Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2013) 21: 1880 – 1892

doi:10.3906/elk-1201-21

Survey of power quality in Turkish national transmission network

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Received: 10.01.2012 • **Accepted:** 30.05.2012 • **Published Online:** 24.10.2013 • **Printed:** 18.11.2013

Abstract: Harmonic distortion and flicker severity have become the main concerns in power transmission networks. Different types of harmonic and flicker sources exist in power systems, such as arc furnaces and cycloconverters. A power quality problem found in networks can cause additional temperature rise, losses, noise, and irritation in the lighting equipment. The aim of this study is to identify the level of harmonics and flicker in the 380-kV transmission network of Turkey. The measurement and analysis are performed using a specially developed power quality analyzer. The effects of harmonics and flicker on the network are discussed based on real measurement results. Moreover, the measurement results are compared to the current regulations in Turkey.

Key words: Transmission network, power quality, harmonic, flicker, power quality events

1. Introduction

In recent years, there has been a large growth in the use of nonlinear loads, which are the cause of power quality problems. The major power quality problems in power transmission lines are the voltage flicker and harmonics. The measurement of these disturbances is standardized by IEC 61000-4-30, which defines the methods for the measurement and interpretation of the results for power quality parameters in 50/60-Hz AC power systems [1,2].

Different types of harmonic and flicker sources exist in power systems, such as thyristor bridges, arc furnaces, and cycloconverters. High harmonic voltages and flicker severity can cause serious problems in various sensitive equipment, additional losses, temperature rise and disturbing torques in induction motors, and flicker in lighting equipment.

Several works have been realized for determining and solving power quality problems on power transmission lines [3–10]. Zhu et al. presented a new monitoring system for China's regional power quality terms [4]. Özdemirci et al. observed the power quality parameters of the Turkish Electricity Transmission System using real-time mobile measurement devices [5]. Gomes et al. explained the definition, index criteria, and monitoring of the power quality of Brazilian Transmission Systems [6]. Qader et al. proposed 2 different methods for predicting voltage sags on the 97-bus model of the 400-kV National Grid of England and Wales [7]. Thiyagarajan and Palanivel developed a microcontroller-based monitoring system for measuring the voltage, current, and temperature values of a distribution transformer [8]. Apostolov detailed the different protection, control, and monitoring system components for small distribution substations that provide a modular, inexpensive, and very

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effective solution for distribution substations [9]. Nath et al. characterized power quality disturbances from recorded voltage waveforms using wavelet transform [10].

This paper presents the detailed results of a survey of the harmonics and flicker conducted in the Turkish power system network. The survey is conducted in 380-kV networks feeding power to various categories of customers. Measurements were performed for 1 week on 18 different plants with different output power levels. The measurement results that are presented in this study were performed within the scope of the Turkish National Power Quality Project.

The mobile measurement results, which were taken from the national power system and the introduction of the mobile measurement system, were given in previous publications by the project [5]. Additionally, the "National Monitoring Center for PQ", which was established for continuous monitoring of the power system, was presented by Demirci et al. [11]. The effects of iron-steel plants on the national power system, which are measured in the scope of the project, were given in another paper [12]. Moreover, detailed investigations of an iron-steel plant for different scenarios were presented by Salor et al. [13]. Furthermore, the active power filter and static synchronous compensator (STATCOM), which are produced by a group of project teams, were presented in the past papers of this project [14,15].

In addition to these studies, the aim of this work is to identify the level of harmonics and flicker in the high voltage side of the network. The measurement and analysis is performed using a specially developed power quality analyzer. In light of the results, the effects of the harmonics, flicker, and events on the network and solutions are discussed and are compared to the current regulations in Turkey.

2. Power quality measurement hardware implementation and data acquisition

In this study, measurements on 380-kV power transmission lines in Turkey were continuously carried out according to IEC 61000-4-30 for 1 week in selected locations [16]. The general schematic diagram of the implemented power quality measurement system on the transmission line is given in Figure 1 [5].

The measurement arrangement consists of the following items: a National Instruments DAQ Card 6036E, National Instruments SC-2040 S/H Card, 3 current probes (1 mV/10 mA), voltage divider cabling (100/3.8 V), a laptop computer, LabVIEW software, MATLAB software, uninterruptible power supply for current probes, and isolation transformers, as shown in Figure 1. A detailed block diagram regarding the power quality measurement system is given in Figure 2 [17].

The measurements performed within the scope of this study were carried out by taking the current and voltage signals. The voltage is measured using a voltage transformer. Moreover, the current values are taken from a current transformer. The measurements are completed at transformer substations to reduce the measurement errors.

The measurement system has been installed in 18 substations rated at 380 kV, shown in the map in Figure 3. The measurement results are evaluated in accordance with the current regulations in Turkey [16,18].

As defined by the IEC 61000-4-30 standard, the voltage harmonics are measured as 3-s average values, the short-term flicker is measured as a 10-min average, and the long-term flicker is measured as a 2-h average. In the case of a power quality disturbance such as a sag, swell, or unbalance during the measurements, the system recorded all of the power quality data starting at 0.5 s before the event and lasting for 2.5 s after the event (total of 3 s) [11].

