Widespread compact fluorescent lamp evaluations in 50 Hz electrical network

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ABSTRACT

Rapid development in electrical technology has imposed strong challenges to modern power system. Power quality has become a great concern due to proliferation of power electronic technology in modern electrical loads. Specifically for lighting load such as compact fluorescent lamps (CFLs), one of the concerning issues is harmonics. CFL is a cost-competitive and energy efficient compared to incandescent lamp. Inevitably, CFL produces harmonics current due to nonlinearity behaviour of the electronic ballast circuit. This paper presents a study on the widespread installation of CFL lamps in electrical power network. Initially, the harmonic current characteristics of local-branded CFL was identified from laboratory measurement. Then, a simulated CFL model was developed in MATLAB/Simulink to replicate the identified characteristics. The same step was repeated for other two different brands where eventually all models were embedded into a distribution network. The results show that at low voltage level, with installation more than 50 units for each type of CFL, the harmonic voltage distortion exceeded the 8% total harmonic distortion (THD) limit as stipulated in EN50160 standard. However, at higher voltage, the amount of THD decreased to average 0.94% and further down to average 0.28% at small transmission voltage level.

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1. INTRODUCTION

The adoption of power electronic based technology load is widely spreading and continuously increasing. The technology applications vary from as small as residential lightings to heavy industrial drives. For many years, fluorescent lamp (FL) has received wide acceptance in residential lighting replacing conventional incandescent lamp because of higher efficiency and longer lifespan [1]. With advancement in power electronic technology, the fluorescent lamp design has also evolved and leads to the invention of compact fluorescent lamp (CFL). CFLs are still widely available in the market because of efficiency and economic value [2]. The global lighting sales report released by international energy agency (IEA) shows CFL holds 28% of market share in 2020 [3].

The electronic ballast of CFL has nonlinear behaviour, hence it distorts the sinusoidal signal of AC current [4]. Distorted sinusoidal signal contains harmonics as shown in Figure 1. In the figure, the reference signal is the fundamental sine wave at 50 Hz frequency while the harmonics are others that exist at multiples order of fundamental frequency which are 150 Hz (3rd order), 250 Hz (5th order), and 350 Hz (7th order) sine waves accordingly.

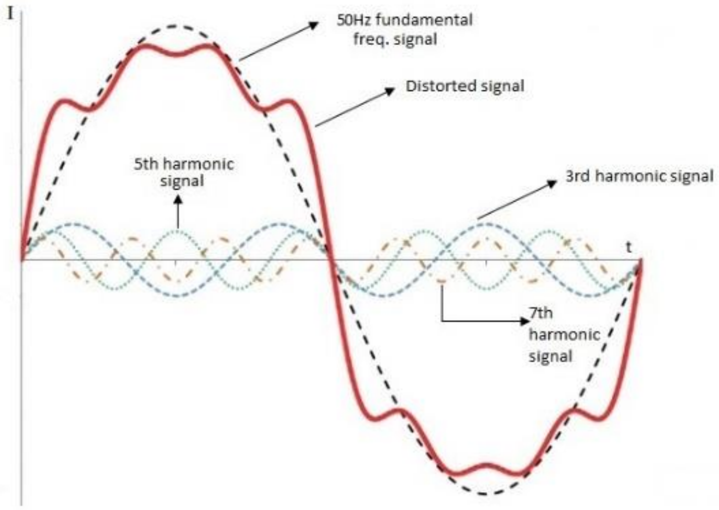


Figure 1. Decomposition of distorted sinusoidal signal

When the distorted current wave passes through impedance in the electrical network it further induces distortion in the voltage waveform that causes adverse power quality issues [5], [6]. Among serious problems caused by the harmonic currents in the power system are power loss, overheating of conductors, overloading of motors and transformers; undesired tripping of protection devices, malfunction of logic controllers and poor power factor [7]–[9]. The operation of nonlinear loads such like switch mode power supplies (SMPS), power converters, variable speed drives and battery chargers continues to increase within the power system. Research by Kalair *et al.* [10] claims reduction in power factor around 60% and an increment in line losses more than 2% due to widespread use of nonlinear loads. Thus, with proliferation in nonlinear loads and widespread installation of energy saving alternatives like CFLs and LEDs, it is important to model the complex interactions and to analyze the impacts on electrical network.

