Turkish Journal of Electrical Engineering & Computer Sciences
http://journals.tubitak.gov.tr/elektrik/
Research Article

Turk J Elec Eng & Comp Sci
(2013) 21: 934 – 944

doi:10.3906/elk-1201-55

Simulation of a large electric distribution system having intensive harmonics in the industrial zone of Konya

Hasan EROĞLU,[1,*] Musa AYDIN[2]
[1]Department of Electrical & Electronics Engineering, Faculty of Engineering, Gümüşhane University, Gümüşhane, Turkey
[2]Department of Electrical & Electronics Engineering, Faculty of Engineering, Selçuk University, Konya, Turkey

Received: 18.01.2012 • **Accepted:** 20.03.2012 • **Published Online:** 03.06.2013 • **Printed:** 24.06.2013

Abstract: In this study, measurements were taken at different points of a sample distribution system in order to analyze the levels of harmonics that appear as a day-to-day increasing problem in electrical distribution systems. According to the measurement values, the dominant harmonics have been determined and an electrical model of the system has been prepared using the SimPowerSystems toolbox from MATLAB and Simulink. The accuracy of the electrical model has been verified by the measurement and simulation values. In addition, the transformer connection types' and impedances' simulations have been presented to understand and solve the harmonic problems in electrical distribution systems. With the help of this study, advanced analysis can be performed in the electrical distribution system for power quality analyses and this study can be a background for similar kinds of simulation studies.

Key words: Harmonics, modeling, simulation, MATLAB

1. Introduction

Nowadays, the stability of electrical energy has come into question due to the increasing number of the nonlinear loads in distribution systems. Harmonic currents and voltages occur as a result of the loads that have nonlinear characteristics. In electrical systems, harmonics can considerably affect the electrical system quality.

Electronic devices work by switching accounts for the current waveforms of electronic systems to have nonlinear characteristics. A nonlinear device is one in which the current is not proportional to the applied voltage. While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a small percentage may cause the current to double and take on a different wave shape. This is the source of most harmonic distortions in a power system [1].

AC power systems have a substantial number of large harmonic generating devices, e.g., adjustable speed drives for motor control and switch-mode power supplies used in a variety of electronic devices such as computers, copiers, and fax machines [2]. The major sources of power system harmonics include switching operations, power electronic devices, and other nonlinear loads. Electronic devices are usually nonlinear, and thus they yield distorted currents even when supplied with a purely sinusoidal voltage. These distorted currents can cause voltage and current distortion throughout the system [3].

The major effects of harmonics on electrical power systems can be summarized as additional losses,

*Correspondence: hasan.eroglu@gumushane.edu.tr

overheating, voltage drops, resonance problems, dielectric strain, and working with errors of measurement, protecting, and control systems.

Increasing the number of power electronic devices used in generation, distribution, and transmission has increased the harmonic problems in power systems. Hence, the importance of studies about decreasing the harms of harmonics in electrical power systems has come into prominence and the analysis of harmonics has become an inevitable part of the systems' design and planning [4].

There are 2 main definitions of the measurement of the harmonic contents in electrical systems. These are total harmonic distortion (THD) and total demand distortion. The THD is a measure of the effective value of the harmonic components of a distorted waveform. That is, it is the potential heating value of the harmonics relative to the fundamental component. The voltage and current distortion can be summarized as shown below.

$$THD_U = \frac{1}{U_1}\left(\sum_{n=2}^{\infty} U_n^2\right)^{\frac{1}{2}} \tag{1}$$

$$THD_I = \frac{1}{I_1}\left(\sum_{n=2}^{\infty} I_n^2\right)^{\frac{1}{2}} \tag{2}$$

Current distortion levels can be characterized by a THD value, as has been described, but this can often be misleading. A small current may have a high THD but might not be a significant threat to the system. For example, many adjustable-speed drives will exhibit high THD values for the input current when they are operating at very light loads. This is not necessarily a significant concern because the magnitude of the harmonic current is low, even though its relative current distortion is high. Some analysts have attempted to avoid this difficulty by referring the THD to the fundamental component of the peak demand load current rather than the fundamental of the present sample. This is called the total demand distortion (TTD) and it serves as the basis for the guidelines in IEEE Standard 519-1992, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems. It is defined as shown below.

$$TTD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \tag{3}$$

I_L is the peak, or maximum, demand load current at the fundamental frequency component, measured at the point of common coupling (PCC). There are 2 ways to measure I_L. With a load already in the system, it can be calculated as the average of the maximum demand current for the preceding 12 months. The calculation can simply be done by averaging the 12-month peak demand readings. For a new facility, I_L has to be estimated based on the predicted load profiles.