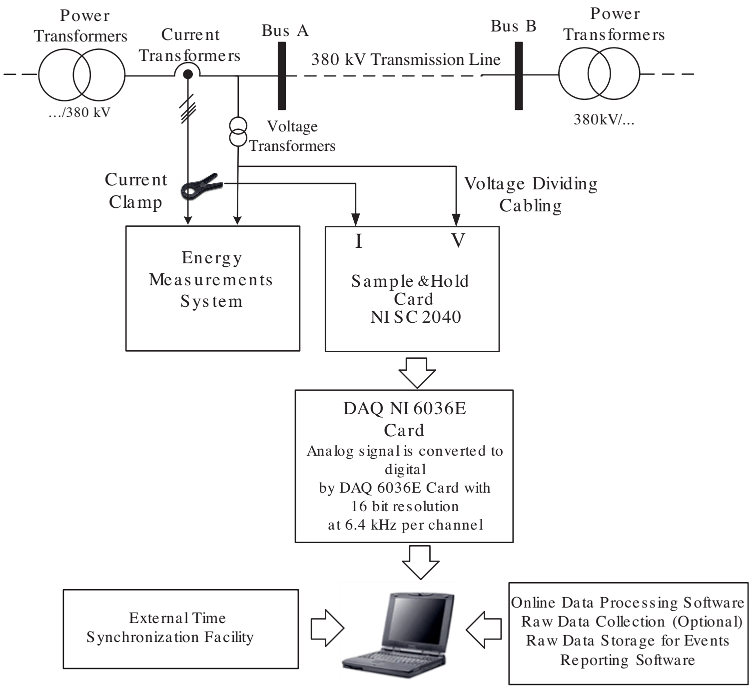

Figure 1. Schematic diagram of the power quality measurement system.

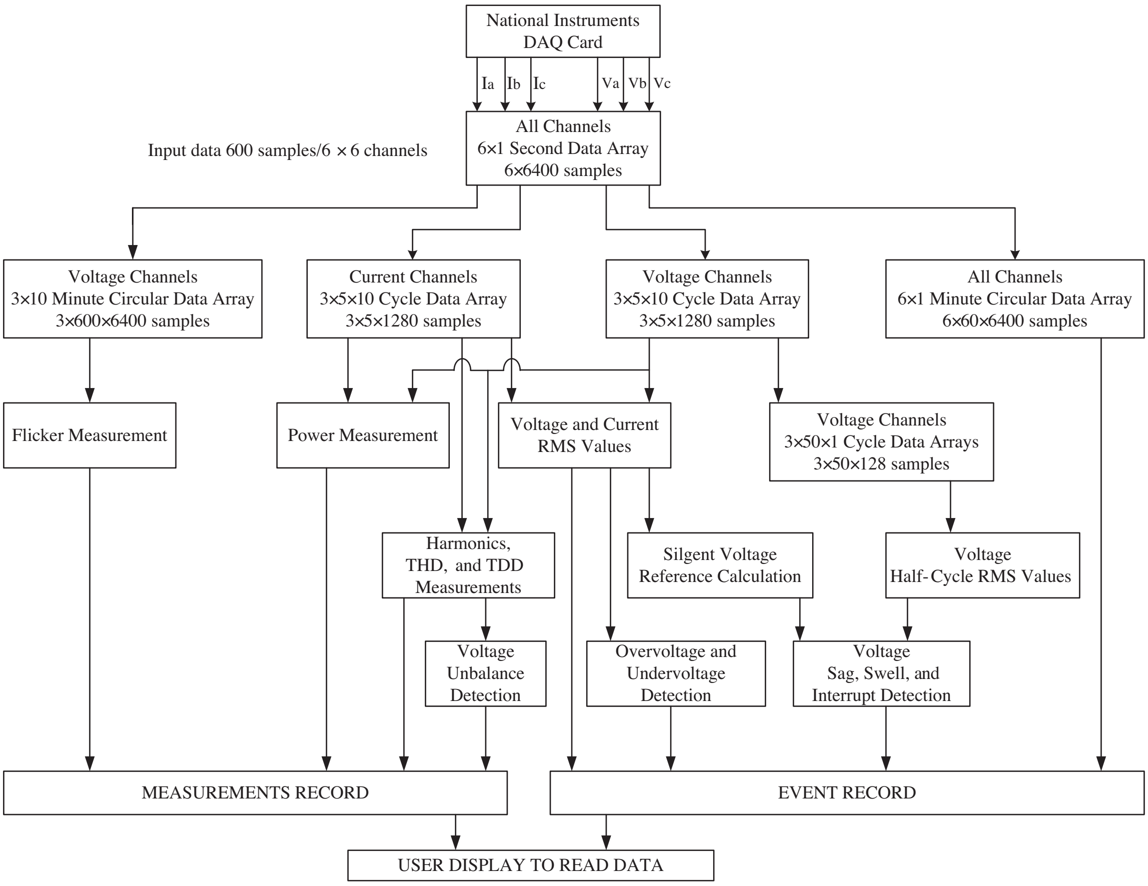

Figure 2. Block diagram for analyzing the power quality measurements.

