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# **Harmonic Effects of Power System Loads: An Experimental Study**

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Celal Kocatepe, Recep Yumurtacı, Oktay Arıkan,  
Mustafa Baysal, Bedri Kekezoğlu, Altuğ Bozkurt and  
C. Fadıl Kumru

Additional information is available at the end of the chapter

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## **1. Introduction**

Today, electric power systems is spreading to a large area and wide variety of loads are connected to energy system. During the planning and management of power systems, accurate determination of load characteristics that connected to power system is very important. Thus, power system problems, that may occur, can be pre-determined and precautions may be taken against them.

Especially with the developing semi-conductor technology, harmonics have become one of the most popular issues in power system. In this study, the measurements for the harmonic effects of the loads in power system were carried out and also contribution of these loads to harmonic distortion was exhibited. Moreover, the effect of harmonics existing in power system on the performance of some equipment was analyzed experimentally. The obtained results were discussed and suggestions were given.

## **2. Power system harmonics**

Harmonics can be defined as components with periodic waveforms having multiples of fundamental frequency. Harmonics, one of the most important issues of power quality, have recently come into prominence though they are known since the early time of the ac power systems. In 1893, only eight years after first ac power plant is built, engineers conducted harmonic analyses to identify and solve the motor heating problem [1]. A paper written by E.J.

Houston and A.E. Kennely in 1894 is one of the first documents in which the word harmonic is used [2]. The issues related to harmonics became widespread especially after power electronic devices are significantly penetrated into power systems. In order to enhance the power quality and to remove the negative effect of nonsinusoidal magnitudes on power system, harmonic magnitude levels are need to be specified and also harmonics have to be analyzed. In this part, the circuit quantities/components are identified and definitions related to harmonic distortion are introduced.

### 2.1. Electrical quantities for non-sinusoidal conditions

Electrical quantities, such as voltage and current, are usually defined for sinusoidal steady-state operating conditions. These electrical magnitudes are, however, needs to be redefined when there are harmonic components due to the nonlinear elements. In this case, instantaneous voltage and current can be represented as following;

$$v(t) = \sqrt{2} \cdot \left( V_1 + \sum_{n=2}^{\infty} V_n \cdot \sin(n\omega_1 t + \theta_n) \right) \quad (1)$$

$$i(t) = \sqrt{2} \cdot \left( i_1 + \sum_{n=2}^{\infty} i_n \cdot \sin(n\omega_1 t + \delta_n) \right) \quad (2)$$

where  $V_n$  and  $I_n$  are the effective values of voltage and current for  $n$ th harmonic level, respectively.  $\theta_n$  and  $\delta_n$  are respectively phase angels of voltage and current for  $n$ th harmonic component with respect to reference angle.  $\omega_1 = 2\pi f_1$  is the angular frequency of the fundamental frequency  $f_1$ . The DC component is assumed to be zero for simplification.

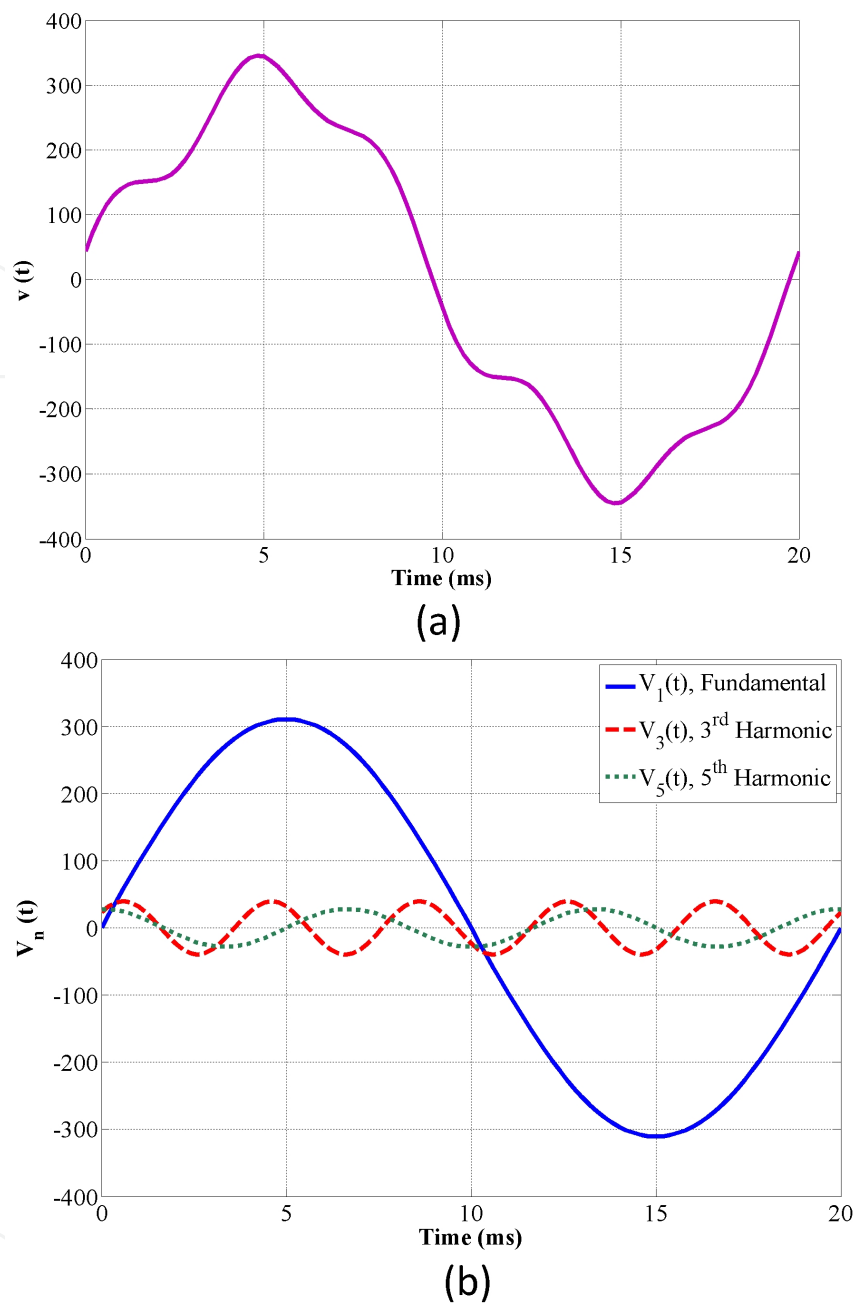
A typical distorted voltage waveform and its harmonic components are shown in Figure 1. The voltage signal has the following function;

$$v(t) = 220\sqrt{2} \cdot \sin\omega t + 20\sqrt{2} \cdot \sin(3\omega t + 90^\circ) + 40\sqrt{2} \cdot \sin(5\omega t + 36^\circ)$$

Real power  $P$  can be represented by the following expression,

$$P = \frac{1}{T} \int_0^T p(t) \cdot dt = \sum_{n=1}^{\infty} V_n \cdot I_n \cos(\theta_n - \delta_n) \quad (3)$$

where  $T = 1/f$  is known as period or cycle. Notice that voltages and currents having different frequencies have no effect on real power value calculated. Expression (e.g. multiplication of 3<sup>rd</sup> harmonic voltage by 5<sup>th</sup> harmonic current is not undefined in real power expression).



**Figure 1.** a) A typical distorted voltage waveform b) components of waveform

Apparent power  $S$  and distortion power  $D$  in power systems are defined as,

$$S = V \cdot I \tag{4}$$

$$D = \sqrt{S^2 - P^2 - Q^2} \tag{5}$$

Distortion power is not identical to real power and its value for sinusoidal conditions is zero.

