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Impact of large-scale installation of LED lamps in a distribution system

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Abstract: The aim of this paper was to examine the utilization of a large number of nonlinear light emitting diode (LED) lamps in a distribution system and its impact on system power quality. Initially, harmonic and others electrical characteristics were identified by carrying out an experiment on four types of LED lamps available on the local market. On the basis of the identified characteristics, a new LED lamp model was developed in MATLAB Simulink. This model is called the time-dependent current source model and gives more accurate results than the fixed current source model. Then this model was applied to a distribution network together other linear and nonlinear loads, namely incandescent lighting, computer loads, and compact fluorescent lamps (CFLs). The simulated results show that the harmonic voltage distortion can exceed the 8% IEC standard limit when 80% incandescent lamps in a distribution power network are replaced with LED lamps. Furthermore, the simulation results show that the active power loss can drastically increase across distribution transformers due to the presence large numbers of LED lamps.

Key words: LED lamps, harmonic distortion, power quality, simulation, losses

1. Introduction

Recently, LED lamps have become popular in lighting applications due to their energy savings and environmental compatibility. However, LED lamps show nonlinear characteristics and create highly distorted harmonic current. This harmonic distortion depends on the internal ballast configuration and exceeds the total current harmonic distortion (THD_I) specified by some standards [1]. Nonetheless, the harmonic current injection from a single LED lamp is not a big problem for the power network because an LED lamp has a small active power rating (below 25 W), which draws small input current. The harmonic effect may become noticeable in a system that contains a large number of LED lamps. This is because widespread adoption of LED lamps can be considered a large harmonic current source. Moreover, harmonic distortion improvement caused by LED lamps is complicated due to their discrete nature. For a big harmonic source, for example an electric furnace, it is easier to design a harmonic filter to reduce systems voltage distortion but it is not easy and effective to design filter for small loads like LED lamps. Moreover, LED lamps' power factor is between 0.5 and 0.7 [2].

The majority of energy efficient lighting loads inject highly distorted harmonic current into the power network. Among them, CFLs are popular and widely used. CFLs are nonlinear, and they create harmonics that highly distort the current wave shape [3–10]. They cause problems if present in large amounts in the operation of sensitive electric power systems. Jabbar et al. [6] conducted an experiment to measure the current

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harmonic distortion in CFLs. In their experiment, they found that most CFLs produce approximately 120% of current harmonic distortion, which significantly affects the power network. Voltage distortion may exceed 5% when a large number of CFLs is used in distribution systems. Matvoz and Maksic [7] analyzed the effects of CFLs in a distribution network and found that harmonic issues mostly occur on the low voltage (LV) level from wherever they initiate. The increasing current on the neutral wire of the LV network is another effect of harmonic currents attributed to CFLs. The tolerable IEEE harmonic limits for nonlinear loads may be exceeded when the amount of CFLs in the system increases. Therefore, Watson et al. [8] recommended CFLs (with embedded harmonics filter) with a "Star Rating" for use. In the related field of LED lamps, several studies have been conducted to investigate the harmonic characteristics of LED lamps [1,2,11–14]. Most of the work was performed on an experimental basis with a small number of lamps. The substantial conversion from incandescent lamps to LED lamps can create serious problems in distribution systems, such as equipment malfunction and intolerable distortion of voltage levels, which may damage power-factor capacitors [12]. Moreover, the resultant harmonic current is not an ordinary arithmetical sum of individual harmonic currents of loads, once a huge amount of harmonic loads is taken into account. There are some effects due to the diversity effect. There is not much literature that deals with the impact of large numbers of LED lamps on the distribution network. This investigation is important because lighting accounts for around 20% of electricity consumption in the world and it is expected that most of the conventional lamps will be replaced by LED lamps within the next few years.

The aim of this study was to determine harmonic distortion levels caused in distribution networks by large numbers of LED lamps. For this purpose, a distribution network was selected that is adopted from the work by Matvoz and Maksic [7]. A new simulation model was developed for different types of LED lamps available on the market. Furthermore, the effect on a distribution transformer and its losses due to LED lamps was investigated by simulation studies. Finally, the voltage distortion level was also compared with IEC standard 61000–2–2 [15].