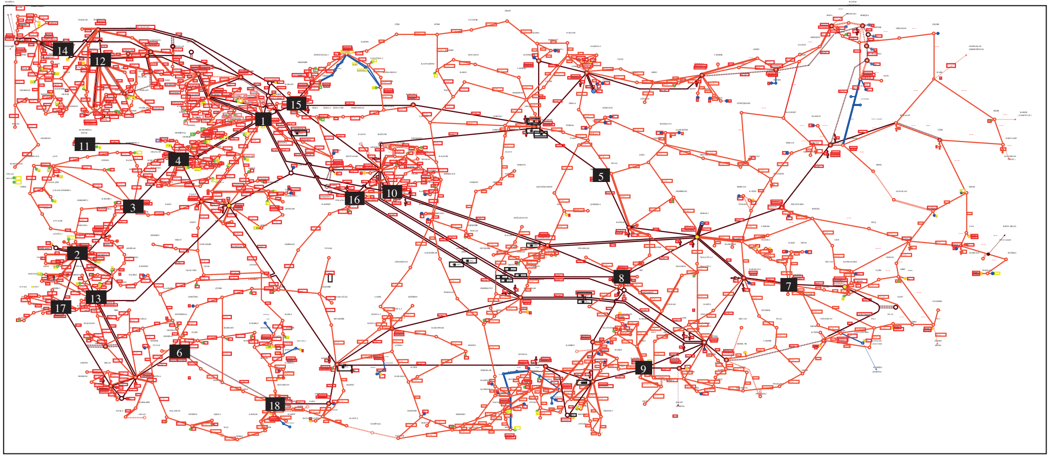

Figure 3. Measurement points on the map of Turkey's transmission grid.

3. Turkish transmission network and measurement points

The Turkish National Transmission System, which transfers the produced electrical energy to consumer centers, consisted of a 47,000-km-long transmission line and had an 82,000-MVA transformer capacity by the end of 2008. The rated voltage levels in the Turkish transmission network are 380 kV, 154 kV, and 66 kV. Under normal operating conditions, a 380-kV system is operated at between 340 kV and 420 kV. The Turkish transmission system is operated by the National Control Center and 9 Regional Control Centers [19].

The National Power Quality Project was launched in cooperation with 4 public universities, the Scientific and Technological Research Council of Turkey, and the Turkish Electricity Transmission Company to monitor the power quality parameters in the Turkish transmission network. Figure 3 shows the map of Turkey's transmission grid and where the measurement points are located.

The technical specifications and load types for the considered measurement points are given in Table 1.

4. Measurement results and discussion

The power quality raw data that are obtained from the measurements are processed in accordance with IEC and IEEE standards (IEC 61000-4-30/Class B, IEC 61000-4-7/Class B, IEC 61000-4-15/Class B, and IEEE 519-1992). This processing involves the computation of the power quality parameters of voltage harmonics, voltage flicker, and events in the voltage such as sag, swell, and unbalance. The recorded parameters are the root mean square values of the 3-phase voltage and current for every 10 power frequency durations; average values of the current and voltage harmonics (up to the 40th harmonic) every 3 s; active, reactive, and apparent power values; and 10-min short-term (P_{st}) and 2-h long-term (P_{lt}) flicker values. If there is no event during the measurement period, the power quality parameters are processed as their average values. Once an event occurs, the data are recorded continuously starting at 1 s before the event and lasting for 1 s after the event.

4.1. Measurement of flicker

The most important problem in the power network is the flicker. A flicker is defined as a periodic voltage drop or rise along 6–7 complete cycles. The flicker problem may occur due to the large loads and nonconstant output power in transmission networks [20].

The P_{st} and P_{lt} values frequently exceed the limits defined in the Electricity Market Grid Regulation given in Table 2 for the measurement period on the 380-kV side.

Table 1. Technical specifications and load types of the considered points.

Transformer substation	Transformer rated power (MVA)	Short-circuit power (MVA)	Load type
Substation 1	600	19,877.00	Industrial and residential
Substation 2	800	11,537.88	Industrial and residential
Substation 3	550	6654.19	Industrial and residential
Substation 4	900	11,649.77	Industrial
Substation 5	200	5199.62	Iron-steel plant
Substation 6	750	4607.25	Industrial and residential
Substation 7	600	5462.88	Industrial and residential
Substation 8	300	12,373.77	Industrial and residential
Substation 9	350	9912.18	Industrial and residential
Substation 10	336	11,649.77	Industrial and residential
Substation 11	500	2501.08	Iron-steel plant
Substation 12	1250	14,940.67	Industrial and residential
Substation 13	800	9300.07	Industrial and residential
Substation 14	310	10,122.79	Iron-steel plant
Substation 15	600	12,373.77	Industrial and residential
Substation 16	1000	16,125.39	Industrial and residential
Substation 17	600	7101.75	Industrial and residential
Substation 18	775	4554.60	Industrial and residential

Table 2. maximum flicker severity limits for the power transmission systems in compliance with the electricity transmission system supply reliability and quality regulation in Turkey.

Voltage level at PCC	Flicker severity			
154 kV and above	0.61	0.85	0.25	0.63
34.5 kV to 154 kV	0.91	0.97	0.37	0.72
1 kV to 34.5 kV	1.52	1.15	0.61	0.85
1 kV and below	1.52	1.15	0.61	0.85

Flicker values (short- and long-term) for the 3 phases based on the measurements performed on the 380-kV lines are given in Table 3. These values are compared to the limits in standard IEC 61000-4-30. This standard says that the number, or percent, of the values during the measurement interval that exceed the contractual values should be in the range of 1% and 5% for P_{st} and P_{lt}, respectively.