Reactive power can be represented by,

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

Power factor concept is used to determine how a current from AC power system is efficiently utilized by a load. In both sinusoidal and non-sinusoidal cases, power factor can be expressed as follows,

$$PF = \frac{P}{S} \quad (7)$$

## 2.2. Total Harmonic Distortion (THD)

Total harmonic distortion, THD, most-widely used index in related standards, is used to determine the deviation of the periodic waveform containing harmonics from the pure sinusoidal waveform. The total harmonic distortion of voltage and current waveform respectively can be expressed as following,

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad (8)$$

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \quad (9)$$

As seen from Eq. (7) and (8), total harmonic distortion is the ratio between rms values of harmonic components and rms value of fundamental component, and, is usually represented in percentage. THD value is equal to zero in a pure sinusoidal waveform.

## 2.3. Total Demand Distortion (TDD)

Total demand distortion, TDD, is related to particular load and defined as total harmonic current distortion,

$$TDD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \quad (10)$$

where  $I_L$  is the maximum demand load current at the point of common coupling, PCC. This current value is the mean of the maximum currents which are demanded by the load through twelve months prior the measurement. TDD index is especially emphasized in IEEE Standard 519.

#### 2.4. Crest factor (Cf)

The crest factor of a non-sinusoidal wave is represented,

$$Cf = \frac{\text{Peak Value}}{\text{RMS Value}} \quad (11)$$

This factor is the ratio between peak value and rms value of periodic wave which is the easiest way to indicate the harmonic components, and it is equal to  $\sqrt{2}$  for a sinusoidal wave.

#### 2.5. Transformer K-factor

The load current flowing through a transformer includes harmonic components when the transformer supplies nonlinear loads. Consequently the transformers under nonlinear loading cannot be run at their rating power. Transformer K-Factor index is used to determine the decrement quantity in nominal loading capacity of standard transformers running under harmonic conditions.

The transformer K-factor can be represented as follows,

$$K = \frac{\sum_{n=1}^{\infty} \left( \frac{I_n}{I_1} \right)^2}{1 + THD_I^2} \quad (12)$$

where  $I$  is effective current and  $I_n$  is current of  $n$ th harmonic component.

To show how the concepts and definition related to harmonic distortion is changed in terms of signal waveform, a comparison is realized using several waveforms of current as shown in Figure 2. Peak values of pure sinusoidal waveform and square waveform are the same, 311 A, while pure sinusoidal waveform and distorted sinusoidal waveform have same rms value, 220 A. Distorted sinusoidal current signal has the identical harmonic components of waveform shown in Figure 2.

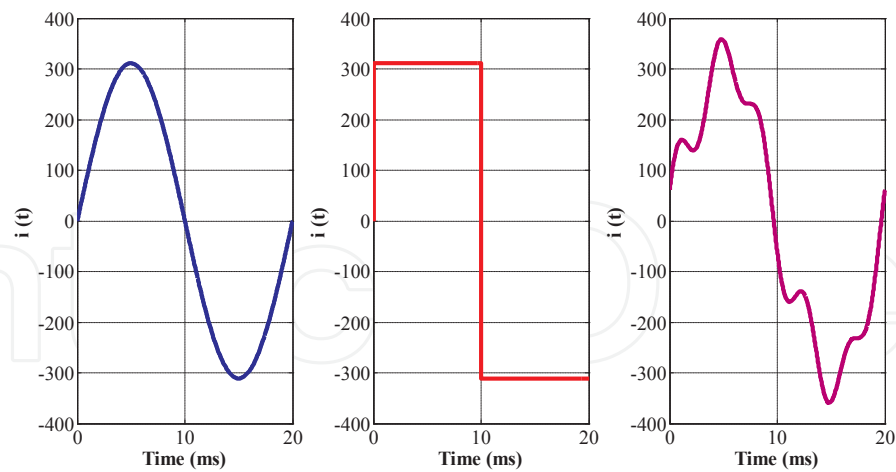


Figure 2. Several current waveforms

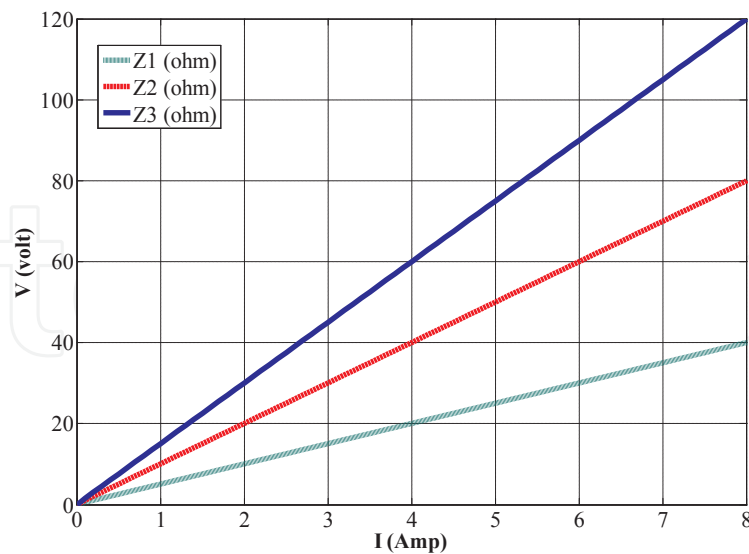
Quantities for the waveforms mentioned above are given in Table 1. The square shape current signal has the highest values for all harmonic indexes except crest factor. This is expected result since square waveform is the most distorted signal among the others. The highest crest factor value is obtained for distorted sinusoidal signal. Notice that, the peak value of the whole waveform would be different if the phase angles of the harmonic components are changed. The crest factor will have another value though the signal has the same harmonic components in that case. Maximum demand load current,  $I_L$ , is assumed to be 311 A for the calculations of TDD.

Electrical Quantity	Pure Sinusoidal	Square	Distorted Sinusoidal
$I$ (A)	220	311	224,5
THD <sub>i</sub> (%)	0	48,17	20,33
TTD (%)	0	43,37	14,38
Crest Factor	1,414	1	1,535
Transformer K-Factor	1	11,35	1,83

Table 1. Harmonic quantities calculated for several waveforms

2.6. Nonlinear elements

An electrical linear element has the constant ratio of voltage to current as illustrated in Figure 3. An electrical element which does not have linear relationship between voltage and current is defined as nonlinear element. When a nonlinear element is connected to a power system, it causes harmonic voltages and currents. These elements have either the electrical or magnetic circuit non-linearity characteristics.

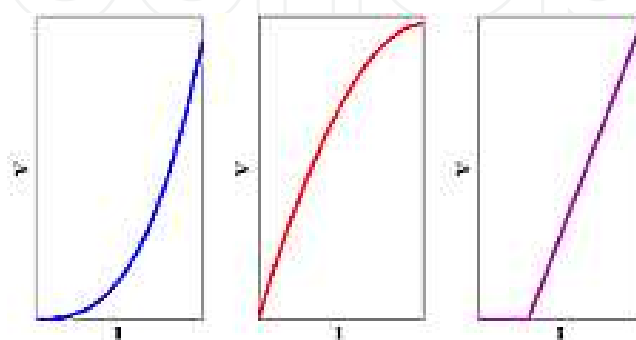


**Figure 3.** Linear electrical element characteristics

The relationship between voltage and current of a nonlinear element is mostly defined as,

$$I = K_1 + K_2 \cdot V + K_3 \cdot V^2 + K_4 \cdot V^3 + \dots \quad (13)$$

where,  $I$  is the current through the nonlinear element and  $V$  is the voltage on the nonlinear element [3]. Constant values such as  $K_1$ ,  $K_2$ ,  $K_3$  and  $K_4$  can be different for every nonlinear element. These constant values given for every nonlinear element changes according to the current-voltage characteristic and acquired experientially. For example, the constant values of current function for a nonlinear element which flows 5,5 A at 100 V, 9 A at 150 V, 14,5 A at 200 V and 18 A at 230 V, are calculated as  $K_1=11,81$ ,  $K_2=-0,19$ ,  $K_3=1,5 \cdot 10^3$  and  $K_4=-2,44 \cdot 10^{-6}$ , respectively. Some of them might be existent in a nonlinear element while some of them might not. Several nonlinear electrical element patterns are shown in Figure 4. Notice that the characteristic on the rightmost is nonlinear though it looks like linear element.