This paper focuses on modelling harmonics current injection of CFL using MATLAB/Simulink to evaluate the effect of CFL widespread installation on power network. Three different units of CFL are studied to include possible varieties in harmonic characteristics. The actual data of current measurements are used as reference to model the harmonic current sources. The interaction of multiple CFLs at different scales of installation is simulated using the proposed harmonic current model with a theoretical electrical network. The simulation model is used to assess the total harmonic distortion (THD) indices in the network at various observation nodes with relate to size of installation.

The remaining part of the paper is as follows. Section 2 discusses some scientific literature related to nonlinear load models to characterize the harmonics current injection. The MATLAB/Simulink model for CFL and descriptions of the study case is given in section 3. Section 4 shows the results and analysis. Lastly, section 5 concludes this study.

2. RELATED WORK

In general, circuit-based and measurement-based are two main methods used in harmonic modelling. Analyzing harmonic models with simulation softwares like power system computer aided design (PSCAD)/electro magnetic transient DC (EMTDC) and MATLAB offer fast and reliable solution. Circuit-based models have been used to assess the harmonic injections from nonlinear loads in several researcher works. Such as in [11]–[14] modelling the equivalent circuit of full wave rectifiers in MATLAB/Simulink to characterize harmonic components. In [15], [16] using a simplified model of SMPS to study harmonics propagation and interaction among end-user loads in PSCAD and [17] using estimated equivalent parameter values of SMPS in modern household appliances for aggregated harmonic analysis. The diversity of harmonics spectrum generated with different set of parameter values in the CFL equivalent circuit was studied by [18] using alternative transients program-electromagnetic transients program (ATP-EMTP) and

MATLAB programs. The study suggested that the behavior of distorted current is not predictable, thus, is vital to find the parameters that describe the distorted current.

For measurement-based model studies the nonlinear load has always been modelled as a source of voltage or current depending on the purpose of study [19], [20]. Research by Skamyin *et al.* [21] deals with deploying passive filter in electrical network in the presence of harmonic currents. The equivalent nonlinear load is represented in the form of current sources at respected harmonic frequencies. The summation or subtraction of the currents due to passive filter deployment is further used in determining the efficiency of the filter. According to Watson *et al.* [22] the spectra of harmonics current from different CFLs were determined by laboratory measurements resulting with representation of Norton equivalent circuit of all CFLs. Sola and Salichs [23] modeled harmonics generated by different CFL types with data from harmonic current measurements. The internal electronics circuits are considered as a “black box”. The harmonics spectra were modeled using Pspice simulation, analytically processed and eventually characterized by means of parametric conductance. A similar work observed by Sainz *et al.* [24] embraces the “black-box” concept from [23] with more comprehensive way of characterizing the waveform using nonlinear least squares method for estimation of parametric conductance.

In real practice, the challenge of circuit-based method is to correctly attain the complete circuitry or circuit parameters, which neither is easy to obtain in modern appliances. On the other hand, several reliable measurement modelling methods have also been adopted. The differences are in the way measurements data being represented in harmonic model which could lead to a compromise between complexity and accuracy. Finally, in modelling any nonlinear load, rather than the modelling approach itself is important, the convenience of applicability in commercial simulation programs is also worth to be considered.