As can be easily seen from Table 3, the short-term flicker measurements of Substations 5, 7, 11, and 13 and the long-term flicker measurements of Substations 2, 5, 7, 11, and 13 exceed the standard values. The long-term flicker severity at Substation 12 remained below the standard value during the measurement duration.

Different iron-steel plants are connected to Substations 5, 11, and 14. In the flicker measurements of Substations 5 and 11, the highest flicker severities are observed. The results show that the highest flicker severity is measured at Substation 11, which has the lowest short-circuit power. On the other hand, the flicker severity remained below the standard limit at Substation 14, because of the higher short-circuit power at Substation 14 compared to Substation 11.

The investigation of both the short- and long-term flicker measurement shows that the flicker problem occurred on some phases of Substations 2, 4, 9, and 17. All of these measurement points feed industrial loads. Moreover, the characteristics of the loads with the connected different phases cause an unbalance on the flicker severity.

Table 3. The percentages of the P_{st} and P_{lt} values that exceed the standard value through the measurement period.

Transformer substation	Percentage value of the 10-min averages (P_{st}) that exceed the limits			Percentage value of the 2-h averages (P_{lt}) that exceed the limits		
	Phase a	Phase b	Phase c	Phase a	Phase b	Phase c
Substation 1	0.2070	0.2076	0	1.1905	3.5714	0
Substation 2	0	0.0916	3.7546	13.2530	13.2530	93.7590
Substation 3	0.1640	0.3281	0.2461	3.3214	3.3333	3.2132
Substation 4	0.5950	1.3889	0.5952	3.5714	5.9524	2.3810
Substation 5	29.8600	28.9683	29.8611	70.2310	69.0476	71.4286
Substation 6	0.6940	0.4960	0.3968	3.5714	2.3809	2.3809
Substation 7	1.6000	1.9000	2.2000	9.5000	8.3000	9.5000
Substation 8	0.3000	0.6000	0.5000	1.2000	4.8000	3.6000
Substation 9	0.8250	0.6601	0.9901	5.8252	3.8835	4.8544
Substation 10	0.7000	0.4000	0.2000	2.4000	3.6000	2.4000
Substation 11	64.7560	69.9653	65.2778	85.4167	91.6667	87.5000
Substation 12	0	0	0	0	0	0
Substation 13	1.3100	1.8800	1.7800	7.6900	12.0900	12.0900
Substation 14	0.1980	0.0992	0.1984	0	0	0
Substation 15	0.1980	0.6944	0.1984	1.1905	3.5714	1.1905
Substation 16	0.3000	0.4000	0	1.3000	2.5000	0
Substation 17	0.1850	0.4646	0.7434	1.0869	6.5217	6.5217
Substation 18	0.7920	0.6930	0.9900	3.6100	4.8200	4.8200

Figures 4a–4j show the variations of the flicker measurement values (P_{lt} and P_{st}) at 5 different substations, where the thick line represents the level of flicker severity for 154 kV or above, as given in Table 2.