**Figure 4.** Nonlinear element patterns



3. Harmonic effects of power system loads

Due to increased diversity of the load that used in power systems, need to analyze load effects on power system occurred. The harmonic effects of the loads in power system were presented in this study. The loads in power system are considered in two different categories: distribution system loads and transmission system loads.

3.1. Distribution system loads

The harmonic effectiveness of the loads used frequently in power system was demonstrated by the performed measurements, in present study. The measurements were carried out for office equipment (computer, printer, scanner), air conditioner, lighting devices, motor drivers and kitchenware (refrigerator, microwave oven).

3.1.1. Office equipment

Many devices have been developed to facilitate professional life depending on technological developments. Growing number of these equipment occurred as power system loads. These office devices such as computer, printer, scanner etc. that involve power electronic components, have distortion effects on electrical power systems.

With the aim of seeing power quality distortions clearly, power quality measurements were performed for desktop computer, printer and scanner as office equipment. The real power, reactive power, total harmonic distortion in current (THD<sub>i</sub>), power factor and cosφ values obtained from the measurement on office equipment are given in Table 2 [4, 5];

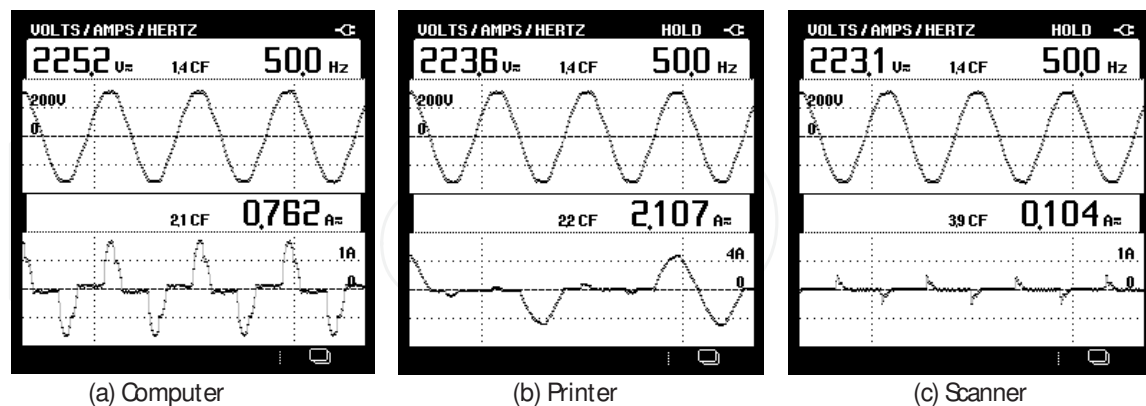
	P (W)	Q(VAr)	THD <sub>i</sub> (%)	PF	cosφ
Desktop Computer	140	100	70.3	0,82	1
Printer	174	154	36.9	0,76	0,92
Scanner	10	13	132.4	0,55	0,92

Table 2. Measurement Results from Office Equipment

As clearly seen in Table 2, THD<sub>i</sub> values of all measured office equipment are exceed the standard values. Printer has worst power quality level with %132,4 THD<sub>i</sub> value. Since power and current values of considered devices are very low, it is assumed that effects of this equipment may not harmful on power system. However, numbers of business centers have been increasing and very significant growth on collectively usage of these devices is observed. With including of individual user in this number, effects of office devices on power systems reach very high level that cannot be ignored.

All measured office equipment take attention with low power factor as seen in Table 2. In this case, it would be appreciate that implementation of compensation filter is realized especially on substations which feed business centers.

In Figure 5, voltage and current waveforms of measured equipment are shown.



**Figure 5.** Voltage-Current Waveforms of Measured Equipment

### 3.1.2. Air conditioning

Air conditioning is used for both cooling and heating nowadays. Especially on summer, respectable increasement is shown on usage of air conditioning. Nevertheless, impact of air conditioning loads on electrical energy system increases. Particularly in warm regions, overload and disruptive effects can be shown on power system. This situation emphasizes the need to analyze the effects of air conditioning loads on power system. In line with this objective, power quality measurements of six commercial air conditioning units are realized and results are given in Table 3.

Air Conditioning	Btu/h	$P_n$ (W)	$I_n$ (A)	Power Factor	THD <sub>v</sub> (%)	THD <sub>i</sub> (%)
A	9000	1.000	4,0	0,98	2,600	17,042
B	9000	1.000	4,0	0,98	2,200	16,313
C	7000	680	3,0	0,98	3,702	17,879
D	12000	1230	5,7	0,99	3,502	14,861
E	21000	2100	9,5	0,57	3,201	19,881
F	11200	1250	6,0	0,99	1,600	13,419

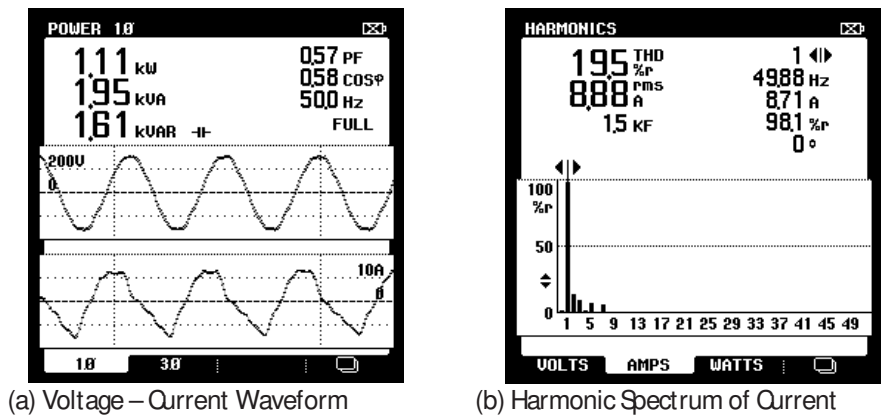
**Table 3.** Measurement Results of Air Conditioners

By examination of Table 3, it can be clearly seen that, except air conditioner E, power factor values of all considered air conditioning unit are over 0,98. Similar with this situation  $\cos\phi$  values of measured air conditioning units are 0,99 or 1,00, except air conditioner E. Air conditioner E has very low power factor with value of 0,57. Therefore, power compensation should be done where these air conditioning units are used. However, considered air conditioning units are single-phase equipment and are used in places without an obligation to

make compensation like houses, offices etc. In this case, reactive power demand is met by distribution transformers and voltage value will be change. This situation cause major problems for distribution transformers especially in summer, due to increased use of air conditioning.

Total harmonic distortion of air conditioner E is the worst one of considered air conditioning units with  $THD_1$  value of %19,881. Also, the power factor value of air conditioner E is very low. Voltage-current waveforms and harmonic spectrum of air conditioner E are given in Figure 6.

With examination of Table 3 values in general, total harmonic distortion values of all air conditioners are over 10%. Consequently, measured air conditioning units act as harmonic source and distort voltage waveform of power system.



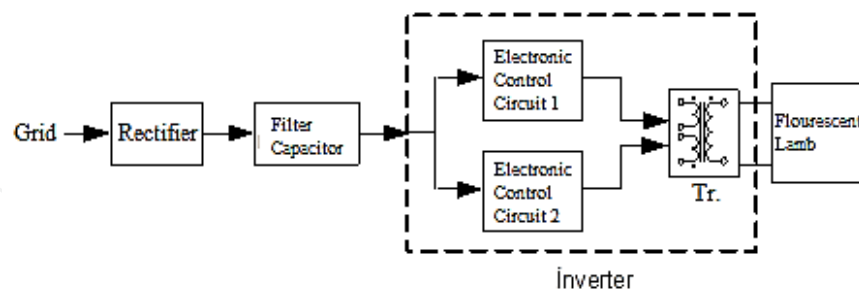
**Figure 6.** Voltage-Current Waveforms and Harmonic Spectrum of Air Conditioner E

As a result of global warming, installed capacities of air conditioners are rising parallel with increased temperature. Correspondingly, harmonic distortion of low voltage power system is rising. In conclusion, filtered compensation is suggested on distribution substations that includes in a large number of air conditioning unit.