3. RESEARCH METHOD AND MATERIAL

3.1. Experiment setup

The proposed study is accomplished through experimental and simulation work. The equipment setup for harmonics measurement in laboratory is shown in Figure 2. The CFL is connected to a circuit that feeds 240 Vrms and 50 Hz supply. The criteria of tested CFL units include identical brand but different color temperature, different brand but identical power rating and identical brand but different power rating. The rated values of the CFL lamps used in the experiment are given in Table 1. Fluke power quality analyzer (PQA) model 437-II and fluke AC current clamp i400 are used in measuring the harmonic currents. The fluke PQA features 16-bit resolution and 200 kS/s sampling rate whereas the current clamp sensitivity is 1 mA/A. Comparatively the sampling rate of the utilized PQA is a bit low which sets some limitation on the measurement results. All collected data is then processed using fluke power log (version 5.9) software installed in personal computer.

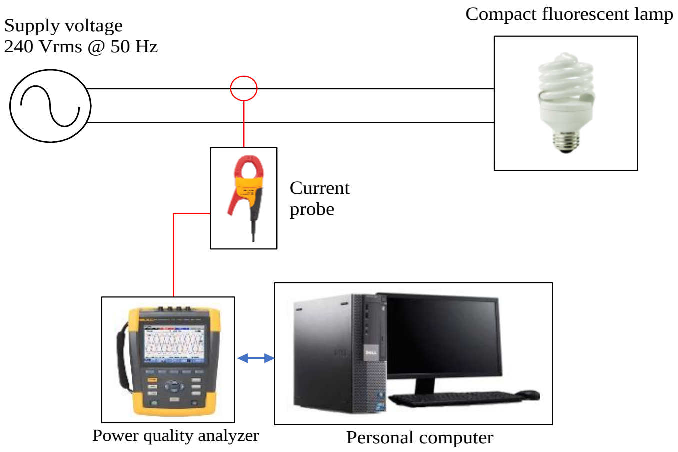


Figure 2. Experiment setup for CFL measurement

Table 1. Rated values for experimental lamps

Lamp brand	Power (W)	Voltage (V)	Frequency (Hz)	Colour
Type 1 (brand A)	18	220-240	50/60	Cool day light
Type 2 (brand B)	18	220-240	50/60	Cool day light
Type 3 (brand B)	20	220-240	50/60	Warm white

3.2. Simulink model

In this work, the proposed harmonic simulation model is developed using MATLAB R2021a with Intel i5-4590 CPU and 8 GB RAM computer. Using common Simulink block, two simulation models were developed to represent the electrical system, namely the CFL current model and electrical distribution model. For CFL current, there are three sub-models representing three different types of CFL lamp and for distribution model, a small theoretical network is considered.

3.2.1. CFL harmonic current model

The behaviour of the measured CFL harmonic current is replicated in MATLAB/Simulink using Fourier series function. The function simply transforms the fundamental and harmonics of current measurements in time domain into frequency domain. Such approach commences from the concept that any function waveform, $S(t)$ can be transformed into fourier series in amplitude-phase form as given by [25].

$$S(t) = \eta + \sum_{n=1}^{N} \left[A_n cos\left(\frac{2\pi nt}{P}\right) - \varphi_n\right] \tag{1}$$

where η is the the mean value of function, A_n is the nth harmonic amplitude, φ_n is the nth harmonic phase shift, n is an integer index which is also the number of cycles the nth harmonic makes in the function period, P is the function period, t is the time index and N is the number of observation terms. Thus, by identifying individually the magnitude and frequency of the measured data, the harmonics waveform is reconstructed by combining a sum of sinusoidal function at identified harmonic frequencies. The CFL model is represented using the Simulink function block and sinusoidal block with each phase has different functional block according to the type of CFL as shown in Figure 3.