The harmonics generated by any harmonic source can be very harmful to other electric energy users that are fed by the same energy distribution system. Due to reasons like this, it is very important to prevent the formation of harmonics in electric systems or to eliminate them after their formation. Nowadays, there are many applications for the elimination of harmonics. However, the most significant factor in eliminating harmonics is to make the electricity users conscious of the harmonics' losses in electric power systems and the spreading applications of harmonic filters.

Many studies on measurements and effects of harmonics have been done in the past and in recent years [5–17]. However, there are not enough studies that model a large distribution system via harmonics or other power quality problems. The simulation of distribution systems is very important to estimate the behavior of harmonics or other power quality events.

In this paper, harmonic measurements were taken both from the 0.4 kV and 31.5 kV sides of the electrical distribution system at the 2nd and 3rd Konya Organized Industrial Area (KOIA). The characteristic values of the distribution system and the factories were taken from the KOIA office. The measurements were taken using the ANALYST 2060 single-phase energy quality analyzer at the 0.4 kV side and the RUDOLF PAK 5 three-phase energy quality analyzer at the 31.5 kV side. The electrical model of the system was prepared with the help of the SimPowerSystems toolbox from MATLAB and Simulink based on the measurements taken. The measurement values and simulation values were compared to confirm the accuracy of the simulation. With the help of the simulation, further analyses can be made to comprehend the behaviors of the power quality events.

2. Measurements

There are 8 shunting stations fed from the "Konya 3 TM" (transformer stations) at KOIA. The apparent power at each shunting station is shown in Figure 1.

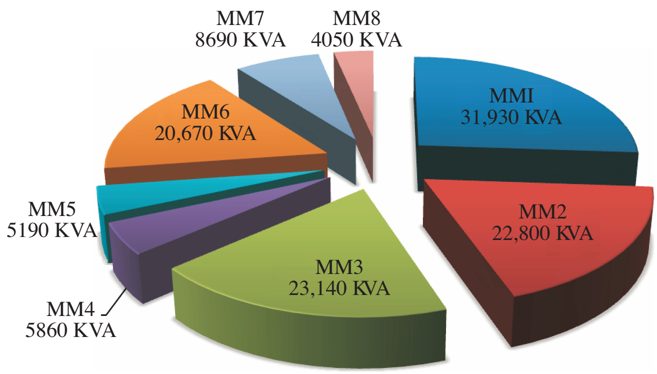

Figure 1. Apparent powers of each shunting station.

The factories and the maximum apparent powers that are measured during the measurements are shown in Table 1.

In order to make true measurements, power readings are taken during the working hours at each factory where one or more working factories are fed from the same feeder. For the 31.5 kV measurements, shunting stations with higher apparent power are preferred. These shunting stations are MM1, MM2, MM3, and MM6. For the 0.4 kV measurements, different types of factories are preferred, as shown in Table 1. The measurement results are shown in Tables 2 and 3.

According to Table 2, the voltage distortions are appropriate to the IEEE 512 Standards, as are the current distortions, except for that of MM6. Sometimes the current distortion of MM6 exceeds the limits. The dominant harmonics are generally the 5th, 7th, and 11th harmonics. Sometimes harmonics that have higher frequency components appear, but they are not continuous.

As shown in Table 3, voltage distortions are appropriate when compared to the IEEE 512 Standards, except in casting factory 4. The electric current drawn by this factory reaches 775 A, with a voltage distortion of 5.6%. This makes the current distortion of casting factory 4 reach 26%. Although the factory measurements are taken at different times where the factories are fed from the same feeder, the voltage distortions are at high values. If all of the factories were working when the measurements were taken, the distortions would be at higher values than the present ones. This condition will be carried out in the simulation studies.

Table 1. The factories and their values.