3.1.3. Lighting devices

Although the lighting loads are not taken into account generally, while the power system loads are ranked. They have an important place in power systems. The effects of lighting loads should be considered especially in the night hours.

Fluorescent lamps, which operate according to gas discharge principle and have high impact factor (effectiveness factor), are preferred instead of the incandescent lamps for lighting. Compact fluorescent lamps are widely used types of these devices. Block diagram of these lamps are shown in Figure 7. [6].



**Figure 7.** Block Diagram of Compact Fluorescent

The grid voltage with 50 Hz (or 60 Hz) main frequency is firstly directed by a rectifier and then filtered by a capacitor. The obtained DC voltage is converted to high frequency (20 kHz – 50 kHz) AC voltage by an inverter and applied to the fluorescent lamp. When the applied voltage frequency is going up, the luminous flux increases and impact factor of the device rises [7].

Fluorescent lamps are producing harmonic components and non-sinusoidal currents, because of their nonlinear current-voltage characteristics. Due to their characteristics, detailed analysis is required where they are used extensively. Power quality measurement results for commercially available devices are given in Table 4 [8].

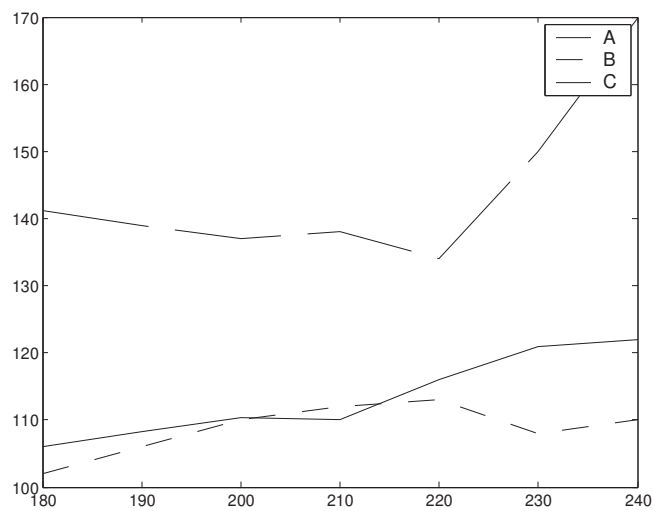
	$I_{rms}$ (A)	P (W)	Q (VAr)	Power Factor	$\cos\phi$	THD <sub>i</sub> (%)
Compact Fluorescent A	0,077	10,3	14,0	0,59	0,89	108,8
Compact Fluorescent B	0,121	16,6	21,6	0,61	0,89	105,4
Compact Fluorescent C	0,170	22	34,0	0,54	0,94	123,3
Flourescent Lamb	0,336	44	62	0,58	0,60	10,3

**Table 4.** Measurement Results of Fluorescent Lambs

According to measurement results THD<sub>i</sub> values of compact fluorescent lamps reaches to % 123. Whereas, THD<sub>i</sub> value of fluorescent lamp was % 10,3. Measurements show that all the lamps have very low power factor values.

The variation of THD<sub>i</sub> according to voltage for compact fluorescent lamps is given in Figure 3.4. As shown in Figure 8, THD<sub>i</sub> values of C lamp is particularly high over 220 V.

The harmonic currents injected into the network by a fluorescent lamp are negligible because of its low power. However, when the large number of fluorescent lamps used together, their effects are important for power quality distortion studies.

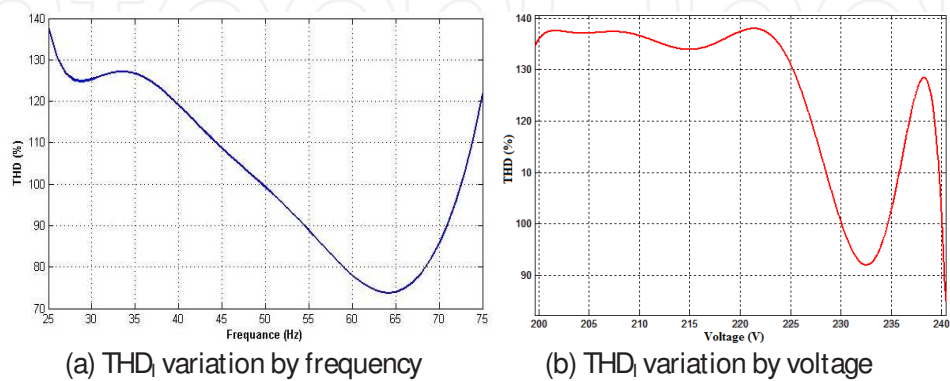


**Figure 8.** The variation of THD<sub>I</sub> values with voltage for several compact fluorescent lamps.

3.1.4. Motor drives

Motor drives act an important role to ensuring control and efficient use of electrical machines. Due to technological developments, motor drives became more advances featured and reached a wider field of use. Many commercial facilities utilize motor drives for their motional systems. Motor drives become a significant power system load with increasement of usage.

Momentary or continuous variations on voltage and frequency can be occurred especially at the points that feed industrial plants. Motor drives are affected by these changes in addition to being a harmonic source. In Figure 9, total harmonic distortion of single-phase motor drive depending on variable voltage and frequency [9]. Voltage level is fixed to motor drives nominal voltage while frequency is variable.



**Figure 9.** THD<sub>I</sub> characteristic of considered motor drive

Total harmonic distortion of motor drive current decreased to minimum value at nominal voltage and frequency levels, as seen in Figure 9. On the other hand, Total harmonic distortion reached very high values at low voltage and frequency levels. It can be suggested that usage of voltage and frequency regulator reduce total harmonic distortion in industrial plants, which includes motor drives.

3.1.5. Household equipment

Despite the conveniences that they create in daily life, household equipment take place in electrical energy system as a power system load. It is considering that household equipment is used several times per day; importance of their effects on power system is appeared clearly. Power quality measurements of an office type refrigerator and microwave oven are given in Table 5 [4, 5].

As seen in Table 5,  $THD_I$  values of all measured household equipment are exceed standard levels. Especially microwave oven has harmful effect on power system with %39,3  $THD_I$  level. However, office type refrigerator have showed worst characteristic in terms of power factor. As a result of analyses, it can be said that other household equipment have similar effects on power system. In this case, characteristics of system loads must be considered and appropriate precautions must be operated during planning of power system.

	THD <sub>I</sub> (%)	I <sub>rms</sub> (A)	P (W)	Q(VAr)	Power Factor	cosφ
Refrigerator	13.3	0.608	97	98	0,70	0,72
Microwave Oven	39.3	5.39	1110	390	0,94	1

Table 5. Measurement Results of Household Equipment

Voltage and current waveforms of measured household equipment are shown in Figure 10.

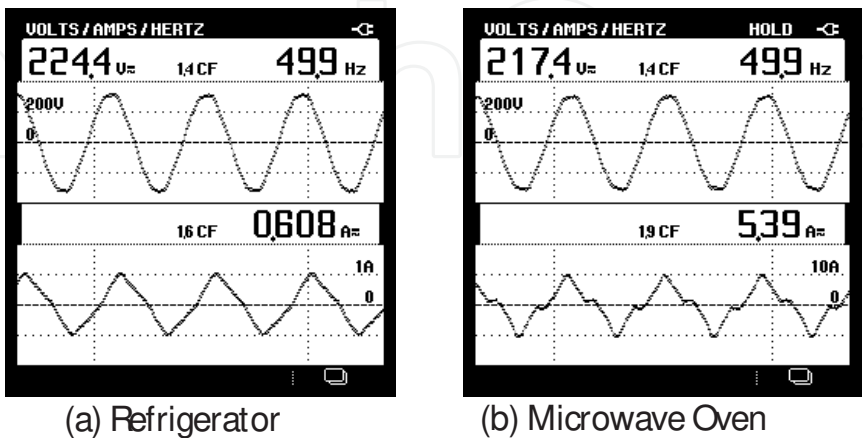


Figure 10. Voltage-Current Waveforms of Measured Household Equipment



3.2. Transmission system loads

The harmonic effectiveness of the loads which are directly connected to transmission system is introduced in this part. Within the scope of National Power Quality Project of Turkey, power quality measurements on more than 150 points were achieved. The results of measurements have been continuously carried out through 7 days and then processed.