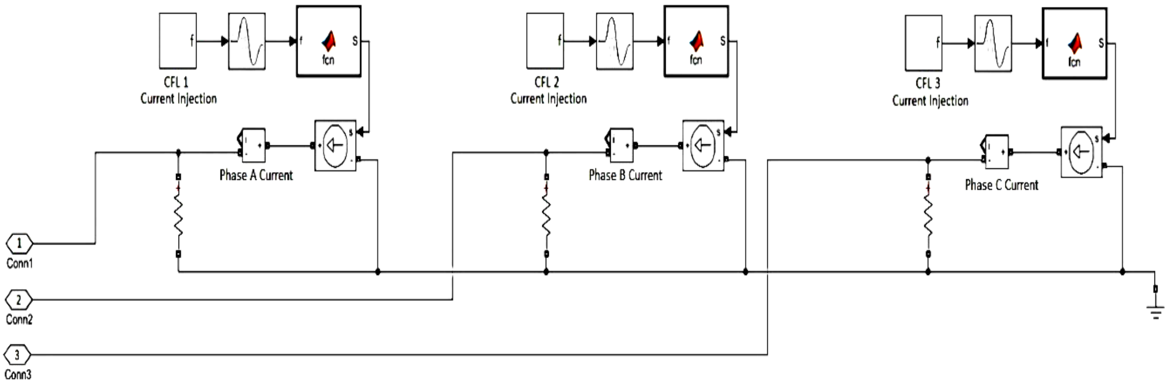


Figure 3. CFL harmonics current model

3.2.2. Theoretical electrical network model

The electrical network is a large system comprises of numerous network components and configuration. For accurate representation of a specific network, adequate information of the components is necessary. Since the purpose of the modelling is to comprehend the idea behind the interaction of CFL harmonics with network impedance, therefore any typical small network is satisfactorily applicable. To purely assess the harmonic effects from CFL, the load system is limited only to a mix of three CFLs without other nonlinear loads. The CFL loads are modeled as current sources that inject various harmonic spectrums into the network. The severity of harmonic impacts is assessed in terms of THD in current (THD_i) and THD in voltage (THD_v). The expressions of THD_i and THD_v are given in (2) and (3) respectively [26]:

$$THD_i(\%) = \frac{\sqrt{\sum_{h=2}^{\infty}|I_h|^2}}{|I_1|} \times 100 \tag{2}$$

where h is the order of harmonic, I_h is the rms value of current component at frequency hf_1 and I_1 is the rms value of fundamental component of the current. Equivalent expression for THD_v is:

$$THD_v(\%) = \frac{\sqrt{\sum_{h=2}^{\infty}|V_h|^2}}{|V_1|} \times 100 \tag{3}$$

where h is the order of harmonic, V_h is the rms value of voltage component at frequency hf_1 and V_1 is the rms value of fundamental component of the voltage. The steps taken for investigating the CFL-network interaction are summarized as follows:

a. A CFL-clustered load comprises of three different CFLs connected to low voltage network. Initial load of 10 clusters is chosen and THD_i is recorded at PCC4 which is the nearest point to the load.
b. Increase load in a step size of 10 clusters per increment and repeat the step until total load reaches 50 clusters.
c. The THD_v of the network is also necessary to be observed. The load size increment procedure is repeated and THD_v is recorded at all PCCs for each event.

The proposed model comprises of a three-phase supply network with illustrated size of CFL loads shown in Figure 4.