	Common information	Max. apparent power during measurement
Plastic factory 1	Garden watering systems	195 kVA
Plastic factory 2	Water pipes and machines for producing these pipes	120 kVA
Casting factory 1	Manholes, sewer system lids, garden and park products	780 kVA
Casting factory 2	Cast iron	430 kVA
Casting factory 3	Bronze, chrome-nickel casting, aluminum injection	212 kVA
Casting factory 4	Cast iron, steel casting	520 kVA
Casting factory 5	Steel casting, iron casting	143 kVA
Textile factory	Fibers, thread products	220 kVA
Food factory	Cube sugar, caster sugar, sugar packaging	113 kVA

Table 2. Measurement results for the shunting stations.

Shunting stations	Currents (A)	Voltage THD (%)	Current THD (%)	Dominant current harmonics
MM1	280–220	2.4–2	4.1–3.5	5 (4%) – 7 (1.8%)
MM2	70–55	2.8–2.1	5.2–4.8	3 (2%) – 5 (3.6%) – 7 (4.1%)
MM3	225–180	2.5–2	4–3.6	5 (3.7%) – 7 (1.2%)
MM6	37–22	2.8–2.2	10.1–7	5 (7.5%) – 7 (2.5%) – 11 (1%) – 21 (5%)

Table 3. Measurement results for the factories.

Shunting stations	Current (A)	Voltage THD (%)	Current THD (%)	Dominant current harmonics
Plastic factory 1	170–290	2.5–2	17–10	3 (2.5%) – 5 (10%) – 7 (12.5%)
Plastic factory 2	90–170	2.2–2	20–10	5 (11%) – 7 (12.5%) – 11 (8%)
Casting factory 1	13.25–14.75	3–2.5	20–15	5 (16%) – 7 (12%) – 11 (3%)
Casting factory 2	500–630	4.3–3.5	28.5–24.5	5 (22%) – 7 (10%) – 11 (8%)
Casting factory 3	140–300	2.6–2.3	22.5–9	5 (6%) – 7 (19%)
Casting factory 4	660–775	5.6–5.3	26–19	5 (21%) – 7 (11%) – 17 (3%)
Casting factory 5	125–230	2.6–2.2	32–8	2 (28%) – 3 (3%) – 4 (8%) – 5 (6%)
Textile factory	400–580	4.4–4.1	18.5–14.5	5 (16%) – 7 (5%) – 11 (5%)
Food factory	90–170	2.5–2.3	22.5–7	3 (8%) – 5 (6%) – 7 (10%) – 9 (6%) – 11 (11%)

Generally, the apparent power of the transformers used in distribution systems is 1250 kVA and the short circuit current for the secondary side is approximately 34 kA. The Isc/I_L ratio of a factory that has a load current of 700 A is approximately 48. Hence, the IEEE 512 standard limit for current distortions in this system is assumed to be 8%, but this value can be changed if the short circuit ratio or other system parameters are changed. According to this limit, the current distortions of the factories exceed the IEEE standards' limits. The reasons for these high distortions are the arc furnaces in the casting factories, adjustable speed drives, soft-starters, inverters, and other equipment that have power electronic devices in the other factories.

The reason why some casting factories fed from MM1 with current distortions of more than 25% have lower distortion values at the HV side is the low distorted currents of the other factories in the measurement system. Low distorted currents lower the total harmonic distortions at the PCC. In addition, harmonic cancellation can occur because of angular differences.

3. Simulations

Today, there are many methods to perform energy quality research. Simulation is one of these methods. After entering the system's parameters into the simulation, some useful results can be taken from the simulation by varying the parameters [4].

An electrical model of the system was prepared in SimPowerSystems, a toolbox from MATLAB and Simulink, based on the measurements taken with the energy quality analyzers and the characteristic values of the transmission system taken from the KOIA office. In a real system, there are many hundreds of transformers with different apparent power values. However, there are approximately 60 distribution transformers with the apparent power of 1250 kVA in the electrical system model, because it is very difficult to model hundreds