In this study, harmonic effects of the loads which are directly connected to the measured transmission system are also demonstrated. In consequence of realized measurements, it has been seen that especially the iron-steel plants and large industrial facilities have considerable disturbance effect on the electrical network.

As an example  $THD_v$  variation with time measured in a distribution substation that feed industrial loads is shown in Figure 11.

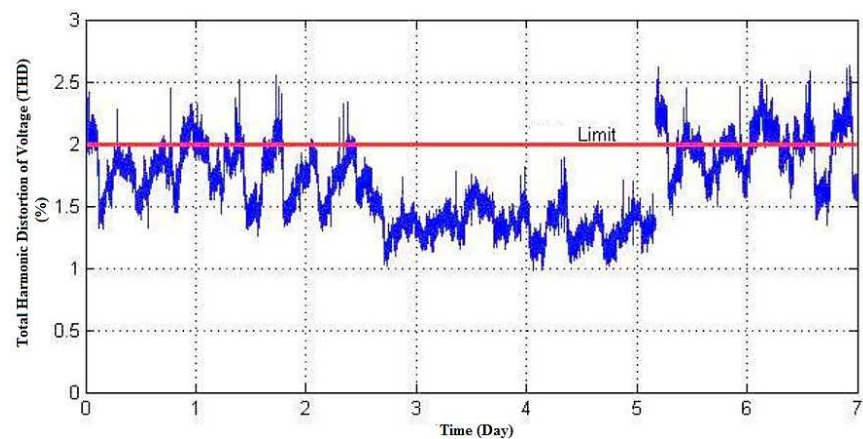


Figure 11. THD<sub>v</sub> variation in time belonging to a distribution substation

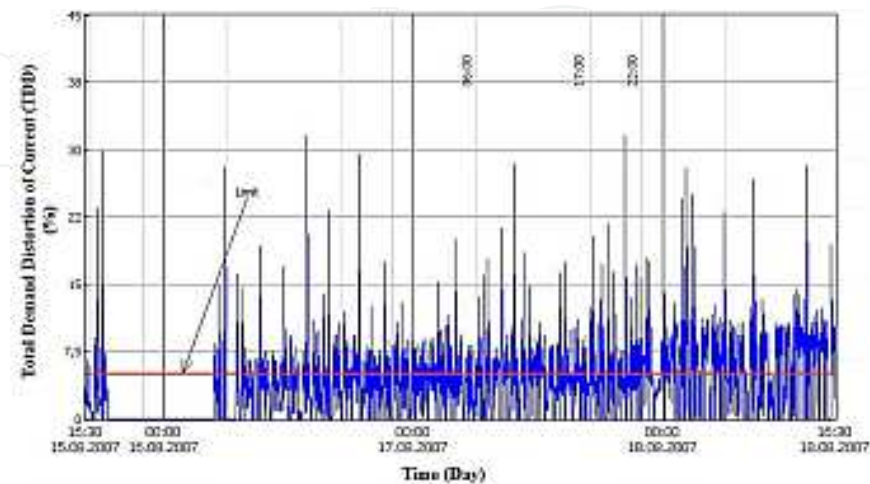


Figure 12. TDD<sub>i</sub> variation of an iron-steel plant

Also, Figure 12 shows the  $TDD_1$  variation for an iron-steel plant. As it can be seen easily from the figure, notable distortions are observed at same substations. Because of that especially effects of large industrial plants and iron-steel plants have to be mentioned and sustainable solutions as harmonic filters, STATCOM etc. should be applied for substations which feed these loads. As a conclusion, it can be said that power quality problems could be seen in transmission system, besides distribution system.

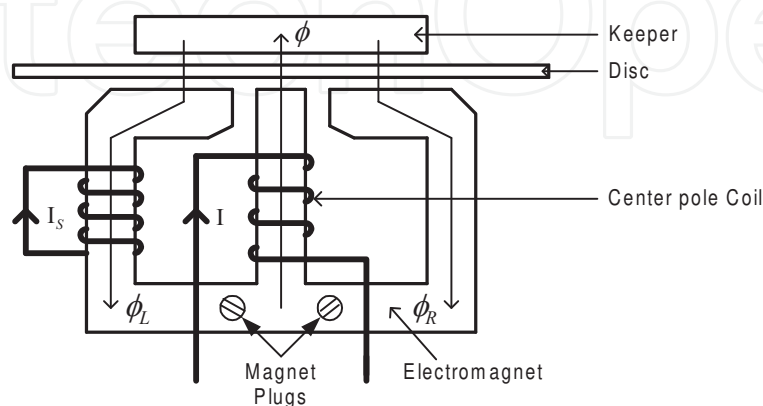
## 4. Effects of harmonics on power system equipment

In power systems, protection relays are crucial elements for the system's reliability and protection. The overcurrent protection relays are used to protect the system's elements from over load and short circuit faults. Electromechanical, static and digital relays are the main types of over current relays. Generally, relay manufacturers design these relays for sinusoidal currents by giving them operating characteristics for sinusoidal conditions. The operation of these relays for non-sinusoidal currents including harmonics is not defined.

In this study, effects of harmonics on overcurrent relays are investigated for static inverse time overcurrent relay, electromechanical inverse time overcurrent relay, electromechanical definite time overcurrent relay.

### 4.1. Electromechanical Inverse Time Overcurrent Relay (EITOCR)

Electromechanical inverse time overcurrent relay (EITOCR) is used for overcurrent and short circuit protection of power systems elements (transmission lines, power transformers, generators etc.) The induction disc unit is the most important part of an EITOCR. The general structure of this relay is shown in Figure 13 [10]. The relay operates when the center coil is energized. As shown in Figure 13, the left pole is equipped with a lag coil while the right pole does not have any. The flux  $\Phi$  is produced by the current of center pole coil. This flux passes through the air gap towards the disc and it reaches to the keeper.

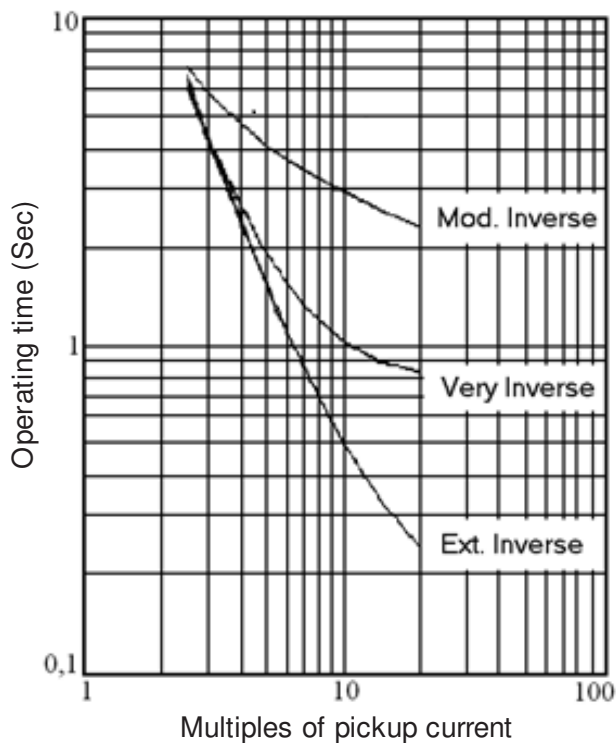


**Figure 13.** Induction disc unit [13]



The flux  $\Phi$  consists of two parts:  $\Phi_L$  through the left-hand leg and  $\Phi_R$  through the right-hand leg.  $\Phi$  is equal to summation of  $\Phi_L$  and  $\Phi_R$ . There is a short-circuited lagging coil on the left leg. This coil causes  $\Phi_L$  to lag both  $\Phi_R$  and  $\Phi$ . When the fundamental pickup current applied to the center pole coil, a torque occurs on the disc. This causes the disc to begin to move. This torque results from the interaction between the disc currents produced by center pole flux and the other two pole fluxes. Directions of these torques are same [10, 11, 12].