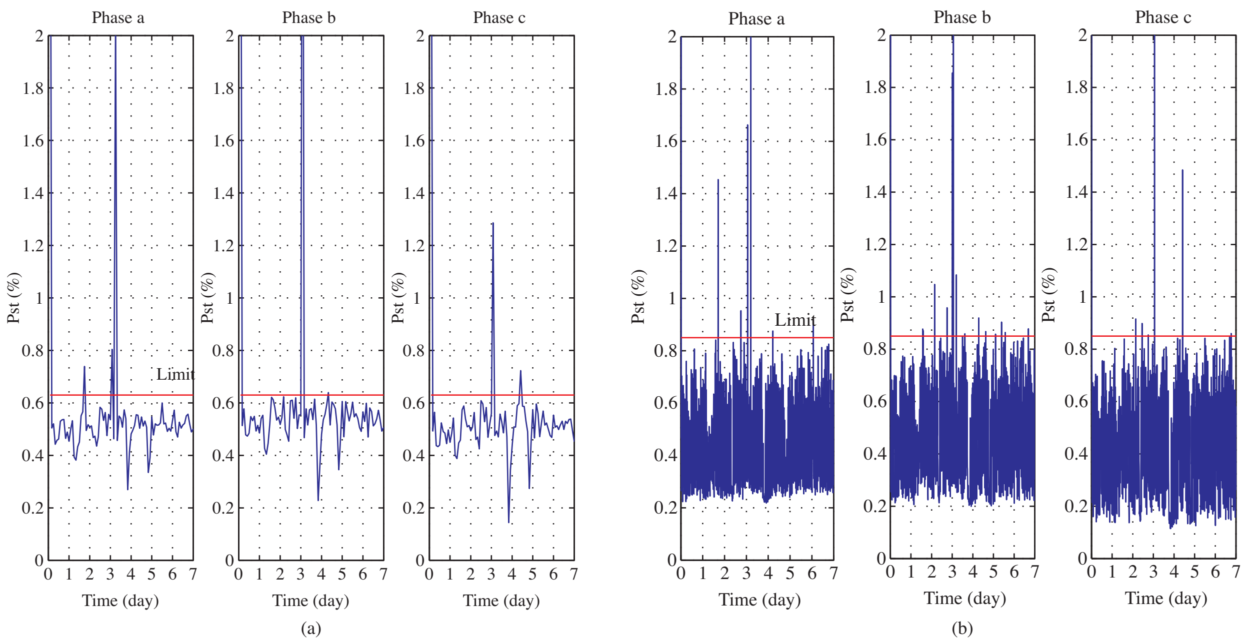

Figure 4. Long- and short-term flicker variation in phases a, b, and c for 5 substations: a) P_{lt} variation of Substation 4, b) P_{st} variation of Substation 4.

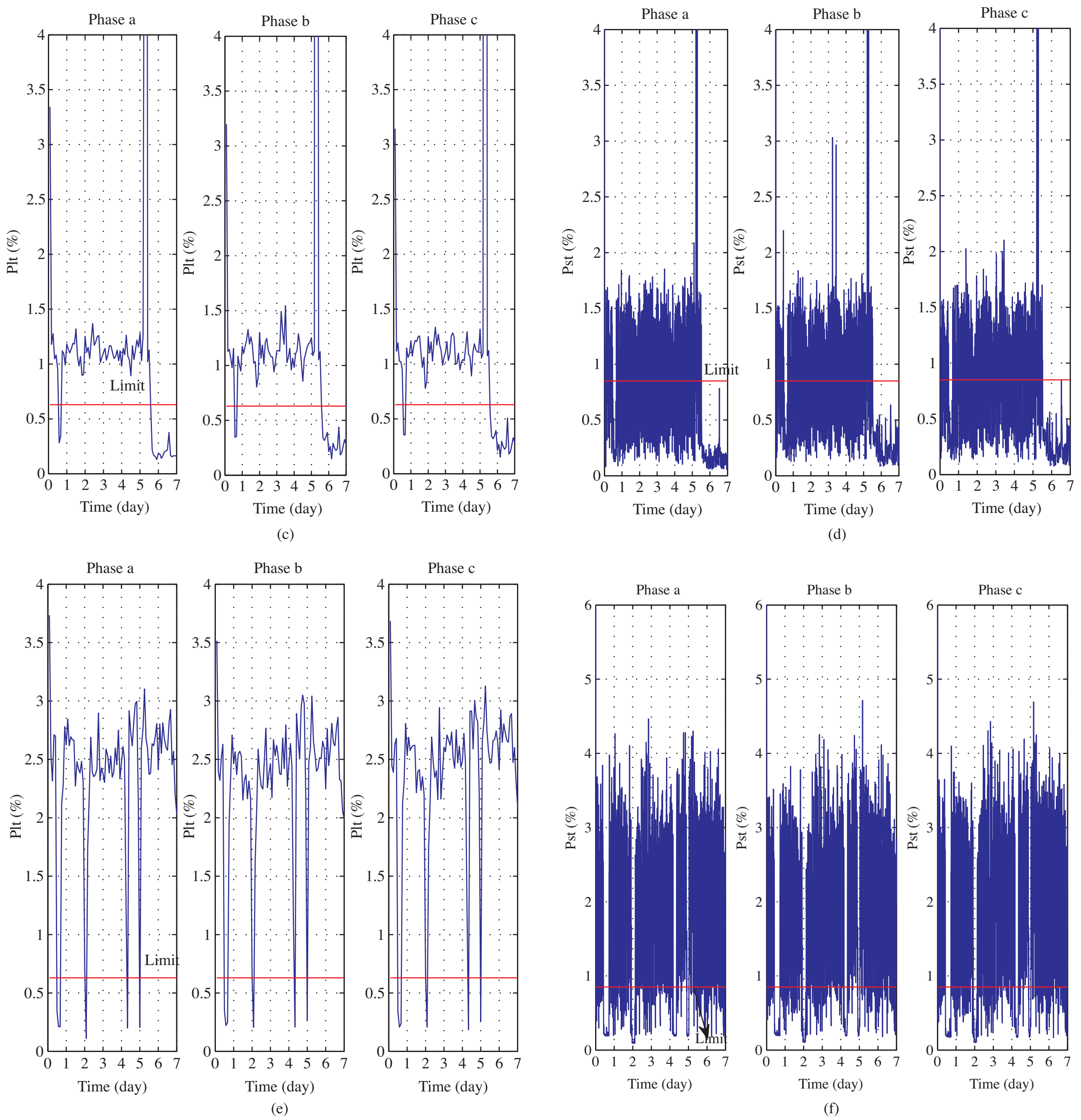

Figure 4. c) P_{lt} variation of Substation 5, d) P_{st} variation of Substation 5, e) P_{lt} variation of Substation 11, f) P_{st} variation of Substation 11.