2. Field measurement

Before a simulation model is developed, it is necessary to know the harmonics and other electrical characteristics of LED lamps. This can be done from experimental measurements. Some lamp samples from different manufacturers with different ratings were selected that are available on the local Malaysian market. Samples are shown in Table 1. Typical time-domain waveforms and corresponding harmonic spectra as recorded in the laboratory using a Fluke–434 are shown in Figure 1. Figure 1 demonstrates that the current waveforms are not sinusoidal, which means they introduce harmonics into the distribution network. Additionally, this outcome shows that the LED lamps use dissimilar types of ballast circuit with different filtering methods to reduce harmonic generation. From the experiment, four types of LED lamps were found. The type of configuration depends on the ballast circuit. The four types of ballast circuit are identified based on their harmonic filtering methods, namely as No-filter (THD_I = 170%–175%), Passive filter (THD_I = 105%–110%), Valley fill (THD_I = 67%–72%), and Active filter (THD_I = 30%–35%). Perhaps ballast without a filter injects higher harmonic current while less harmonic current is observed for ballasts with active filter circuits. The overall harmonic distortion level from individual LED lamps is recorded in Table 2. From the table, it can be seen that most of the lamps exceed the IEC harmonic standard limit [16]. This type of lamp is more problematic in power system networks.

Table 1. Technical data for the test lamp.

Lamp ID	Nominal power P (W)	Equivalent to incandescent P (W)	Power factor	Luminous flux (lm)	Life span (years)
LED – 1	5	40	0.48	230	6
LED – 2	7	40	0.7	350	25
LED – 3	10	50	0.89	950	25
LED – 4	5.5	30	0.59	290	20
LED – 5	7	40	0.51	350	20
LED – 6	6	30	0.52	365	25
LED – 7	5	40	0.67	350	25
LED – 8	3	15	0.5	150	18
LED – 9	8	40	0.82	450	25
LED – 10	4	25	0.66	250	25