In Figure 14, the standard current-time characteristic curves of EITOCR are given. [13].



**Figure 14.** Time-current curves of an EITOCR [13]

In the lag coil circuit, increasing the frequency of the input current causes a little change in the current that is induced in the coil. The flux in this pole will decrease in inversely proportional to increasing of frequency. Because of this case, disc rotation slows down and the pick current of relay increases. Slowing down in disc rotation causes the operation time to increase. Frequencies of harmonic currents are different from the fundamental current's frequencies. Therefore, currents that include harmonics would have serious effects on pick up current and operation time of EITOCR.

In order to investigate the effects of harmonics on EITOCR, an experiment circuit was implemented. The experiment circuit for EITOCR is shown in Figure 15. Harmonics, pickup currents and operating times of the relay are measured and analyzed by means of data acquisition hardware and LabVIEW programme.

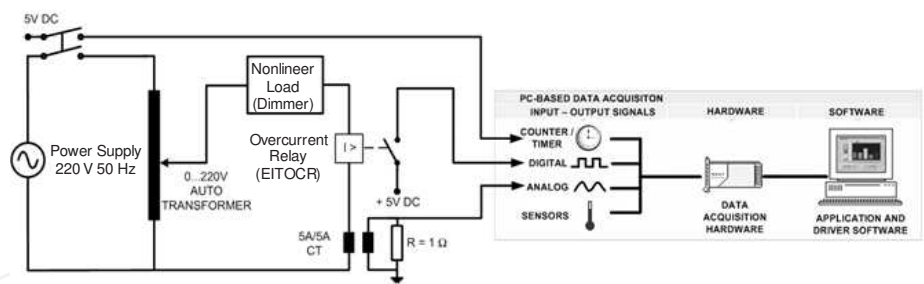


Figure 15. Experiment circuit for EITOCR [14]

The rms value of current ( $I_{rms}$ ), total harmonic distortion of current ( $THD_i$ ), rms value of fundamental current ( $I_1$ ) and the relay's operating time ( $t$ ) are measured for six modes. For all measurement modes, the relay's pickup current is set to 1 Amps for sinusoidal current and this pickup current value of relay is not changed during the experiments.

According to the experimental results, the pickup current of the relay and THD value of the non-sinusoidal current are given in Table 6. While THD value of current is increased, the pickup current of the relay increases. When  $THD_i$  is approximately 85%, although pickup current of the relay is set to 1 Ampere for sinusoidal current, it operates at 1.9 Ampere. Increasing in the pickup current of the relay shows that the relay cannot perform a suitable protection function and causes damage or heating up depending on the rms value of current in power system components such as transmission lines, motors and transformers.

Mode	$\alpha$	$I_1$ (A)	$I_{rms}$ (A)	$THD_i$ (%)
0	0°	1.0975	1.10	6.0010
1	30°	1.1422	1.20	35.3101
2	60°	1.2177	1.30	46.0880
3	90°	1.3352	1.60	68.9976
4	120°	1.3888	1.68	70.6527
5	150°	1.4583	1.90	85.8677

Table 6. Pickup current values and  $THD_i$  values of EITOCR

The variation of relay's operating time versus the relay's rms current is shown in Figure 16. The EITOCR has different operating time values for the same current value which is applied to the relay for six modes as shown in Table 7. While THD value of current increases, operating time of relay increases. According to this result, power system elements that are protected by this relay will be damaged because of the increase in the operating time of the relay.

Mode	$I_{rms}(A)$	$THD_i(\%)$	$t(s)$
0	2.00	6.43	4.634
1	2.00	27.45	5.268
2	2.00	35.12	5.984
3	2.00	59.50	8.682
4	2.00	65.23	9.582
5	2.00	85.20	14.964

Table 7. Operating times of EITOCR for six modes

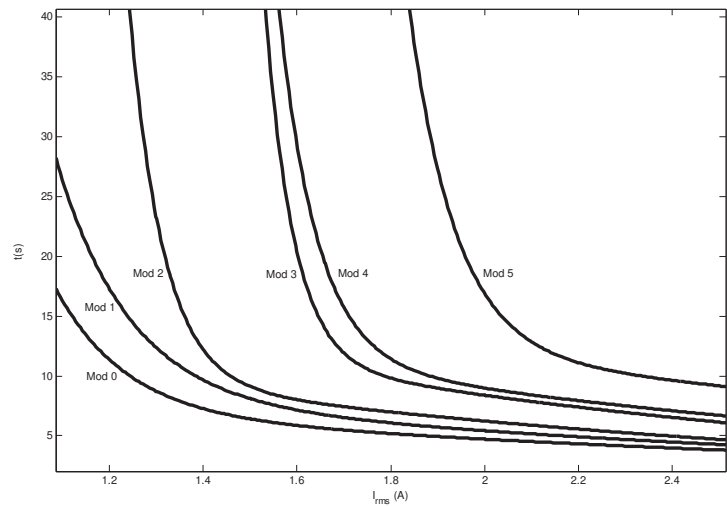


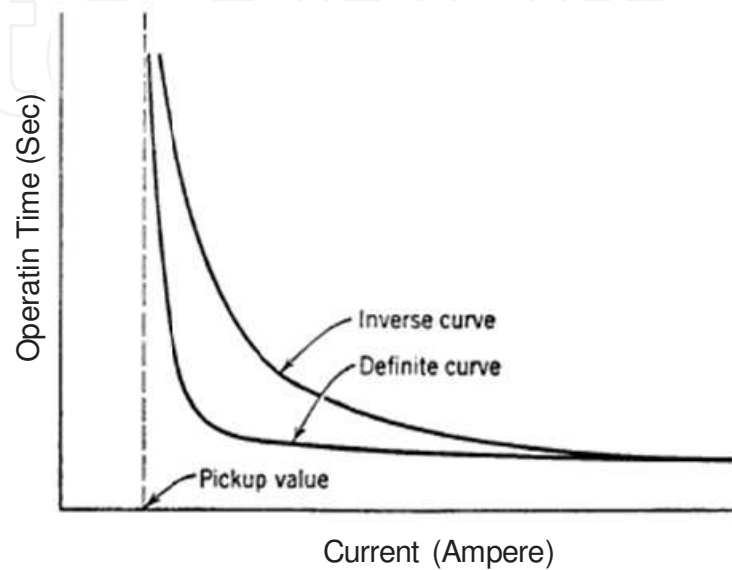
Figure 16. Operating time curves of relay versus rms values of current [14]

4.2. Electromechanical Definite Time Overcurrent Relays (EDTOCR)

Non-sinusoidal load currents contain harmonic components. Each frequency component produces an independent and cumulative effect on relay operation. This effect appears as an increasing in pickup current of electromechanical definite time overcurrent relay. For very high frequencies, the pickup current of EDTOCR increases since the frequency increases [15]. Because of the unexpected increase of the pickup current value, this type of protection relays may not protect the power system elements reliably.