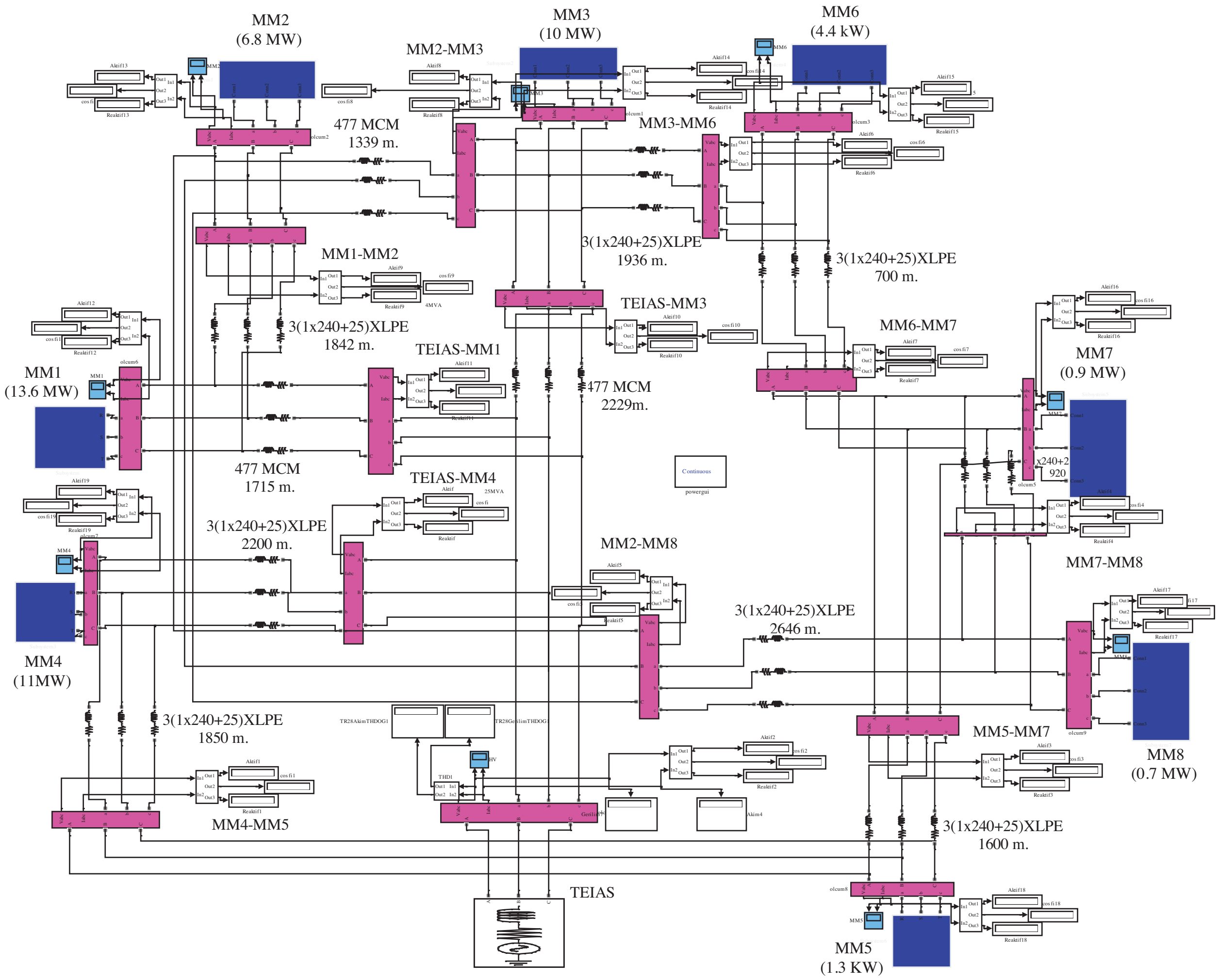

Figure 2. Electrical model of the electric transmission system at the KOIA.

of transformers, loads, harmonic current sources, measurement blocks, and many other simulation system components in the simulation program. Therefore, the components' values of the simulation system were entered according to the real measurements' values. The other factories' values were taken from the KOIA office and used in the simulation.

Harmonic sources, which are nonlinear elements, are generally considered to be injection sources into the linear network models. They can be represented as current injection sources or voltage sources. For most harmonic flow studies, it is suitable to treat harmonic sources as the simple sources of harmonic currents [1].

