a compact AC/DC converter to supply DC current to LED chips, which introduces nonlinearity [3]. It is seen that the most dominant components are the 3rd and 5th components while the others are not very high.

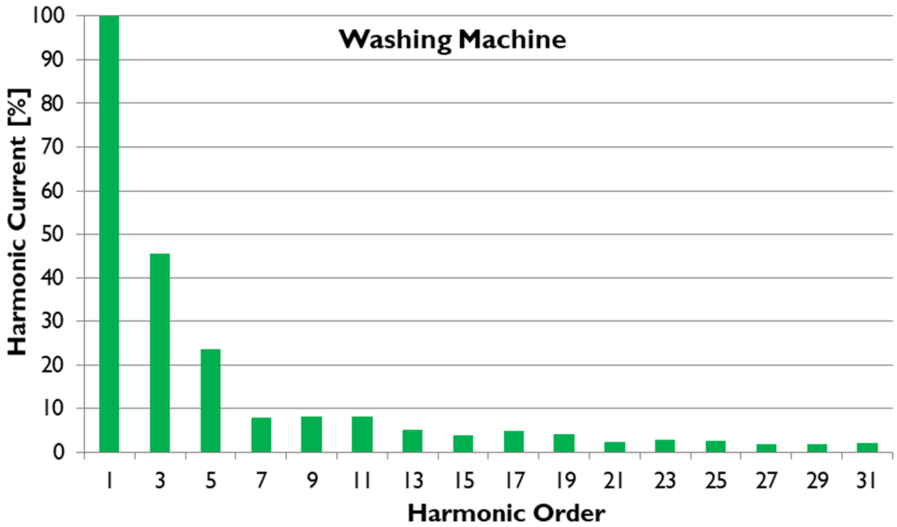

Fig. 6 *Current spectrum of the washing machine.*

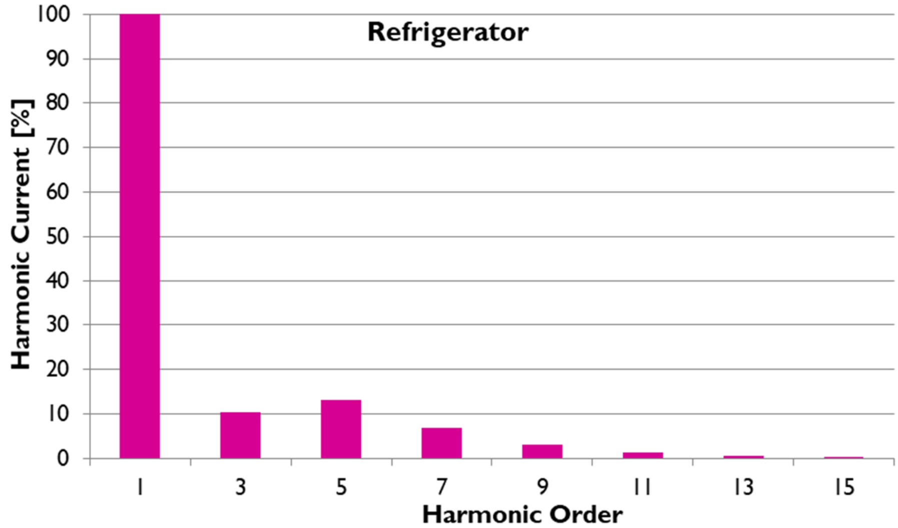

Fig. *7 Current spectrum of the refrigerator.*

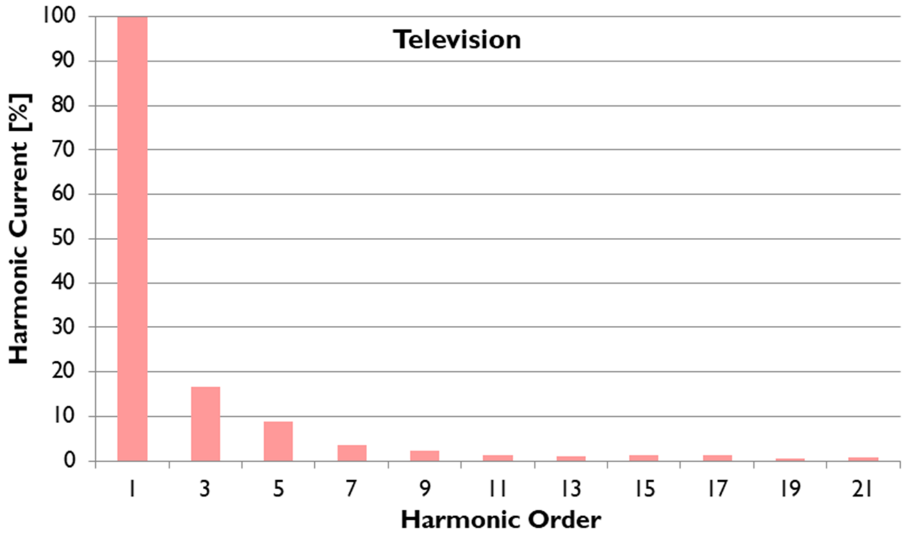

Fig. 8 *Current spectrum of the TV.*

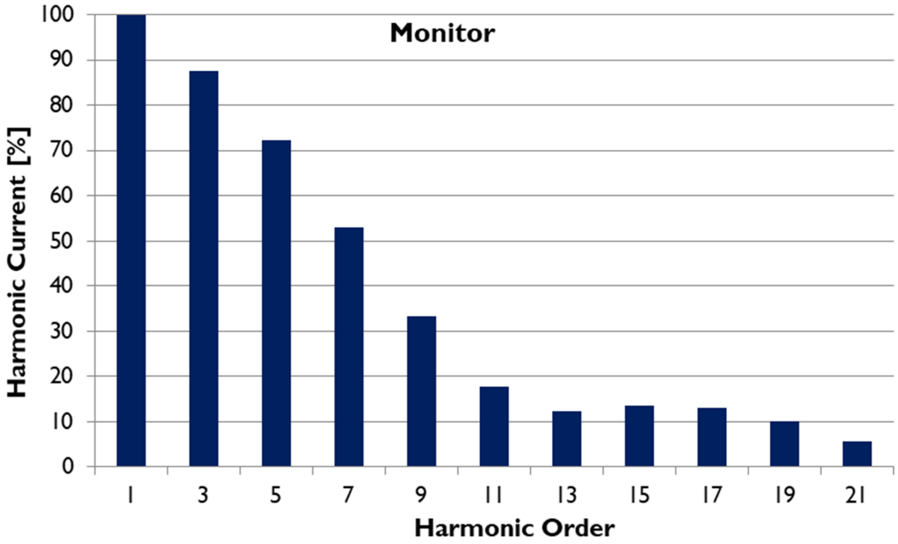

Fig. 9 *Current spectrum of the monitor.*

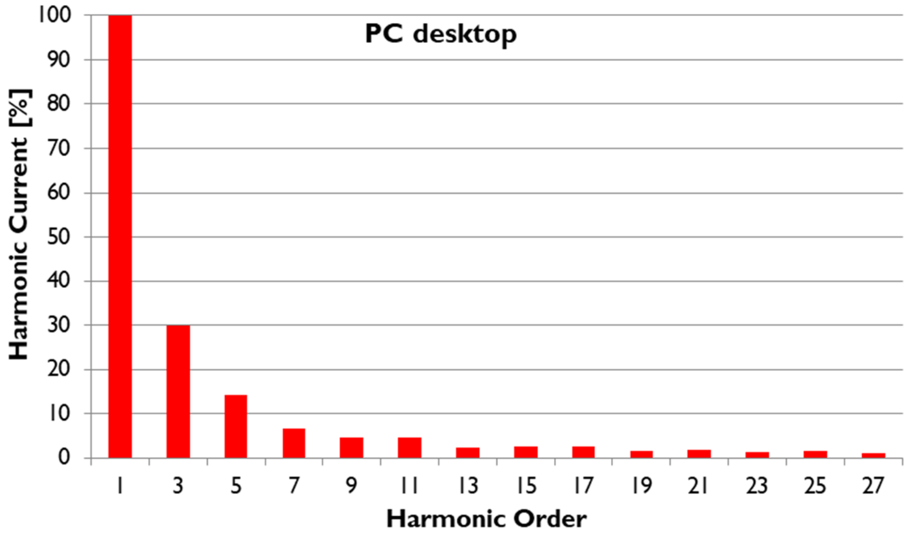

Fig. 10 *Current spectrum of the PC desktop.*

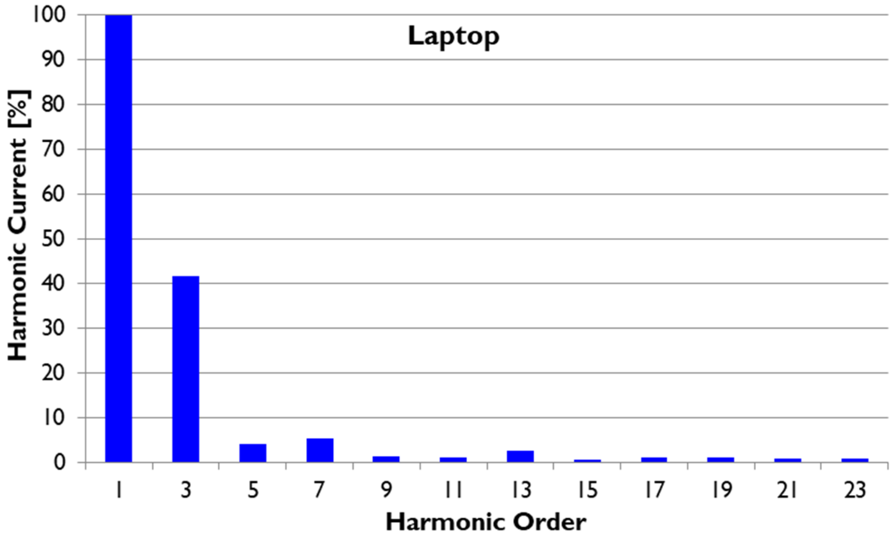

Fig. 11 *Current spectrum of the laptop.*

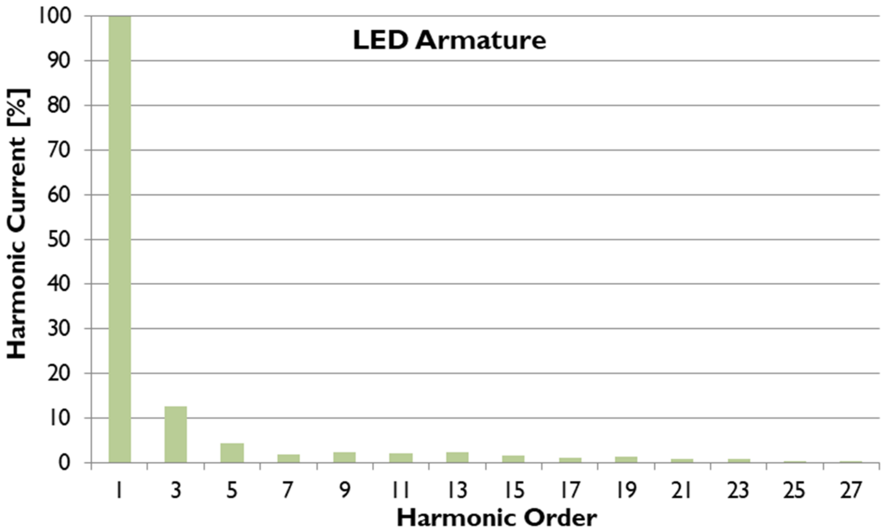

Fig. 12 *Current spectrum of the LED armature.*

The components of the current harmonics of the dishwasher are shown in Fig. 13. The most dominant component is the 5th component. It can be stated that the harmonic distortion of this appliance is not too high among the harmonic generating appliances.

In addition to the harmonic measurements, active, reactive and apparent power of each appliance is measured. When active power measurements are examined, it can be seen that the nominal power of household appliances appears to be high. However, it is well known that the appliances do not continuously draw rated power from the grid. For instance, although the washing machine has a rated power of 1.8 kW, it does not continuously draw this power during its operating period as shown in Fig. 14. It was found that the washing machine draws an average power of 0.373 kW considering whole operational period.

The abovementioned comments are also valid for the refrigerator. Although the nominal power of the refrigerator is 0.150 kW, it draws nearly 0.850 kW at the first start-up. The power curve of the refrigerator is given in Fig. 15.

Furthermore, there are many resistive loads in the smart home that should be considered when improving management strategies since it is observed that the current harmonic components of the resistive loads such as oven, kettle, iron, toaster, hair dryer are close to zero. Therefore, reduction in the harmonic contents can be provided by operating these types of linear loads with non-linear appliances.

Figure 16 shows the TDD_i variation during the representative day for Base Case. At the beginning of the period, the TDD_i is increasing and then decreasing depending on the working loads.