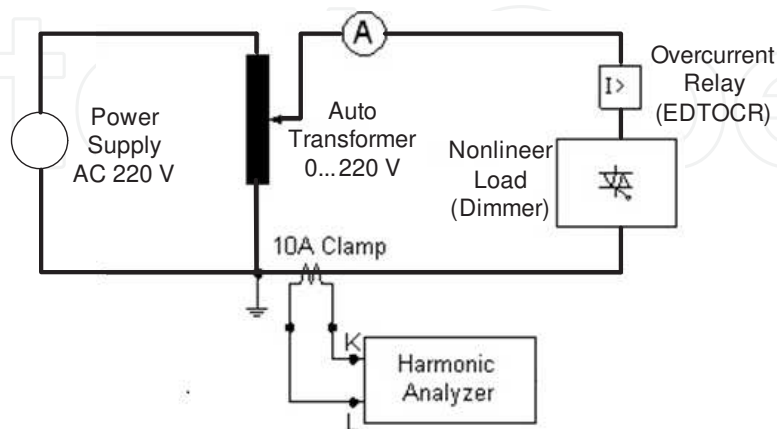
There are two types of time-current curves for overcurrent relays: inverse curve and definite curve. Operating time is inversely proportional to the current in inverse curve. As shown in Figure 17 [15, 16], operating time in definite curve is approximately constant if current is higher than several times of pickup current. Instantaneous relays have definite curve. These

relays are used for short circuit protection. If an instantaneous relay have a time delayed unit, then this relay is suitable for overcurrent protection. Instantaneous overcurrent relays are also called as definite time overcurrent relay. Generally, time-current curves of these relays are given for sinusoidal current and they may be affected by current harmonics [15, 17].



**Figure 17.** Operating time-current curves of overcurrent relays

In order to investigate the effects of harmonics on EDTOCR, an experiment circuit was implemented. The experiment circuit for EDTOCR is shown in Figure 18.



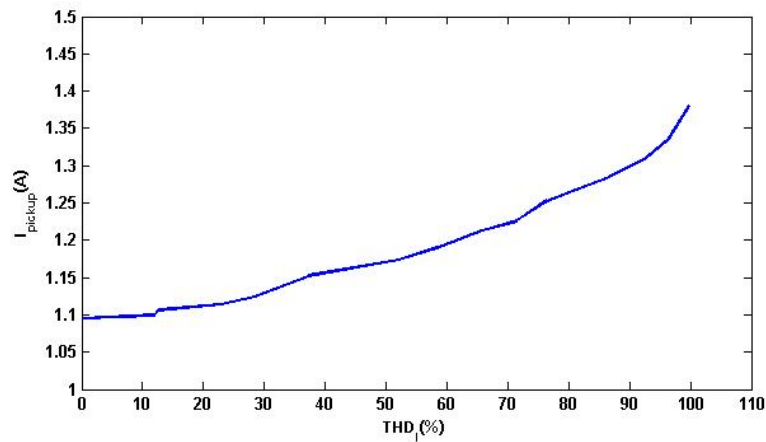
**Figure 18.** Experiment circuit for EDTOCR [17]

The pickup current value of EDTOCR ( $I_{pickup}$ ), total harmonic distortion value ( $THD_I$ ), rms value of fundamental current ( $I_1$ ) and rms value of harmonic currents ( $I_n$ ) for 3<sup>rd</sup>, 5<sup>th</sup>, 7<sup>th</sup>, 9<sup>th</sup>, 11<sup>th</sup> and 13<sup>th</sup> harmonic components are measured for each firing angle ( $\alpha$ ) value. For all measurements the pickup current of relay is adjusted to 1.095 Ampere for pure sinusoidal current and this setting is not changed during the experiments. The experimental results are given in Table 8.

$THD_I$ (%)	$I_1$ (A)	$I_3$ (%)	$I_5$ (%)	$I_7$ (%)	$I_9$ (%)	$I_{11}$ (%)	$I_{13}$ (%)	$I_{pickup}$ (A)
0.0	1.095	0.0	0.0	0.0	0.0	0.0	0.0	1.095
11.9	1.091	3.2	9.4	3.4	3.1	2.7	2.1	1.099
12.6	1.102	3.1	10.1	3.6	3.2	2.6	1.8	1.106
22.8	1.085	13.6	13.2	6.6	5.8	4.0	3.3	1.114
28.4	1.081	20.5	13.4	8.5	5.7	4.4	4.1	1.124
37.3	1.078	30.0	12.8	10.8	6.6	6.4	4.8	1.152
52.0	1.042	46.1	12.2	10.9	10.2	6.6	6.2	1.174
58.3	1.030	51.6	15.0	11.5	10.4	7.7	6.9	1.190
65.8	1.017	57.3	19.8	13.3	10.2	9.3	7.0	1.213
71.5	0.997	61.4	23.7	15.2	10.3	10.5	7.5	1.226
76.4	0.994	64.6	27.4	17.2	11.3	10.8	8.8	1.253
79.6	0.984	66.2	30.6	18.6	12.5	10.9	9.4	1.262
86.7	0.965	70.1	35.7	22.1	16.3	11.8	11.5	1.285
92.8	0.963	72.6	39.4	24.6	18.9	12.9	11.7	1.311
96.4	0.960	74.0	41.1	25.7	19.8	13.8	13.0	1.335
99.8	0.959	75.1	43.7	27.6	22.6	15.8	13.2	1.380

**Table 8.** Experimental results of EDTOCR [17]

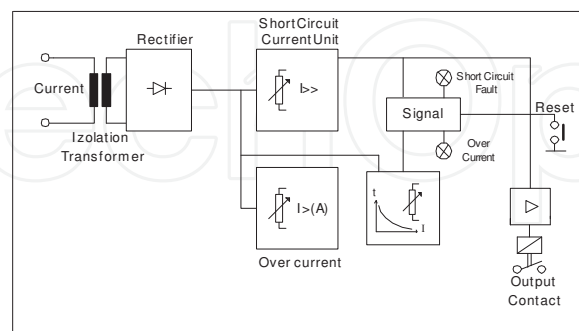
According to the experimental results, the variation of relay’s pickup current versus to  $THD_I$  is given in Figure 19. Pickup current value of the relay increases as long as  $THD_I$  values of relay current increases. Because of this problem, the relay is not suitable to protect the system and this circumstance causes damage or heating in power system elements.



**Figure 19.** The pickup current values of EDTOCR versus % THD<sub>I</sub> [17]

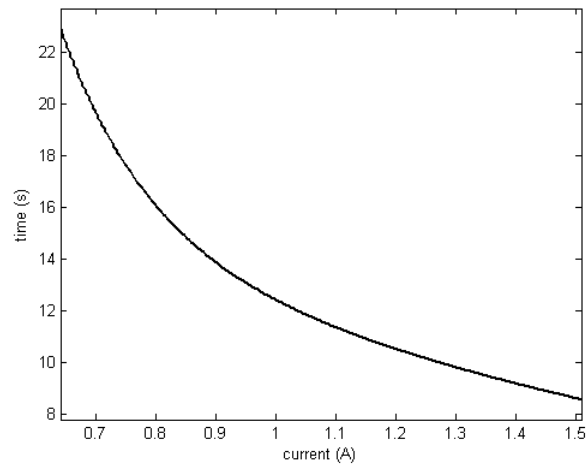
#### 4.3. Static Inverse Time Overcurrent Relay (SITOCR)

Time-current curves of static over current relays are similar to the electromechanical relay's curves, but the structures of them are quite different. Static relays consist of analogue electronic circuits elements. In Figure 20, the general block diagram of a static inverse time over current relay is given [14]. When a short circuit fault occurs in the power system, the current increases to a very high value and the short circuit unit ( $I >>$ ) of the relay operates instantly. In the event of a fault, if the current value is between nominal load current and short circuit current, the over current unit ( $I >$ ) of the relay operates with a time delay. This time delay is called as operating time of relay [14].