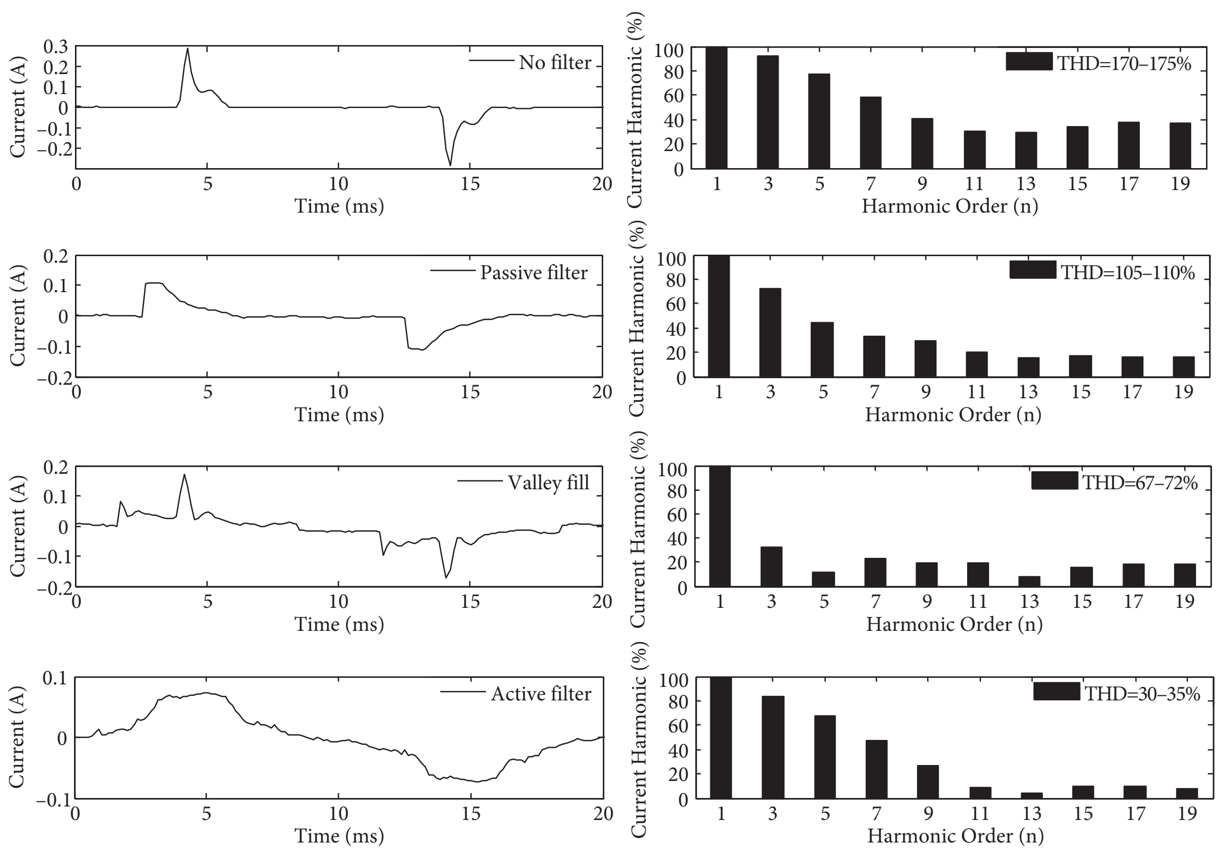


Figure 1. Current waveforms and harmonic spectrum obtained from numerous tests LED lamps.

3. Proposed LED lamp model

The fixed current source method becomes complex when a large number of consumers are connected. Moreover, this method provides approximate results because it can consider only odd-order harmonics [17–19]. A significant number of interharmonics can be presented in such a system, and thus all harmonics should be considered for accurate analysis.

Table 2. Harmonic level for the test LED lamps.

Lamp ID	Type of filter	THD_I (%)
LED – 1	No filter	171.9
LED – 2	Valley fill	71.23
LED – 3	Active filter	34.8
LED – 4	Passive filter	106.3
LED – 5	No filter	168.2
LED – 6	No filter	174.3
LED – 7	Valley fill	69.83
LED – 8	No filter	164.4
LED – 9	Active filter	30.94
LED – 10	Valley fill	67.05

This paper presents a time-dependent current source model based on experimental data produced from LED lamps. Figure 2 shows the procedure for the development of the proposed LED lamp model. The proposed model is developed using MATLAB Simulink tools. The time-dependent voltage and current are taken from experimental data. The experimental data are converted to appropriate voltage or current source through controlled voltage or controlled current source, respectively. The current source is injecting current into the supply through resistance. Figure 3 shows the overall model, where a very high resistance is connected in parallel with each LED model to calculate voltage harmonic distortion at every bus bar with extra resistance. This model offers more accurate results in the case of harmonic attenuation because it can calculate all harmonics including even-order and interharmonics.

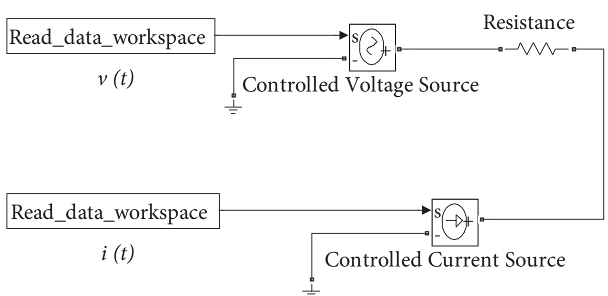


Figure 2. LED model developed in MATLAB Simulink.

3.1. Verification of the LED lamp model estimation

The measured characteristics are used to develop the simulation model elaborated in section 3. Figures 4 and 5 show the time-dependent current signal characteristics of two lamps during simulation and compare the performance with a fixed current source model and experimental data. The results are in accordance with the measured ones rather than with those of the fixed current source model. From the figures, time-dependent current wave shape and peak current are good agreement with the measured ones while current wave shape is diverse and has a lower peak current. Moreover, the time dependent model for two other lamps is shown in Figure 6. Table 3 shows the RMS current, active power, and THD_I of the two lamps. As can be seen in Table 3, all characteristics of the time dependent model are in agreement with the measured values but this is not the case for the fixed current source model. The other lamps displayed similar characteristics. Therefore, the proposed model is better than the fixed current source model.

In Table 3, meas, fx, and td indicate the measured, fixed current model, and time dependent model, respectively.

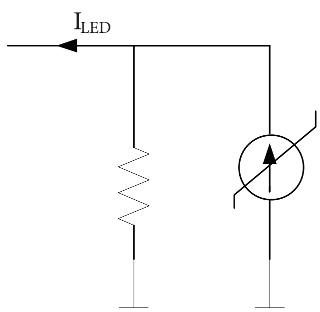


Figure 3. Equivalent current source model.