Although kettle and hair dryer has very low harmonic current content, operating both of them between 07:05 and 07:10 causes TDD_i value to increase slightly. During 08:00 to 11:00 and 23:00 to 07:00, only refrigerator is working as it can be seen in the graph.

At 11:00, TDD_i becomes nearly 5.7%, which can be evaluated as high. The main reason is that LCD-TV causes harmonic pollution due to its electronic components. Then, air conditioner is operated in cooling mode between 12:00 to 15:00 and also iron is used from 13:00 to 13:57. Air conditioner causes to increase TDD_i less than LCD-TV; however, iron has good impact in terms of mitigating harmonics which helps to decrease TDD_i slightly.

The TDD_i reaches its highest point between 20:00 and 21:00. The PC monitor, desktop, laptop, dishwasher, LCD-TV and washing machine are operated in a period starting from 19:00, which causes TDD_i to exceed the limit of 10%. Therefore, it is to be highlighted that many residential appliances cause harmonic pollution, which brings significant difficulties in the system operation that should be dealt with.

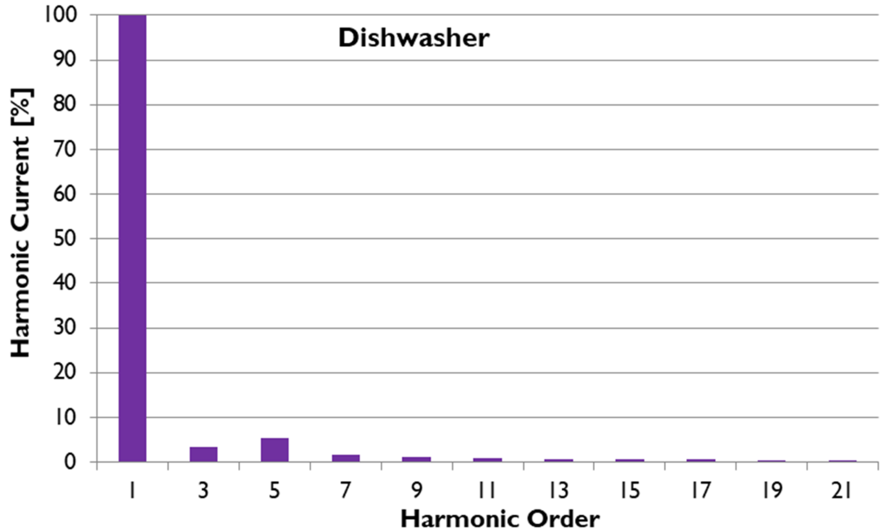

Fig. 13 *Current spectrum of the dishwasher.*

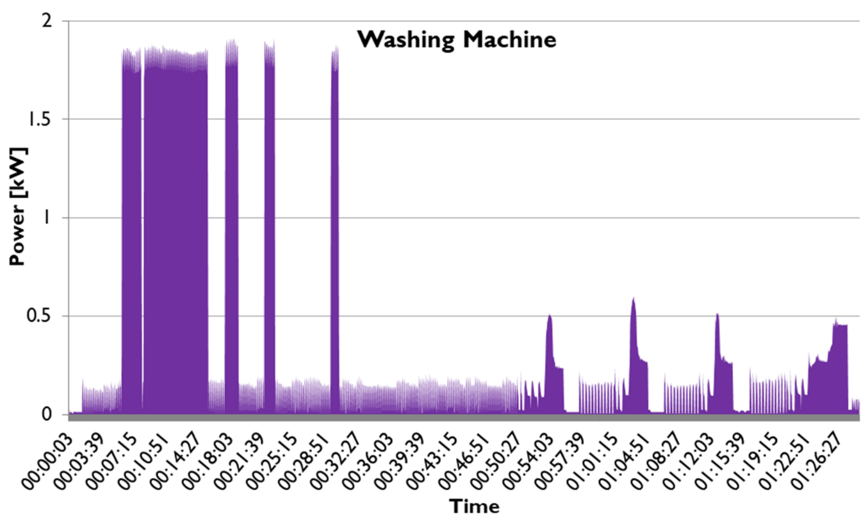

Fig. 14 *Power consumption of washing machine during its operating period.*

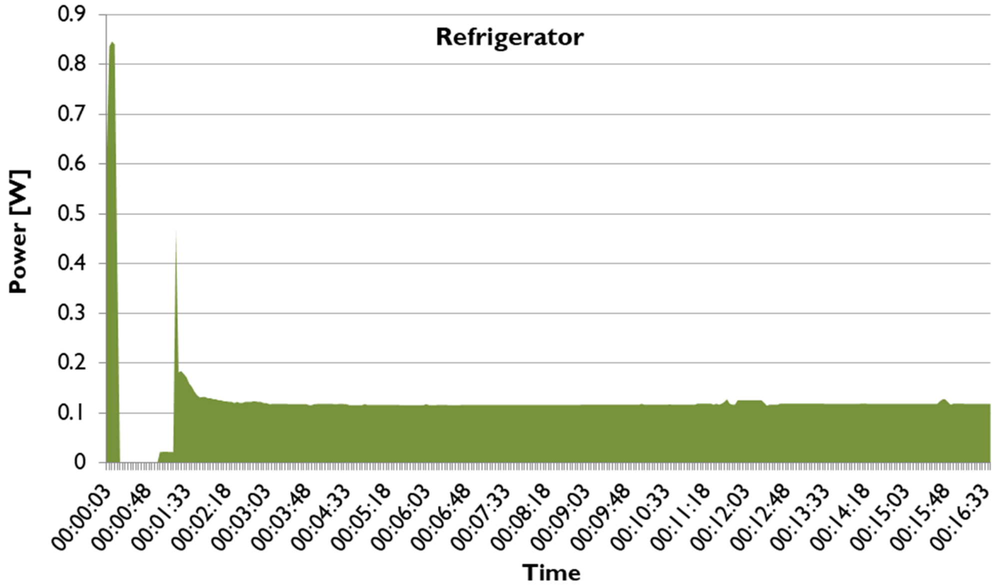

Fig. 15 *Power consumption of refrigerator during its operating period.*

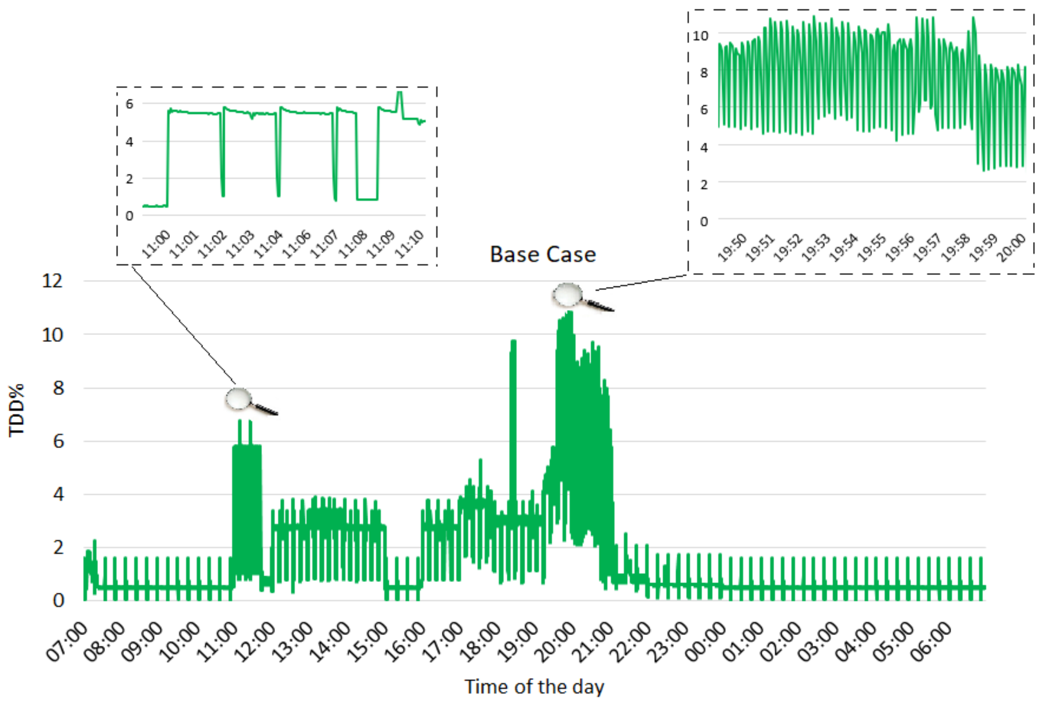

Fig. 16 *The TDD_i variation in percentage during simulation time for Base Case.*

In order to investigate the load shifting strategies on TDD_i, the management strategies are developed for Case 2 and different TDD_i variations are obtained as shown in Fig. 17. In this case study, washing machine is shifted to 09:00, which increases TDD_i in a way that it even exceeds the 6% limit.