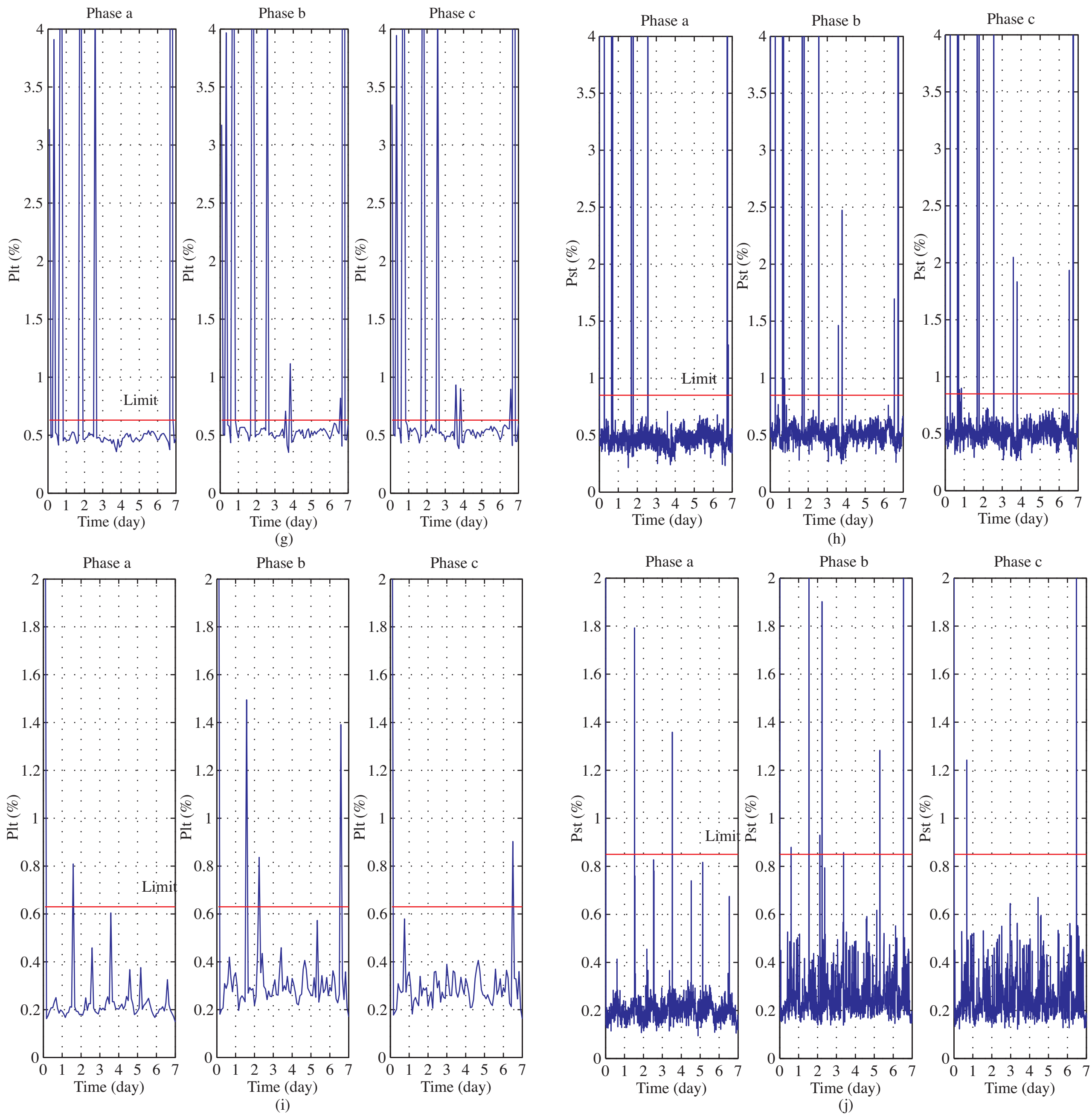

Figure 4. g) P_{lt} variation of Substation 13, h) P_{st} variation of Substation 13, i) P_{lt} variation of Substation 15, j) P_{st} variation of Substation 15.

As shown in Table 3, when the PCC points are analyzed, it is easily seen that the flicker values decrease on the measurement points with high short-circuit power. The higher flicker severity has specifically occurred on buses where the iron-steel plants are connected. As an example, an iron-steel plant has been feeding on Substation 11, causing both characteristics of the connected iron-steel plant and low short-circuit power on the PCC, and the flicker measurements exceed the standard limit. The P_{lt} and P_{st} variations of Substation 11 are shown in Figures 4e and 4f, respectively. Contrary to Substation 11, no flicker problem has been observed throughout the measurement period on Substation 12 with high short-circuit power.

As a result, the flicker problems (P_{lt} and P_{st}) occur at 17 measurement points.

4.2. Measurement of the harmonics

The voltage and current harmonics are evaluated as 1-s averages. The acceptable voltage harmonic limits in the Electricity Market Grid Regulation are given in Table 4 [13]. The evaluation of the voltage harmonics for the measurement points are given in Table 5.

Table 4. Acceptable harmonic voltage limits for the 380-kV power transmission systems in compliance with electricity market grid regulation in Turkey.