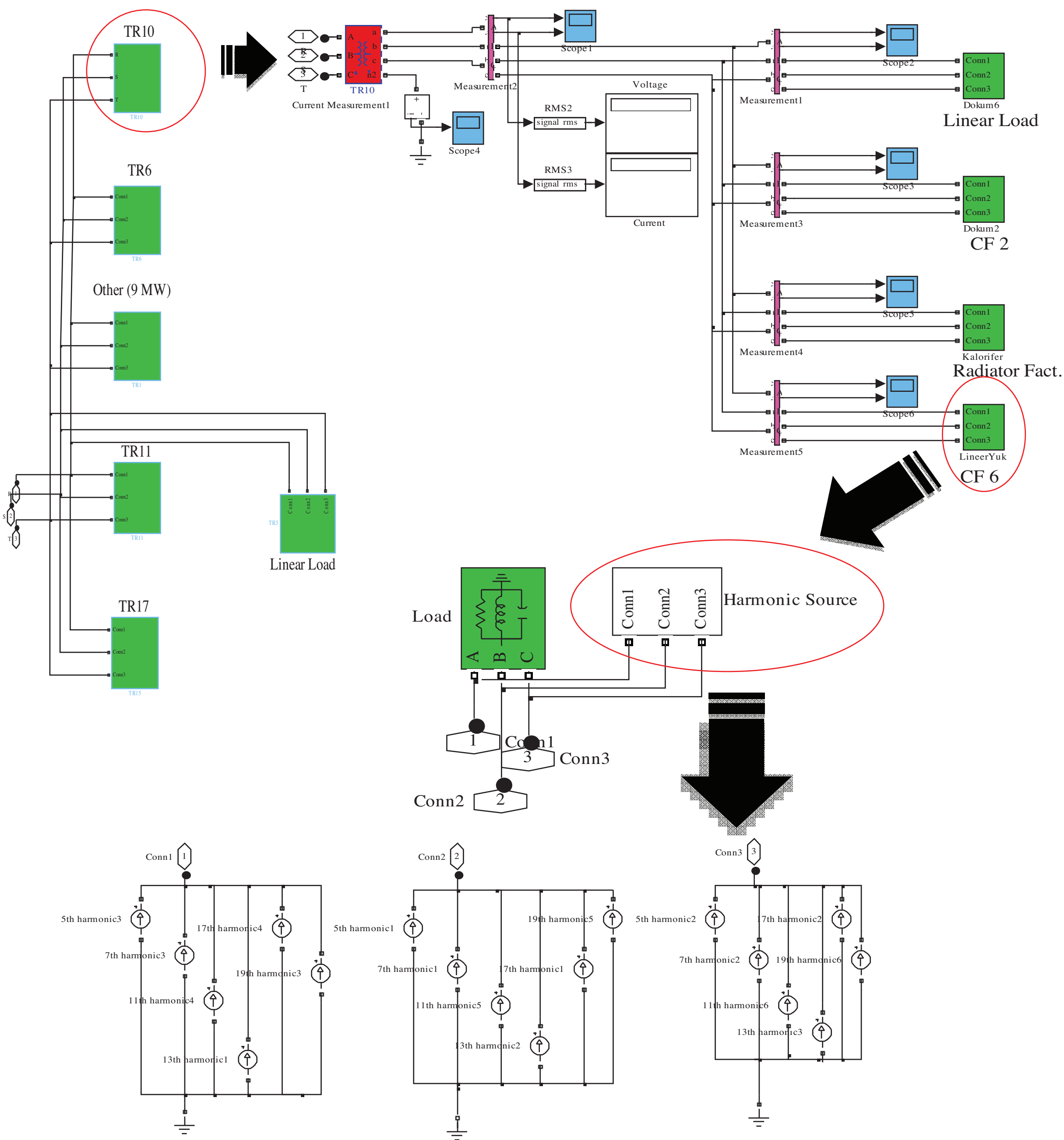

Figure 3. Simulation representations of transformers, loads, harmonic sources, and other components in shunting station MM1.

Shunting stations are modeled with boxes that include transformers, linear and nonlinear loads, measurement blocks, and other transmission elements, as shown in Figure 2.

The representation of the transformers, loads, harmonic sources, and other equipment in MM1 are shown in Figure 3. The active-reactive powers and power factors of the shunting stations can be measured with measurement blocks with their direction as illustrated in Figure 4.