LCD-TV is operated from 11:00 to 12:00, which is the same as in Base Case. Since iron and oven are also operated together at 11:00, a lower rise occurs in TDD_i compared to Base Case. The resistive characteristics of these appliances have positive impacts on harmonic elimination as demonstrated.

For the purpose of reducing TDD_i value of 10% at 20:00, the dishwasher is shifted at 21:00. PC desktop and monitor are also operated in the other periods of the day. Scheduling the appliances' operating periods has great impact on reducing TDD_i, which decreases it below the 7% limit. On the other hand, iron and oven are shifted to 13:00-13:57 and 18:00-18:45 in Case 3, respectively. The other appliances are working at the same periods.

Since PC desktop, laptop and monitor are shifted at 19:00, the TDD_i reaches its highest value as shown in Fig. 18. They all cause harmonic pollution in the system, which affects the power quality negatively.

The assessment for the TDD_i value is based on whether 95% of the total time is below or above the required value. According to the standards, the values 5, 8, 12, 15 and 20 are considered for these limits. For each case study, Table 5 shows how many percent of the TDD_i values are provided according to the limit of 5, 8 and 12. It is to be noted that the residential end-users can be connected to the system from different nodes and there is no clear information for indicating the transformer I_{SC} values. Therefore, three limitations are taken into consideration in this study. Since the required value must be at least 95% of the relevant standards, this number is expected to be 95% and above. It was found that 5% limit value could not be achieved in Base Case and Case 3. For the 8% and 12% limits, any problem is not observed. It is seen that the limit of 12% was never exceeded in any case study.

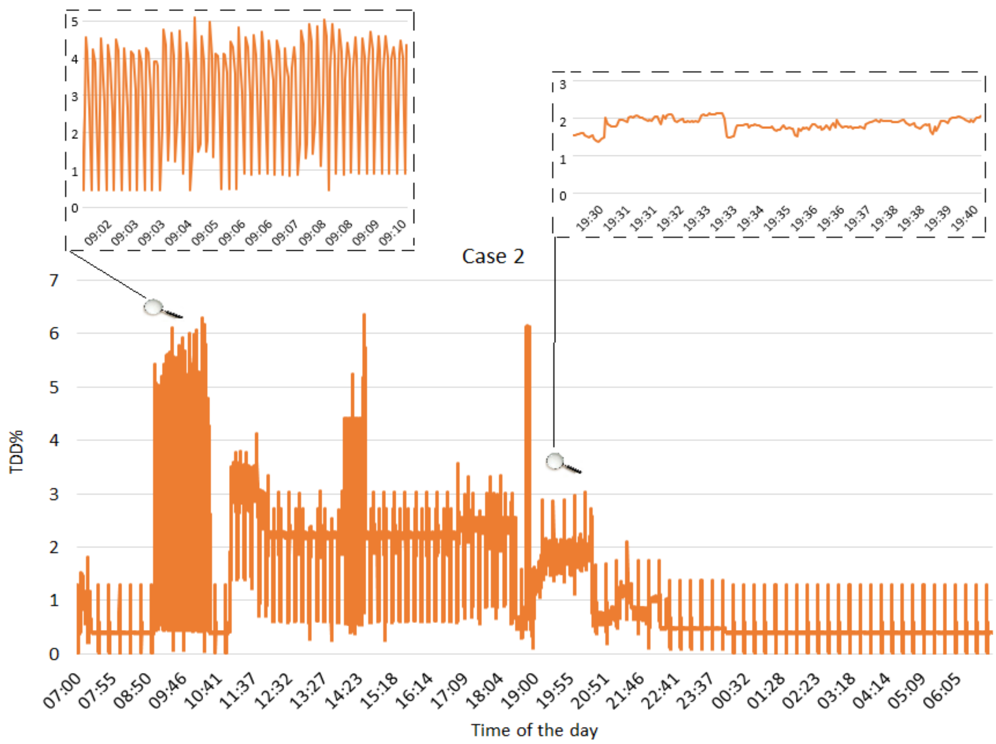

Fig. 17 *The TDD_i variation in percentage during simulation time for Case 2.*

Table 5. The TDD_i limitations in percentage for related case studies.