Odd harmonics (nontriplen)		Odd harmonics (triplen)		Even harmonics	
Harm. order	Harm. voltage (%)	Harm. order	Harm. voltage (%)	Harm. order	Harm. voltage (%)
5	Oca.25	3	1	2	0.75
7	1	9	0.4	4	0.6
11	0.7	15	0.2	6	0.4
13	0.7	21	0.2	8	0.4
17	0.4	> 21	0.2	10	0.4
19	0.4			12	0.2
23	0.4			> 12	0.2
25	0.4				
> 25	0.2 + 0.2 (25/h)				
Total harmonic distortion limit: 2%					

Table 5. Percentage value of the THD_v that exceed the limits and mean value of THD_v along the measurement period.

Transformer substation	T_{THD}	$Mean_{THD}$
Substation 1	0	0.7696
Substation 2	0	0.7743
Substation 3	39.5172	1.8840
Substation 4	18.7141	1.7047
Substation 5	52.0567	2.0491
Substation 6	0	0.8626
Substation 7	0.0074	0.7265
Substation 8	0	0.6267
Substation 9	0.0012	0.6900
Substation 10	0	0.5590
Substation 11	0.0001	1.0072
Substation 12	0	0.6819
Substation 13	0.2022	0.5195
Substation 14	0	0.7875
Substation 15	1.7009	0.9962
Substation 16	99.5913	2.7457
Substation 17	0	0.7081
Substation 18	0.0006	0.8564

Measurements are carried out and it is seen that the THD_v value of Substation 16 exceeds the standard value for almost all of the measurement duration. Moreover, the THD_v value exceeds the standard value for a large part of the measurement period for Substations 3, 4, 5, and 16. During the measurement period, 8 of the measurement points have THD_v values below the standard THD_v value.

The THD is the percentage value of the total time period for which the THD_v exceeds the limit for the duration of the measurement and the $Mean_{THD}$ is the mean value of the THD_v for the duration of the measurement. Formulation of the $Mean_{THD}$ is given below:

$$Mean_{THD} = \frac{t_{\lim it}}{t_{total}} \times 100, \tag{1}$$

where t_{limit} is the time exceeding limit THD_v along the measurement period and t_{total} is the total measurement period.

The most remarkable result of the harmonic measurements occurs at Substation 11, where an iron-steel plant with low short-circuit power is connected. Despite the higher flicker severity and power quality event rate of Substation 11, the harmonic measurements are within the standards for the harmonic distortion. The effective harmonic filter system of the iron-steel plant that is feeding from Substation 11 is the reason for the low harmonic distortion. Similarly, it is observed that the total harmonic distortion values are within the boundaries of the standard limit where power quality correctors such as harmonic filters, static VAR compensator (SVC), and the STATCOM are effectively used.

Figures 5a–5e show the variations of the total harmonic distortion at the 5 substations, where the thick line represents the limit of the total harmonic distortion stated in Table 4.

Substation 3 consists of industrial and residential loads. Due to the low short-circuit power, the THD value exceeds the limit value at Substation 3. At Substation 4, the harmonic values are high because of the large industrial plants. The effects of the iron-steel plant with lower short-circuit power cause high THD values at Substation 5. Contrary to Substation 5, no harmonic problem has been observed throughout the measurement period at Substation 14 with high short-circuit power. Since a thermal power plant is connected on the same bus as the iron-steel plant, and the harmonic filters are used effectively at Substation 11, the harmonic effects are under the limit values, despite the low short-circuit power. At Substation 16, the industrial and residential loads are supplied. Nevertheless, the THD value is high because of the series compensation feeder.

5. Measurements of power quality events

Power quality events that have occurred during the measurement period for all of the measurement points are listed in Table 6. Substation 11 has been identified as the point at which the most events have occurred. Moreover, there are no events at 2 measurement points during the measurement duration.

The measurements show that the power quality events are associated with the short-circuit power of the common coupling point. The effects of the short-circuit power on the power quality events are clearly seen with the investigation of the iron-steel plant measurements. A total of 428 power quality events are recorded at Substation 11, which has the lowest short-circuit power of the 3 measured iron-steel plants. However, there is no recorded power quality event throughout the measurement period at Substation 14 with high short-circuit power.

Substation 11, which feeds an iron-steel plant, is connected to the power system via a very long radial transmission line, which causes the short-circuit power of the PCC to decrease and the effects of the power quality problems to increase. It is noteworthy that the number of events that occurred at the measured substations with high short-circuit power is lower than at the other substations.