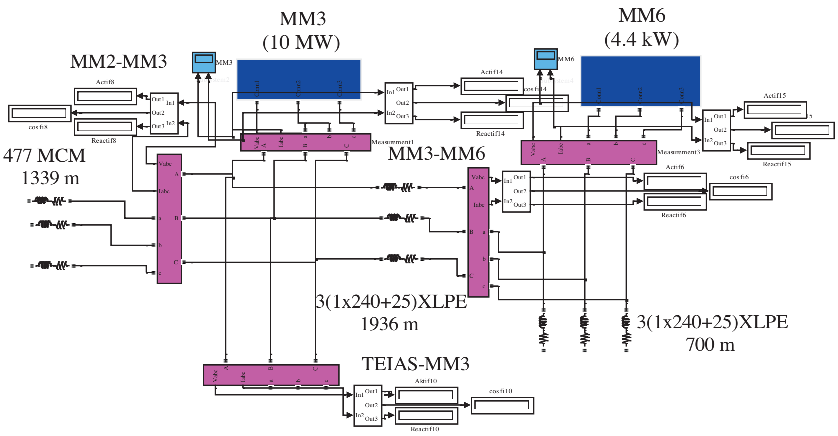

Figure 4. Active-reactive power and power factor measurement of the shunting stations.

Tables 4 and 5 represent the values of the "Konya 3 TM" (transformation center), the main sources of the electrical system, and the distribution transformers, respectively.

Table 4. The values of the "TEIAS Konya 3 TM" (the main transformer station of the system).

Phases	RMS value of the voltage	Phase degree	Frequency (Hz)	Three-phase short circuit power	X/R ratio	Capacitance
V_A	34500 V	0	50	680 MVA	323.5	inf.
V_B	34500 V	–120	50			inf.
V_C	34500 V	120	50			inf.

Table 5. Values of the distribution transformers.

Nominal power Pn [Va], frequency [Hz]	[1250e3, 50]
Winding 1 connection	D1, D11, Y
Winding 1 parameters [V1 Ph-Ph (Vrms), R1 (pu), L1 (pu)]	[34500 12.85 0.177]
Winding 2 connection	Yn, Yn, Yn
Winding 2 parameters [V2 Ph-Ph (Vrms), R2 (pu), L2 (pu)]	[400 0.001727 2.832e-005]

For the simulation, the short circuit ratio of the main voltage source "TEIAS Konya 3 TM" transformer and the X/R ratio are calculated as 680 MVA and 323.5.

Underground and overhead lines are used between the shunting stations. Three (1 × 240 + 25) XLPE cables are used as the underground line cables, and 477 MCM (Hawk) lines are used as the overhead lines. In order to make real simulations with the current harmonic values measured before, the resistance and impedance values of the lines between the shunting stations should be calculated according to their respective distances. The resistance and impedance values of cables used in the electrical distribution system are shown in Table 6.

Table 6. The resistance and impedance values of the cables.

	Resistance of the conductor at 20 °C (ohm/km)	Inductance (mH/km)
477 MCM (Hawk)	0.12	0.95
240 mm^2 XLPE	0.0754	0.531

Line inductances and resistances according to the types of cables and line distances are shown in Table 7.

Table 7. Line inductances and resistances according to the types of cables and line distances.

Lines	Types of cables	Distances	Resistances and inductances according to line distances	
TEIAS-MM1	477 MCM	1715 m	0.2058 ohm	0.5145 mH
MM1-MM2	3 (1 × 240 + 25) XLPE	1842 m	0.1388 ohm	0.9781 mH
MM2-MM3	477 MCM	1339 m	0.1606 ohm	0.4017 mH
MM2-MM8	(1 × 240 + 25) XLPE	2646 m	0.1995 ohm	1.407 mH
TEIAS-MM4	3 (1 × 240 + 25) XLPE	2200 m	0.1658 ohm	1.168 mH
MM4-MM5	3 (1 × 240 + 25) XLPE	1850 m	0.13949 ohm	0.9842 mH
MM5-MM7	3 (1 × 240 + 25) XLPE	1600 m	0.1206 ohm	0.8512 mH
MM3-MM6	3 (1 × 240 + 25) XLPE	1936 m	0.145977 ohm	1.029952 mH
MM6-MM7	3 (1 × 240 + 25) XLPE	700 m	0.05278 ohm	0.3724 mH
TEIAS-MM3	477 MCM	2229 m	0.2676 ohm	0.669 mH
MM7-MM8	3 (1 × 240 + 25) XLPE	920 m	0.06936 ohm	0.489 mH

A reference simulation should be carried out in order to understand the differences of the simulation.