Case Studies	The limit of TDD_i [%]		
	5	8	12
Base Case	93,25347	98,38194	100
Case 2	99,21181	100	100
Case 3	94,24653	97,77431	100

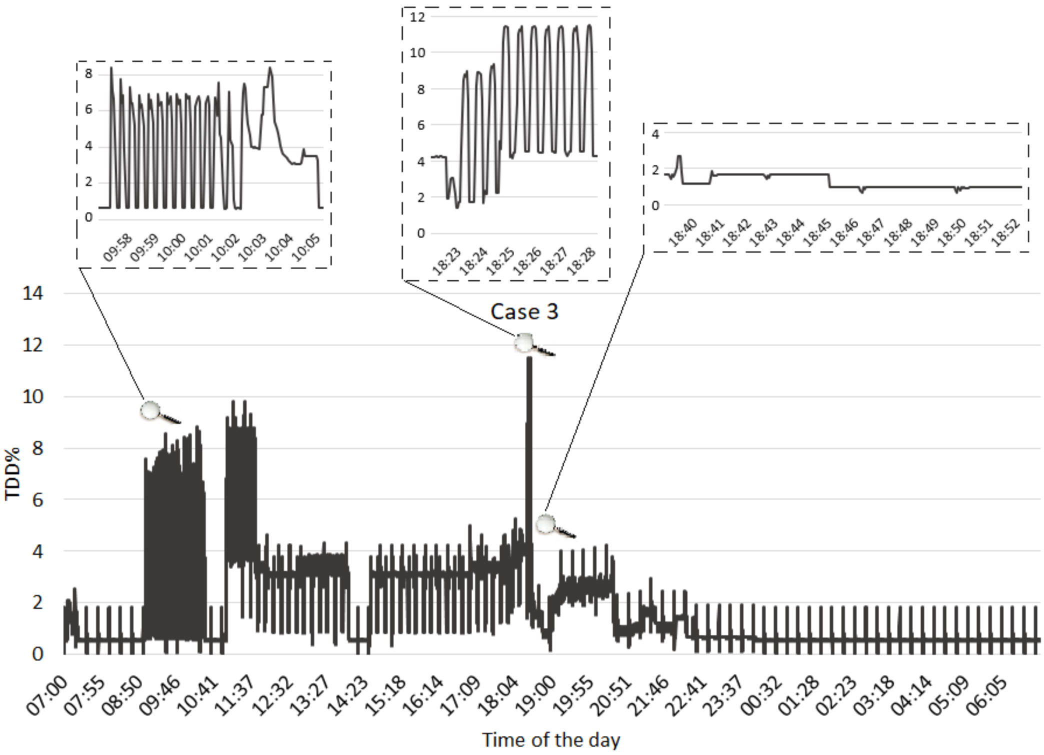

__Fig. 18__ The TDD_i variation in percentage during simulation time for Case 3.

4. Conclusion

In general, the residential appliances have nonlinear load characteristics that affect the power quality in the distribution system negatively. It is observed that the usage of these types of equipment has been increasing and the system operators have faced with harmonic pollution problem more frequent than the past. To address the abovementioned power quality issue, a comprehensive harmonic analysis was conducted, and the evaluations were presented from different points of view in this study. In the Smart Home Laboratory, real measurements of harmonic components of almost every equipment found in a typical family house were performed with an analyser. The current and voltage harmonics (up to 50^{th}) with theirs phase angles; active, reactive, apparent powers as well as power factor and frequency were measured. Based on these values, realistic power curves were obtained for three case studies. By implementing a manual load shifting strategy, which is one of the most promising solutions in power quality improvement techniques, harmonic distortion level was aimed to be appropriate in terms of the standards. The harmonic sources were operated in different periods and TDD_i values were calculated for each case study. Considering different connecting points of the grid for residential end-users and hence different short circuit current levels, TDD_i values were evaluated for providing the 5%, 8% and 12% TDD_i limitations. According to the results, more than 97% limit was achieved for each case study considering 8% and 12% limitations. On the other hand, 5% limitation was only provided in Case 2 and TDD_i was improved substantially. Therefore, it is worth noting that load shifting strategies have the capability of providing a promising solution especially for power quality requirements. Although the proposed scheme is performed for only one home, different types and numbers of residential end-users can be considered in a microgrid scale to show its effectiveness in more populated area. Mostly possible PCC values can be considered under different case studies to investigate whether the related standards are satisfied or not thanks to the load shifting algorithm. An optimization based system modelling framework considering the network constraints may be taken into consideration in a future study.

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