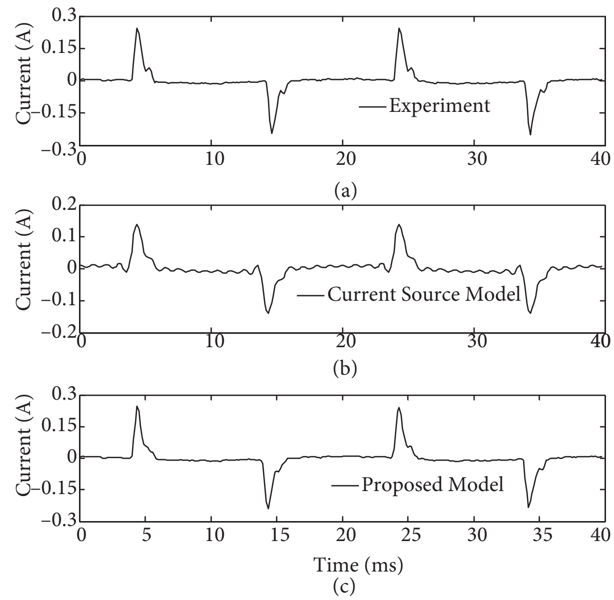


Figure 4. Simulated current waveforms with experiment for LED Lamp – 1.

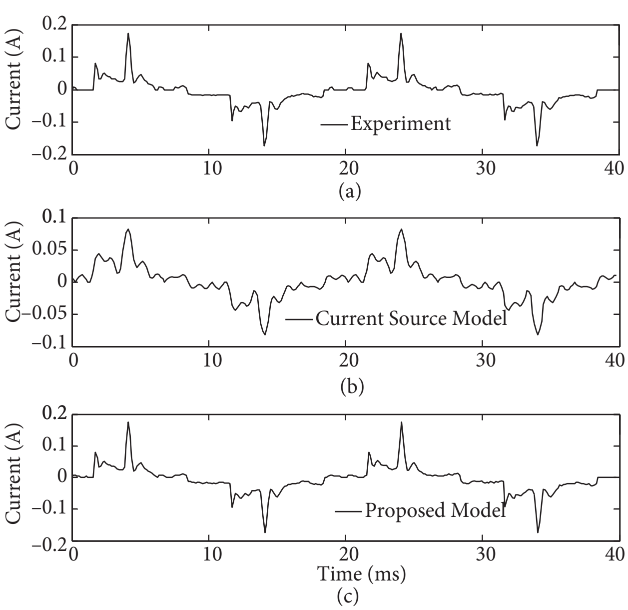


Figure 5. Simulated current waveforms with experiment for LED Lamp – 2.

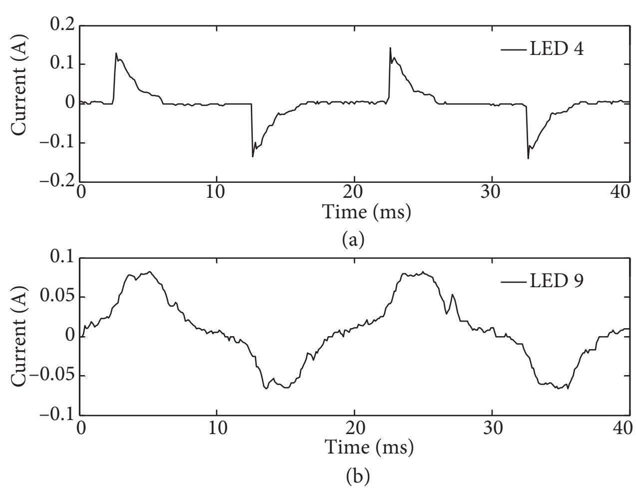


Figure 6. Simulated current waveforms with proposed model for LED Lamp – 4 and Lamp – 9.

Table 3. Simulated model verification with the measurement.