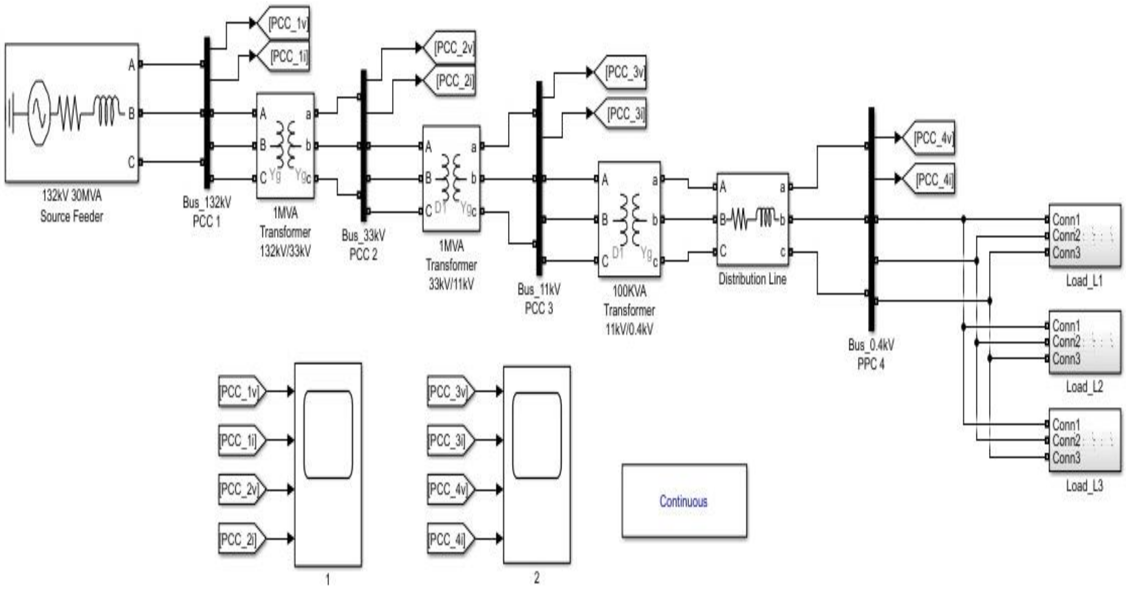


Figure 4. CFL harmonic model in electrical network

4. RESULTS AND DISCUSSION

The current waveforms for CFL measured from the experiment in are presented in Figure 5. All waveforms almost similar in shape with small differences in magnitude. Some oscillations in the waveforms are due to measurement noise. The time-domain harmonic signals were analyzed using power log tool by fluke to be transformed into frequency-domain spectrum as shown in Figure 6. It shows that CFL type 3 produces slightly higher current distortion under the same operating voltage. The spectrum considers harmonic order from 2^{nd} to 20^{th} because the effects of harmonics is usually prominent up to 25^{th} order for lighting device; for harmonic order 21^{st} and onwards the magnitudes are considerably small.