Dyn11 connection-type transformers are especially used in electrical systems. Therefore, a reference simulation is simulated according to Dyn11 connection-type transformers, and it is the one that all of the factories are working with. The reference simulation values are shown in Table 8.

Table 8. Reference simulation values.

Place	Voltage THD (%)	Current THD (%)
MM1	2.13	3.58
MM2	2.18	5.02
MM3	2.16	3.73
MM6	2.2	8.94
CF2	11.24	23.57
CF6	11.24	22.78
Linear load	11.24	22.89

If the reference simulation values and measurement values in Tables 2 and 3 are compared, it can be seen that the current distortion values are close to each other, but the voltage distortions are high in the simulation.

3.1. Effects of transformer connection on harmonics

In order to analyze the effects of the transformer connection types on the distribution harmonics, first, all of the transformers' connection types are assumed to be the Dyn11 connection-type in the reference simulation. Next, the Dyn1, Yyn, and Ynyn types are chosen, respectively. The simulation results are given in Table 9.

Table 9. Transformer connection types simulation results.

	THD (%)							
	MM1		MM2		MM3		MM6	
Connection types	V	A	V	A	V	A	V	A
Dyn11	2.13	3.58	2.18	5.02	2.16	3.73	2.20	8.94
Dyn1	2.13	3.58	2.18	5.02	2.16	3.74	2.20	8.93
Yyn	1.90	3.22	1.95	4.60	1.93	3.24	1.96	8.33
Ynyn	1.91	3.23	1.96	4.60	1.94	3.34	1.97	8.34

3.2. Effects of transformer leakage impedance on harmonics

The values of the 1250 kVA transformer impedances that are used in the simulation are shown in Table 10. The changed THD values of the shunting stations and some factories are given in Table 11 after increasing the impedance values of the Dyn11 connection-type transformers from 100% to 50%.

Table 10. The reference impedance values and increased values of the transformers used in the simulation.

	Reference values		Increased values (50%)	
	Primer	Seconder	Primer	Seconder
R (ohm)	12.85	1.73E-03	19.275	2.59E-03
L (H)	0.177	2.83E-05	0.2655	4.25E-05

Table 11. The values obtained by increasing the transformer impedances.

	THD (%)													
	MM1		MM2		MM3		MM6		CF2		CF6		Linear Load	
	V	A	V	A	V	A	V	A	V	A	V	A	V	A
Reference values	2.13	3.58	2.18	5.02	2.16	3.73	2.20	8.94	11.24	23.57	11.24	22.78	11.24	22.89
Changed values	1.89	3.20	1.93	4.55	1.92	3.30	1.95	8.26	13.78	22.04	13.78	22.46	13.78	25.37
Percentage comparison	–11.27	–10.61	–11.47	–9.36	–11.11	–11.53	–11.36	–7.61	22.60	–6.49	22.60	–1.40	22.60	10.83

4. Conclusion

In this study, an electrical model of a large distribution system was made according to the measurement values taken from the KOIA in order to comprehend the behaviors of the harmonics in large electrical distribution systems.

The measurement values and simulation values were compared to confirm the accuracy of the simulation. If the comparison of the reference simulation values in Table 8 and the measurement values in Tables 2 and 3 are compared, it can be seen that the current distortion values are close to each other. However, the voltage distortions are high in the simulation because all of the nonlinear factories are working in the simulation, and the distorted currents induce distorted voltages in the lines.

In addition, the transformer connection types' and impedances' simulations were presented to understand and solve the harmonic problems in electrical distribution systems.

According to Table 9, changing the transformer connection types changes the voltage and current total harmonic distortion of the shunting stations, causing the transformer connection types Dyn11 and Dyn1 to make almost no changes in the voltage and current total harmonic distortion. However, at the Yyn and Ynyn transformer connection types, it has been seen that the voltage and current distortion dropped by about 10% according to reference simulation.

According to Table 11, increasing the transformer impedances decreases the voltage and current distortion of MM1, MM2, MM3, and MM6.