Lamps	RMS current (A)			Active power (W)			THD_I (%)		
	I_{meas}	I_{fx}	I_{td}	P_{meas}	P_{fx}	P_{td}	meas	fx	td
LED – 1	0.05	0.041	0.053	5.0	4.18	5.08	171.9	155.87	170.36
LED – 2	0.04	0.036	0.042	7.0	6.19	7.17	70.5	63.54	71.23

4. Distribution system modeling

This paper mainly aims to examine the effects of LED lamps on an electric power network. To achieve this goal, the distribution network model from the work by Matvoz and Maksic (2008), which supplies urban and rural customers, is adopted (Figure 7). This system is supplied through overhead lines. Circled numbers in Figure 7 indicate the location numbers in the network.

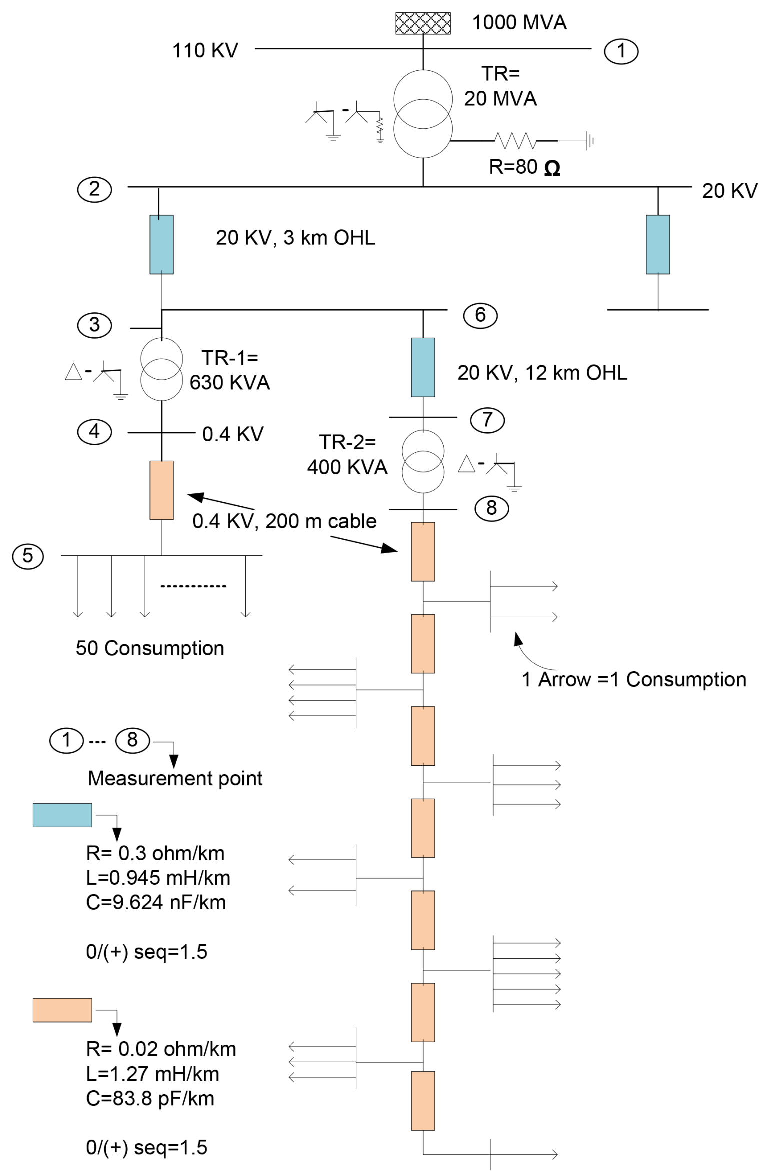
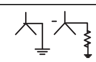
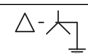
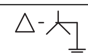


Figure 7. Distribution network.

The distribution system contains a 110 kV source voltage connected with a 20 kV line via a 110/20 kV transformer (TR). Some metropolitan customers are connected 3 km away from the substation on low voltage (LV) feeders via a 20/0.4 kV distribution transformer (TR – 1). Approximately 50 consumers are connected in each phase. A different group of consumers in a rural network is connected with another 20/0.4 kV distribution transformer (TR – 2), which is 12 km downstream from TR – 1. The distance of the 0.4 kV cables between the last consumer and the TR – 2 of the rural network is 1.4 km. Other specifications of the network are listed in Table 4. Simulation is conducted using the MATLAB Simulink program. Points ①—⑧ in Figure 7 represent the measurement points. The terminal voltage, current, THD_V, THD_I, active power, apparent power, power factor, and power losses in each point are measured.