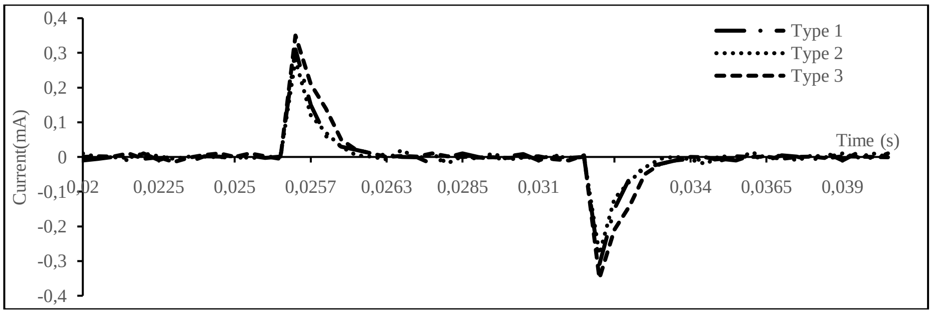


Figure 5. Current measurement waveforms for three different CFL types

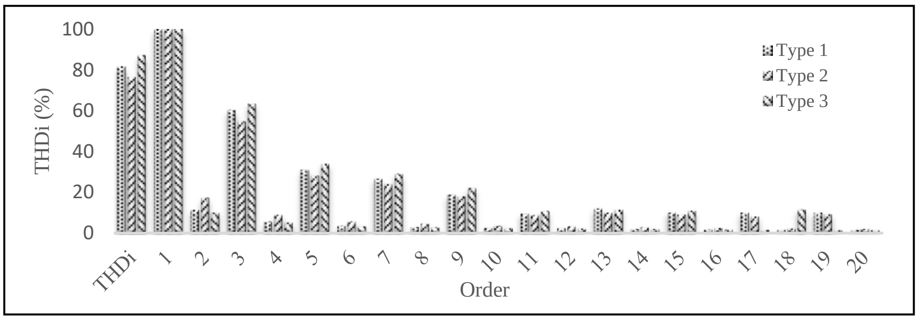
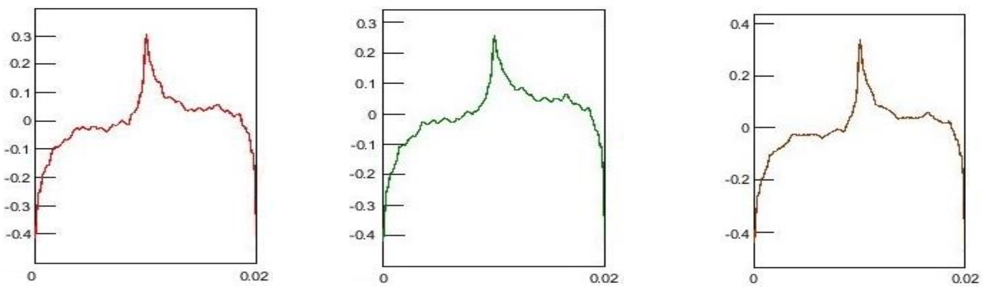


Figure 6. Harmonic spectrum of current measurement for three different CFL types

Based on the measurement results, the harmonic waveforms were reconstructed as shown in Figure 7. The waveforms in Figures 7(a), 7(b) and 7(c) represent harmonic current for CFL type 1, CFL type 2 and CFL type 3 respectively. The shape of the modelled harmonic current approximately matches with measurement current. Some variations were probably due to measurement noise and the range of harmonics order. More important is the current amplitudes at lower frequencies are much higher particularly in third order and few other odd orders that give the sharp increase in current amplitude as observed in the waveform.



(a) (b) (c)

Figure 7. Harmonic waveforms of modelled current (a) CFL type 1, (b) CFL type 2, and (c) CFL type 3

Table 2 summarizes the simulation results after increasing the load size. In general, the simulation results indicate the magnitude of harmonic current varies insignificantly with addition of harmonic sources, correspondingly the THD_i remains constant around 78%. The THD_i obtained is in line with experiment results achieved by [26] using three different CFL units whereby the THD_i equals to 84%. It can be seen that increasing the cumulative harmonic disturbance by identical group of harmonic sources at the same proportion does not change the total harmonic current distortion at the same point of connection.

On contrary, the total voltage distortion or THD_v listed in the last column of Table 2 shows some increase with addition of harmonic sources. It can be seen in every cluster size, the THD_v almost equals to arithmetic sum between the present and initial THD_v values. This situation is consistent with the Ohm's law:

$$V = I \times Z \tag{4}$$

where V is rms value of voltage, I is rms value of harmonic current and Z is impedance of network. Assuming Z is constant, the fundamental current and each harmonic current that pass through the impedance will cause a voltage drop across the impedance that eventually distort the waveform of voltage. Thus, it can be seen that the amount of voltage distortion at a location depends upon the size of the harmonic sources. Figure 8 illustrates the relation between various harmonic components and size of CFL loads.

Table 2. Harmonic current magnitudes with varying size of CFL clusters

No. of clusters	% 3^{rd}	% 5^{th}	% 7^{th}	% 9^{th}	% 11^{th}	% 13^{th}	% 15^{th}	% THD_i	% THD_v
10	54.44	27.97	23.96	17.96	8.48	9.98	8.97	78.21	1.66
20	54.43	27.96	23.96	17.96	8.48	9.97	8.96	78.19	3.31
30	54.43	27.99	23.98	17.96	8.47	9.97	8.96	78.19	4.96
40	54.43	27.96	23.95	17.95	8.47	9.97	8.96	78.18	6.62
50	54.43	27.96	23.96	17.96	8.48	9.97	8.96	78.19	8.29