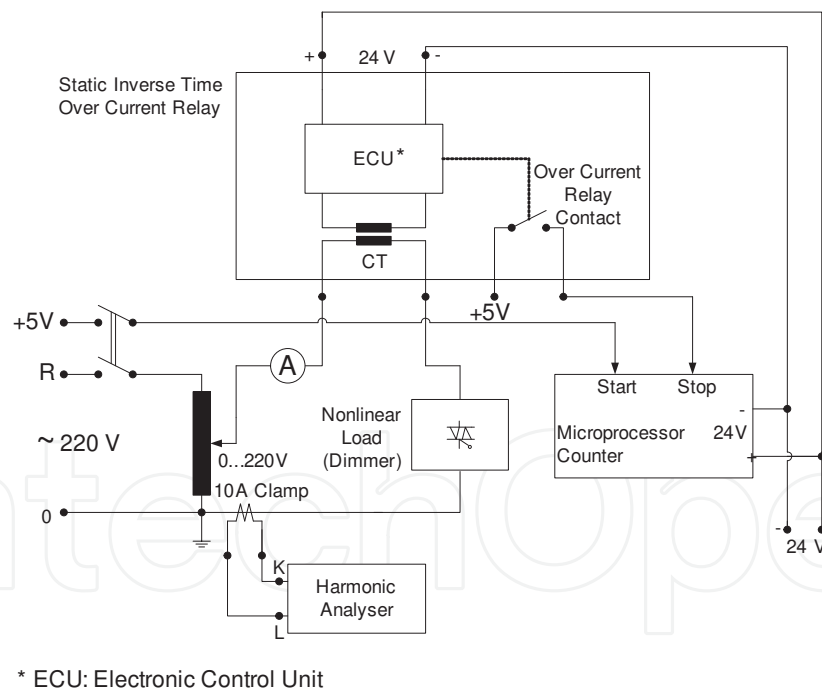
**Figure 20.** General block diagram of the SITOCR [14]

Time-current curve of a SITOCR is given in Figure 21. (pickup current of SITOCR is adjusted to 0.6 Amps). As shown in Figure 21, operating time of SITOCR is inversely proportional to the relay current.



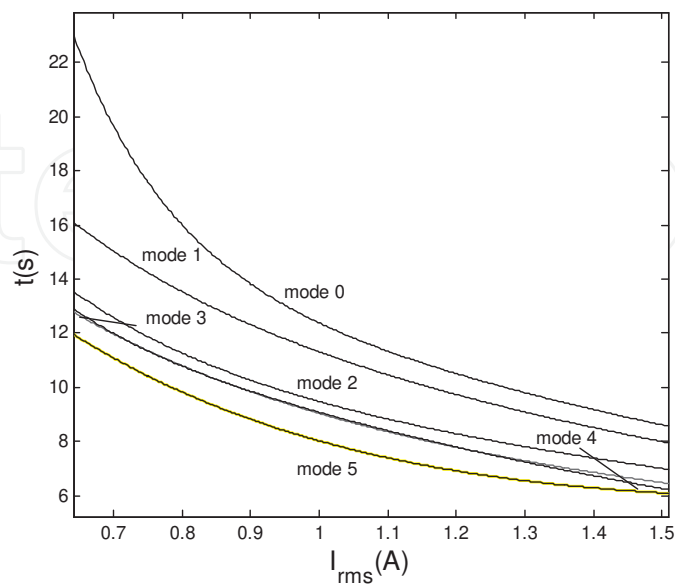
**Figure 21.** Current-time characteristic of the SITOCR

In order to investigate the effects of harmonics on SITOCR, an experiment circuit was implemented. The experiment circuit is shown in Figure 22.



**Figure 22.** Experiment circuit for SITOCR [14]

The rms value of current ( $I_{rms}$ ), total harmonic distortion of current ( $THD_I$ ), rms value of fundamental current ( $I_1$ ) and the relay's operating time ( $t$ ) are measured for six modes. For all measurement modes, the relay's pickup current is set to 0.6 Amps for sinusoidal current and this pickup current value of relay is not changed during the experiments.



**Figure 23.** Operating time curves of relay versus rms current [14]

The experimental results for all modes are given Figure 23. Generally, the overcurrent relay characteristic for pure sinusoidal current (mode-0 curve) is given by the manufacturer of the relay. The other curves of modes (mode 1-5) are obtained for nonsinusoidal currents in the study. The most distorted case for current is mode-5. Although the RMS value of current is constant for all modes, the operating times of the relay is not. Operating time of relay decreases, whereas THD value of current increases as shown in Table 9.

Mode	$I_{rms}(A)$	THD <sub>i</sub> (%)	t(s)
0	1,5	4,45	8,493
1	1,5	24,99	7,998
2	1,5	56,68	6,986
3	1,5	82,04	6,416
4	1,5	92,60	6,302
5	1,5	120,73	6,078

**Table 9.** Operating times of relay for all modes

As shown in Table 9 and Figure 23, while THD value of current increases, the operating time of relay decreases. Therefore, the selectivity cannot be provided in protection systems when harmonics exist in power systems.



## 5. Conclusion

Harmonic effects in power system are inspected in this study. This effect will further increase depending on the use of more devices which are produced by semiconductor technology. Furthermore, impact of iron-steel plants and large industrial areas on power quality disturbances cannot be ignored.

The representations of electrical quantities are modified due to harmonic components. These modified equations are given in subsection two. By using these equations, more realistic calculations could be realized. Especially when used in the systems with effective harmonic components, these equations lead to more reliable systems.

The distortion effects of distribution system loads and transmission system loads are given in subsection three. Influence of these loads can be easily seen from the given figures and tables. All of the office equipments and air conditioning units have significant harmonic distortion. In particular, this distortion effect increases in parallel to the size of the business center. In order to obtain a reliable and sustainable power system, these effects ought not be ignored. Furthermore, lighting devices, motor drives and household equipments are analyzed by using measurement results. As it can be easily seen from experimental results, all of them have harmful effects on distortion systems. According to the results of the studies, compact fluorescent lamps have more  $THD_1$  value when compared to fluorescent lamps. Use of a large number of these equipments could have an effective impact on the distortion of distribution systems. When focused on the motor drives, it can be said that frequency and voltage level variations have a considerable impact on the  $THD_1$  of these devices. By analyzing the measurement results, it has been seen that household equipments have harmful effects. Especially, the microwave oven, which has a greater power, has a remarkable  $THD_1$  value. As a result of analyses, it can be said that other household equipment have similar effects on power system. In this case, characteristics of system loads must be considered and appropriate precautions must be operated during planning of power system.

Furthermore, power quality disturbances on transmission lines are analyzed in this study. Turkey's power quality disturbance on transmission system is investigated by National Power Quality Project. According to the results of this project, it is seen that large industrial facilities and iron-steel plants have a disturbance effect on the network. Therefore, this impact has to be considered while planning and operating the power system. Electrical equipment as harmonic filter, STATCOM etc. should be used to eliminate the negative effects of nonlinear loads which have large application area on power systems. Thus, the quality of the power system would be at a better level.

In addition, influences of harmonics on power system equipment are very important. Results of an experimental study which performed on relays are given in subsection four in order to show these effects. According to the experimental results for over current protection relays, the operating time of static inverse time overcurrent relay decreases while  $THD$  value of current increases. Therefore, when harmonics exist in power systems, the selectivity cannot be achieved in protection systems. The operating time and pickup current of electro-

mechanical inverse time overcurrent relay increase, while THD value of current increases. Similarly, electromechanical definite time overcurrent relay's pickup current increases, as THD value of current increases. According to the results it is seen that these relays cannot perform a suitable protection function and cause damage or heating up depending on the rms value of current in power system components such as transmission lines, motors and transformers. Finally, according to results of this study, the effects of harmonics on overcurrent relays are not same for all relays. These effects change depending on the type and the structure of overcurrent relays.

As a result of experimental studies, we can say that harmonic effects of power system loads and influence of harmonic components on power system equipment may create serious problems on system. Therefore, it can be clearly seen that power quality studies have great importance on the establishment and operation of the system.

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## Author details

Celal Kocatepe, Recep Yumurtacı, Oktay Arıkan, Mustafa Baysal, Bedri Kekezoğlu, Altuğ Bozkurt and C. Fadıl Kumru

Yildiz Technical University, Department of Electrical Engineering, Istanbul, Turkey

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