The voltage distortions of the CF2 and CF4 at the low-voltage side of the transformers whose impedances are changed increased to 13.78% from 11.24%. The current distortions, on the other hand, decreased. As being fed from a feeder that has a lower-voltage harmonic distortion is much more important for distribution system users at the low-voltage side, the voltage THD increase in the low-voltage side is much more important than the voltage THD decline in the high-voltage side. In other words, it is an undesirable situation for distribution systems because the increases of the transformer impedances increase the voltage THD of the factories. Hence, the short circuit ratio of the factories' transformers is better at high levels. The higher transformer short circuit ratio means lower transformer impedances. On the other hand, overloading of the transformers causes much more voltage THD because overheating increases the impedance value. Hence, the short circuit levels of the transformers should be selected properly by making good plans for the factories that will be fed from these transformers.

Acknowledgments

The authors acknowledge the support for this study provided by Selçuk University Scientific Research Projects. The authors also wish to thank TÜBİTAK for support of this study.

References

[1] R.C. Dugan, F.M. McGranaghan, H.W. Beaty, Electrical Power Systems Quality, New York, McGraw-Hill, 1996.

[2] H. Temurtas, F. Temurtas, "An application of neural networks for harmonic coefficients and relative phase shifts detection", Expert Systems with Applications, Vol. 38, pp. 3446–3450, 2011.

[3] Y.P. Chang, C.N. Ko, "A PSO method with nonlinear time-varying evolution based on neural network for design of optimal harmonic filters", Expert Systems with Applications, Vol. 36, pp. 6809–6816, 2004.

[4] H. Eroğlu, "Harmonic and power quality analysis of a distribution system", Selçuk University Graduate School of Natural and Applied Sciences, Konya, 2009.

[5] S. Jain, A. Pramod, H.O. Gupta, "A survey of harmonics: Indian scenario", IEEE India Annual Conference, pp. 84–89, 2004.

[6] S.N. Govindarajan, M.D. Cox, F.C. Berry, "Survey of harmonic levels on the Southwestern Electric Power Company system", IEEE Transactions on Power Delivery, Vol. 6, pp. 1869–1875, 1991.

[7] S.B. Fadel, "Simulation of harmonic currents and voltages due to power electronic equipment", University of Queensland, School of Information Technology and Electrical Engineering, Queensland, 2002.

[8] C. Yang, Z.L. Piao, X.W. Sun, "Harmonic simulation analysis of reactive power compensation equipment and its application", Power and Energy Engineering Conference, pp. 1–5, 2010.

[9] D.M. Said, N. Ahmad, A.A.M. Zin, "Power supply quality improvement: harmonic measurement and simulation", National Power and Energy Conference, pp. 352–358, 2003.

[10] S. Wu, X. Li, "Harmonic suppression and simulation based on Matlab", International Conference on Computational Intelligence and Software Engineering, pp. 1–3, 2009.

[11] Y. Hao, X, Yonghai, L. Yingying, Z. Yongqiang, X. Xiangning, "Simulation and harmonic analysis on ultra high voltage AC transmission system", International Conference on Energy and Environment Technology, pp. 283–286, 2009.

[12] C.L. Fan, G.N. Wu, X.Y. Zhang, Y.F. Wang, "The measurement and simulation research of electrified railway harmonic", International Conference on Condition Monitoring and Diagnosis, 2008.

[13] P. Li, G. Li, Y. Xu, S. Yao, "Methods comparation and simulation of transformer harmonic losses", Power and Energy Engineering Conference, pp. 1–4, 2010.

[14] D.M. Said, K.M. Nor, "Simulation of the ımpact of harmonics on distribution transformers", 2nd IEEE International Conference on Power and Energy, pp. 335–340, 2008.

[15] T. Manmek, C. Grantham, T. Phung, "A real time power harmonics measuring technique under noisy conditions", Australasian Universities Power Engineering Conference, 2004.

[16] A.E. Emanuel, A.J. Orr, D. Cyganski, E.M. Gulachenski, "A survey of harmonic voltages and currents at the customer's bus", IEEE Transactions on Power Delivery, Vol. 8, pp. 411–421, 1993.

[17] A.E. Emanuel, A.J. Orr, D. Cyganski, E.M. Gulachenski, "A survey of harmonic voltages and currents at distribution substations", IEEE Transactions on Power Delivery, Vol. 6, pp. 1883–1890, 1991.