Table 4. Specification of distribution network.

Name	Type	Specification
Transformer, TR		20 MVA, 110/20 KV
Transformer, TR – 1		630 KVA, 20/0.4 KV
Transformer, TR – 2		400 KVA, 20/0.4 KV
Overhead line (OHL)	∏	R = 0.3 ohm/Km
		L = 0.945 mH/Km
		C = 9.624 nF/Km
0.4 KV cable	∏	R = 0.02 ohm/Km
		L = 1.27 mH/Km
		C = 83.8 pF/Km

The simulation is started with classic incandescent light bulbs (scenario 1) combined with other linear and nonlinear loads only. In the other cases (scenarios 2–5), incandescent lamps were replaced with LED lamps. In scenarios 2, 3, and 4, only LED – 1 lamps were used for the worst scenario while four types of LED lamps (LED – 1, LED – 2, LED – 4, and LED – 6) with different types of ballast circuit were used in scenario 5. Load consumptions of the different scenarios are presented below.

Scenario 1: Incandescent Lamps

L1: 480 W incandescent lamps + 100 W CFLs + 320 W computer (2 pieces) with CRT + 600 W load at PF = 0.95.

L2: 600 W incandescent lamps + 120 W CFLs + 900 W load at PF = 0.90.

L3: 240 W incandescent lamps + 60 W CFLs + 1200 W load at PF = 1.

Scenario 2: Replace 50% Incandescent Lamps with LED Lamps

L1: 240 W incandescent lamps + 30 W LED lamps + 100 W CFLs + 320 W computer (2 pieces) with CRT + 600 W load at PF = 0.95.

L2: 280 W incandescent lamps + 40 W LED lamps + 120 W CFLs + 900 W load at PF = 0.90.

L3: 120 W incandescent lamps + 15 W LED lamps + 60 W CFLs + 1200 W load at PF = 1.

Scenario 3: Replace 80% Incandescent Lamps with LED Lamps

L1: 80 W incandescent lamps + 50 W LED lamps + 100 W CFLs + 320 W computer (2 pieces) with CRT + 600 W load at PF = 0.95.

L2: 120 W incandescent lamps + 60 W LED lamps + 120 W CFLs + 900 W load at PF = 0.90.

L3: 840 W incandescent lamps + 25 W LED lamps + 60 W CFLs + 1200 W load at PF = 1.

Scenario 4: Replace All Incandescent Lamps with LED Lamps

L1: 60 W LED lamps + 100 W CFLs + 320 W computer (2 pieces) with CRT + 600 W load at PF = 0.95.

L2: 75 W LED lamps + 120 W CFLs + 900 W load at PF = 0.90.

L3: 30 W LED lamps + 60 W CFLs + 1200 W load at PF = 1.

Scenario 5: Replace All Incandescent Lamps with Different Types of LED Lamps

L1: 60 W LED lamps + 100 W CFLs + 320 W computer (2 pieces) with CRT + 600 W load at PF = 0.95.

L2: 75 W LED lamps + 120 W CFLs + 900 W load at PF = 0.90.

L3: 30 W LED lamps + 60 W CFLs + 1200 W load at PF = 1.

With all the above scenarios, L1 represents one consumer, L2 is another consumer, and so on. When several consumers are associated with the same LV feeder, consumers L1, L2, and L3 are connected randomly, that is, the phase arrangement is rotated. Consequently, this system becomes closer to a balanced and more realistic system.

5. Simulation results and discussion

A large number of LED lamps with linear and nonlinear loads are connected in a distribution system network to determine the impact of harmonic distortion. All scenarios' results are listed in Table 5. The major harmonic distortion was found to occur at the LV side of the distribution transformers TR – 1 and TR – 2. The distortion level of the HV side was negligible because of the distribution transformer configuration, high voltage, and low current. Therefore, a $\Delta - \mathrm{Y}$ winding type transformer was used to prevent some of the harmonic currents from penetrating into the upstream network.

Table 5. Voltage THD (%) at the testing point of all the electric networks under all scenarios.