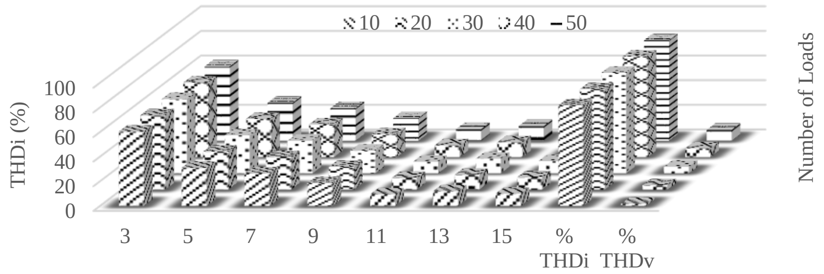


Figure 8. Relation between harmonic components and size of CFL loads

Additionally, the interaction of harmonic currents with system impedance is further investigated. The observation of total voltage distortion, THD_v is extended to other PCCs in the network. It is observed that the THD_v at all PCCs shows increment trend with the increase in number of CFL loads. Figure 9 illustrates the relation between harmonics voltage distortion and distance of common coupling point with different size of CFL loads.

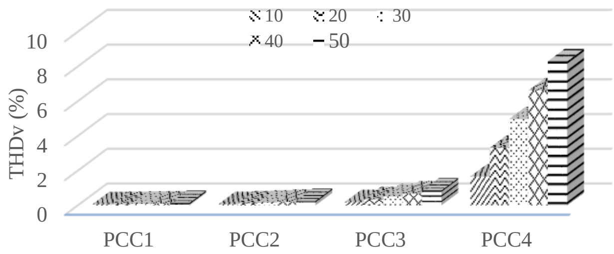


Figure 9. Relation between THD_v and distance of PCC

Table 3 shows variation of harmonics distortion indices with respect to size of CFL loads at different coupling point. The obtained results show THD_v in the network ranges from 0.06% to 8.29%, with the lowest distortion recorded at PCC1 and highest at PCC 4 for every cluster size. Evidently, the simulation results are justified with theoretical explanations based on Ohm's law given in (4) as the greater impedance of the feeder, the higher the amount of voltage distortion. Since PCC 4 is the farthest point away from the main supply, so it accounts for the largest impedance in the network. Therefore the THD_v recorded at this point with the maximum size of CFL cluster is the highest. Overall, it can be concluded that the amount of THD_v is a function of load current, harmonic distorted currents and system impedance. The point of connection of harmonic-infested load in the network will determine the amount of distorted harmonic voltage at the chosen PCC.

In this part, the THD_i results were also investigated at PCC 1, PCC 2 and PCC 3 during the simulation. Clearly, the current harmonic distortion shows the highest magnitude at low voltage feeder which is PCC 4 where the harmonic currents initiated. On contrary, the lowest magnitude of current distortion is recorded at PCC 1. Primarily, this is due to the attenuation since PCC 1 is the most distant point from where the harmonic current sources are located. Using the same concept, it can easily clarify the reason for THD_i in PCC 3 is higher than PCC 2.

On additional note, Table 3 also indicates amplification in harmonic current distortion with increasing size of CFL loads for every PCC except for PCC 4 which is against the prior finding. It can be seen that the increment trend is not similar and unpredictable. A possible explanation to this variation is the effect of X/R ratio which is the ratio of the system reactance to resistance. In the network model, each PCC is identified with different level of voltage and accordingly its X/R ratio also has different value. The differences in X/R ratio will possibly cause diversity effect which harmonic currents with different phase angles are formed resulting with variation in harmonic spectrum. Eventually, it can be concluded the severity of harmonic current distortion is not purely dependent on the size of harmonic sources but also on attenuation factor and diversity factor of the network.