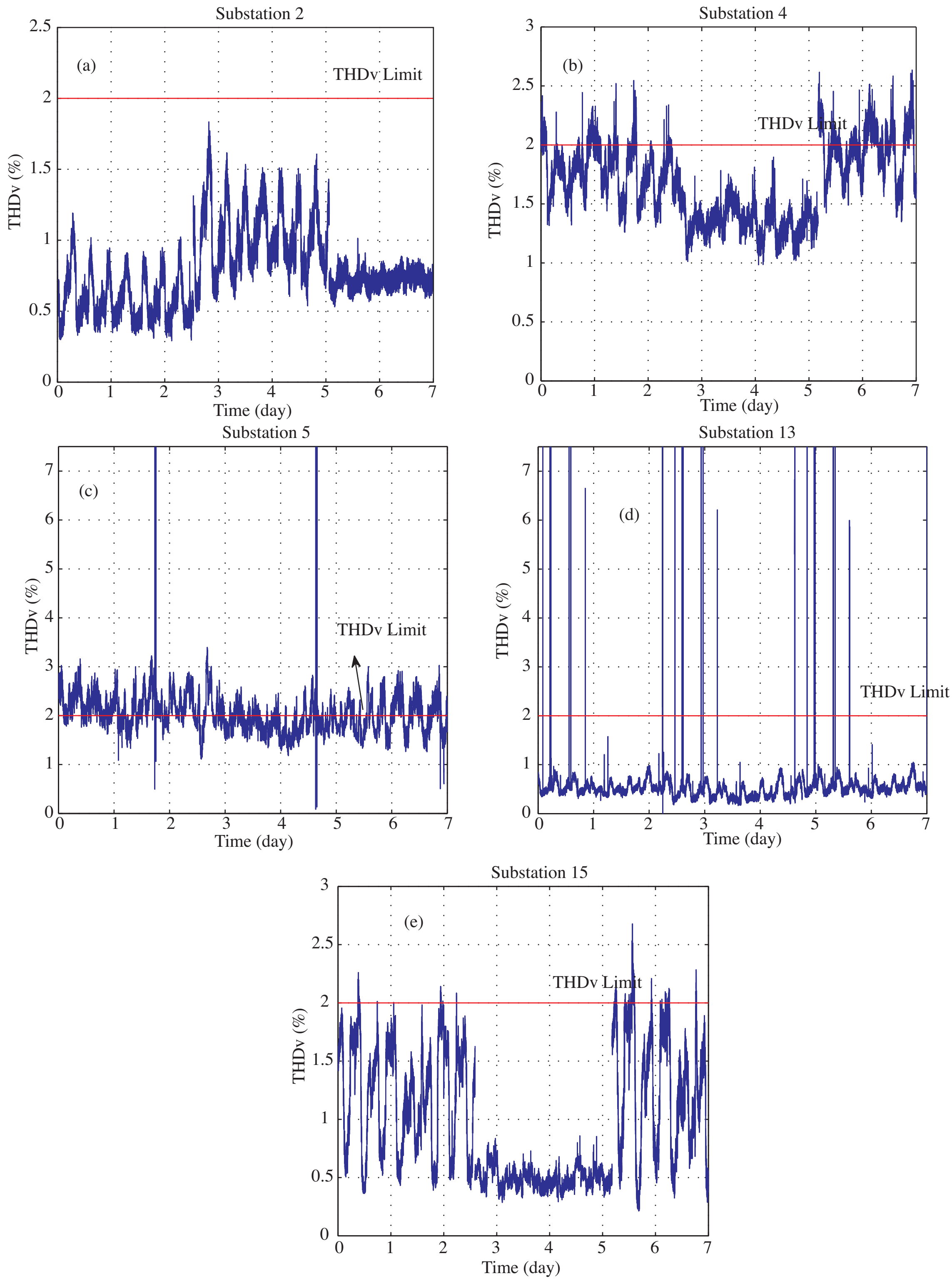

Figure 5. Total harmonic distortion for 5 substations: a) total harmonic distortion for Substation 2, b) total harmonic distortion for Substation 4, c) total harmonic distortion for Substation 5, d) total harmonic distortion for Substation 13, e) total harmonic distortion for Substation 15.

Table 6. The list of power quality events in the voltage.

Transformer substation	Number of events	Number of voltage sags	Number of voltage swells	Number of voltage unbalances
Substation 1	10	5	0	5
Substation 2	0	0	0	0
Substation 3	8	5	2	1
Substation 4	6	2	1	3
Substation 5	32	22	4	6
Substation 6	4	0	3	1
Substation 7	21	10	0	11
Substation 8	8	4	0	4
Substation 9	19	6	1	12
Substation 10	9	4	1	4
Substation 11	428	0	0	428
Substation 12	2	1	0	1
Substation 13	25	13	7	5
Substation 14	0	0	0	0
Substation 15	9	6	0	3
Substation 16	7	4	0	3
Substation 17	5	1	3	1
Substation 18	12	3	6	3

6. Conclusions

In this study, the evaluation of the voltage flicker, harmonic distortion, and power quality events were completed through 18 measurement points in the 380-kV Turkish transmission system. The analysis of the measurement results demonstrates the overall power quality performance of the transmission network.

According to Tables 3 and 5, most of harmonics and flicker parameter values are not in accordance with the standards established in Turkey. The most commonly observed type of event is unbalanced parameters.

Measurement results show that low harmonic level and flicker severity are observed at measurement points with high short-circuit power. The type of load has direct effect on harmonic and flicker values. In light of this situation, it is recommended that the load type of the measurement points must be considered for similar studies. The largest values of the power quality indices are observed in the nodes closest to the iron-steel industry. However, it is seen that the power quality problems are reduced using convenient harmonic filter and compensation systems.

Regarding the solution consideration, it is proposed that the short-circuit power of the system and the generating units should be increased. Moreover, it can be suggested that efficient technical equipment, such as the SVC or STATCOM, should be used on buses with high-power quality problems.

Acknowledgments

The authors would like to thank the Public Research Support Group (KAMAG) of the Scientific and Technological Research Council of Turkey (TÜBİTAK) for full financial support of the project, namely the National Power Quality Project of Turkey, Project No: 105G129.

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