Test point		THD_V (%)				
		Scenario				
		1	2	3	4	5
TR	Phase – A1, B1, C1	0	0	0	0.1	0
	Phase – A2, B2, C2	0	0	0	0.1	0.1
TR – 1	Phase – A1, B1, C1	0.01	0.02	0.02	0.02	0.02
	Phase – A2	3.8	5.93	7.97	9.83	8.65
	Phase – B2	3.61	6.36	8.15	10.86	8.95
	Phase – C2	3.38	6.27	8.36	10.98	9.12
TR – 2	Phase – A1, B1, C1	0.02	0.03	0.03	0.03	0.03
	Phase – A2	3.28	6.68	8.42	10.12	9.2
	Phase – B2	3.73	6.13	8.13	9.59	8.45
	Phase – C2	3.65	6.53	8.5	11.74	9.75

In Table 5, Phases A1, B1, and C1 denote the primary side and Phases A2, B2, and C2 the secondary sides of Phases A, B, and C of the transformer, respectively.

The most significant conclusions for all the examined scenarios are presented and discussed below.

Scenario 1

In this scenario, the maximum voltage distortion of the LV line was found to be 3.8% and occurred in Phase A of TR – 1. Figure 8 shows the voltage waveform of the Phase – A of TR – 1. The voltage waveform was only slightly distorted because the loads are linear, except for the harmonic injecting computer loads that are connected to the system. The voltage harmonic spectrum and phase angle are recorded in Table 6.

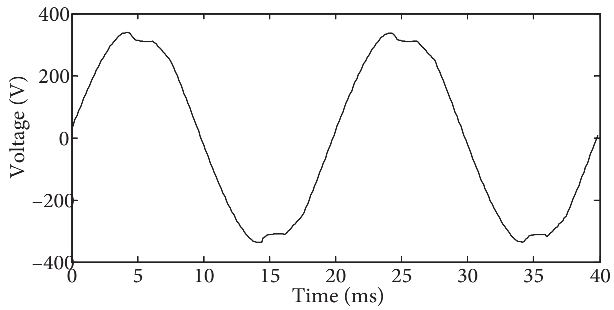


Figure 8. Voltage waveform of the 0.4 kV side with incandescent lamps.

Table 6. Voltage harmonic and phase angle of TR – 1 at phase – A for scenario 1.

Harmonic order (n)	Voltage harmonic (%)	Angle (degree)
1	100	15.6
3	2.81	11.4
5	2.14	159.9
7	0.96	0
9	0.66	187.8
11	0.56	7.2

Scenario 2

In this scenario, 50% of incandescent lamps were replaced with LED lamp – 1. The maximum voltage distortion of the LV line was 6.68% and occurred in Phase – A of the TR – 2. Therefore, increasing LED lamps led to voltage distortion in a distribution system. This scenario is acceptable because it does not exceed the IEC standard limit.

Scenario 3

In this scenario, 80% of incandescent lamps were replaced with LED lamp – 1. The maximum voltage distortion of the LV line was 8.5% and occurred in Phase – C of the TR – 2. Therefore, the system exceeded the 8% IEC standard limit when 80% of the incandescent lighting loads were replaced with LED lamps. Furthermore, almost every phase of both distribution transformers exceeded the 8% limit. Figure 9 shows the voltage waveform at Phase – A of TR – 2. This voltage was more distorted than that in Scenario 1. The power quality may be affected by the installation of many LED lamps in the system.

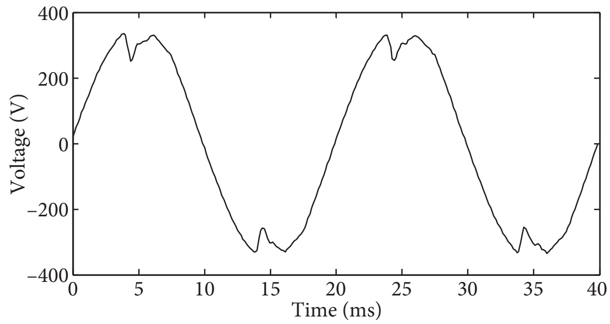


Figure 9. Voltage waveform of the 0.4 kV side with 80% LED lamps.

Scenario 4

The harmonics interfere more with the distribution network when all the incandescent lamps are completely replaced with a large number of the same type of LED lamps. The maximum THD_V reached 11.74% in the LV line at Phase – C of TR – 2. The voltage waveform in Figure 10 shows more distortion compared to Figure 9. The harmonic spectrum and phase angles are shown in Table 7.

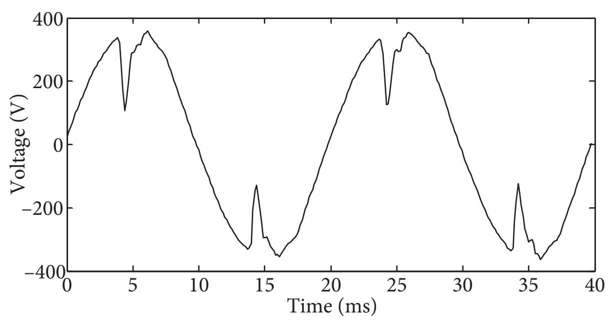


Figure 10. Voltage waveform of the 0.4 kV side with all LED lamps.

Table 7. Voltage harmonic and phase angle at phase – C of TR – 2 in scenario 3.

Harmonic order (n)	Voltage harmonic (%)	Angle (degree)
1	100	137.8
3	11.14	44.5
5	8.75	0
7	5.97	0
9	5.44	263
11	4.26	220.2

Scenario 5

In this scenario, four types of LED lamps were selected, including LED – 1, LED – 2, LED – 4, and LED – 6. The highest THD_V reached 9.75% at Phase C of TR – 2. Therefore, voltage distortion can be mitigated with different types of LED lamps instead of only one type.

The overall voltage distortion of all scenarios compared with the IEC standard limit is shown in Figure 11. From the figure, it is clear that the voltage distortion exceeds IEC standard value 8% in Scenario 3 (80% LED lamp replacement). The active power losses for all simulated scenarios are presented in Table 8. The losses across transformers increased with the addition of more LED lamps in the network but decreased across the transmission line. Therefore, a large number of LED lamps is more problematic for transformers. Total distribution network loss can be reduced by replacing the LED lamps.

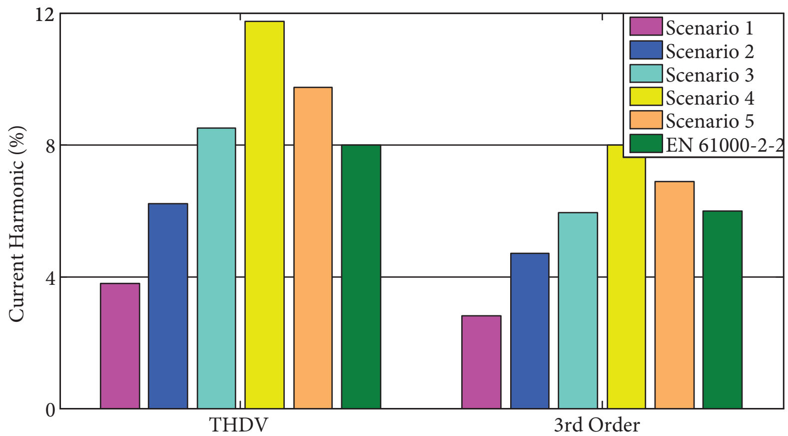


Figure 11. Voltage distortions of different scenarios with IEC 61000–2–2 standard limit.

Table 8. Active power losses for all cases without LV network.

Active power losses (W)	TR	20 kV network	TR 1	TR 2	Total losses
Incandescent lamps	218.8	1036.4	155.1	43	1453.3
80% LED lamps	309.4	688.5	197	73.5	1268.4
All LED lamps	375.6	443.3	231.3	92.6	1142.8

6. Conclusion

A simulation model of the LED lamps, without considering their internal electronic circuits, was developed as a time-dependent current source model using MATLAB Simulink tools. The proposed model was easy to implement because it is less complex than the fixed current source model. This model is compatible for representing huge numbers of LED lamps in a distribution network. The proposed model was applied to a distribution system, and the impact of large number of LED lamps on the network was observed. The major harmonic distortion was found to occur at the LV side of distribution transformers. The distortion level of the high voltage side was negligible due to distribution transformer configuration, high voltage, and low current. The voltage distortion exceeded the IEC standard limit of 8% when 80% of the incandescent lamps were replaced with LED lamps. Furthermore, the active power loss is marginally reduced across transmission lines while it rises in distribution transformers.

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