Table 3. THD_v and THD_i at all PCCs with varying CFL clusters

	PCC 1		PCC 2		PCC 3		PCC 4	
No of clusters	%THDv	%THDi	%THDv	%THDi	%THDv	%THDi	%THDv	%THDi
10	0.06	3.67	0.07	16.03	0.18	41.00	1.66	78.21
20	0.07	6.95	0.11	24.80	0.34	43.80	3.31	78.19
30	0.09	9.88	0.16	29.99	0.51	44.78	4.96	78.19
40	0.10	12.50	0.20	33.34	0.68	45.28	6.62	78.18
50	0.13	14.85	0.25	35.66	0.85	45.59	8.29	78.19

5. CONCLUSION

It is found that increasing the generation of harmonic currents from purely similar group of harmonic source causes varying reaction to the network. The simulation results indicate the magnitude of harmonic current does not vary significantly with an increase in harmonic sources as the THD_i remains at 78% for the chosen point of observation. However, voltage distortion or THD_v shows significant increment between 1.66% and 8.29% when the size of harmonic sources is increased five times larger. The severity of voltage distortion at other coupling points is directly determined by its equivalent impedance. The results show THD_i varies between 3.67% and 78.19% while THD_v varies between 0.06% and 8.29%, with the lowest recorded at PCC far from harmonic sources and the highest at PCC near to harmonic sources. It is clear, the installation of CFLs in large quantities profoundly reduces the power quality in terms of harmonic distortion especially at low voltage network.

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REFERENCES

[1] A. Tanushevsk and S. Rendevski, “Energy efficiency comparison between compact fluorescent lamp and common light bulb,” *European Journal of Physics Education*, vol. 7, no. 2, pp. 21–27, 2016, doi: 10.20308/ejpe.88140.

[2] N. Hudallah, Isdiyarto, S. Sukamta, P. K. Nashiroh, M. Harlanu, and S. Purbawanto, “Comparison of CFL lights and led lights reviewed from the side of the price, strong light and heat caused,” *IOP Conference Series: Earth and Environmental Science*, vol. 700, no. 1, pp. 1–9, 2021, doi: 10.1088/1755-1315/700/1/012014.

[3] T. Abergel, K. Lane, and Y. Monschauer, “Global lighting sales, historical and in the Net-Zero Scenario, 2010-2030,” *IEA Tracking Report*, 2021.

[4] J. R. -Fuelagán, J. E. C. -Becerra, and F. E. Hoyos, “Power factor correction of compact fluorescent and tubular LED lamps by boost converter with hysteretic control,” *Journal of Daylighting*, vol. 7, no. 1, pp. 73–83, 2020, doi: 10.15627/jd.2020.6.

[5] A. S. Koch, J. M. A. Myrzik, T. Wiesner, and L. Jendernalik, “Harmonics and resonances in the low voltage grid caused by compact fluorescent lamps,” in *Proceedings of 14th International Conference on Harmonics and Quality of Power - ICHQP 2010*, 2010, pp. 1–6, doi: 10.1109/ICHQP.2010.5625425.

[6] R. A. Jabbar, M. Akmal, M. A. Masood, M. Junaid, and M. F. Akram, “Voltage waveform distortion measurement caused by the current drawn by modern induction furnaces,” in *2008 13th International Conference on Harmonics and Quality of Power*, 2008, pp. 1–7, doi: 10.1109/ICHQP.2008.4668764.

[7] V. E. Wagner *et al.*, “Effects of harmonics on equipment,” *IEEE Transactions on Power Delivery*, vol. 8, no. 2, pp. 672–680, 1993, doi: 10.1109/61.216874.

[8] M. S. Bajwa, A. P. Memon, J. A. Ansari, and M. T. Bhatti, “An experimental investigation based on mathematical and software modeling of total harmonic distortion in personal computer,” *Bahria University Journal of Information and Communication Technologies*, vol. 9, no. 1, pp. 62–73, 2016.

[9] M. J. H. Rawa, D. W. P. Thomas, and M. Sumner, “Experimental measurements and computer simulations of FL and CFL for harmonic studies,” in *2014 UKSim-AMSS 16th International Conference on Computer Modelling and Simulation*, 2014, pp. 335–339, doi: 10.1109/UKSim.2014.13.

[10] A. Kalair, N. Abas, A. R. Kalair, Z. Saleem, and N. Khan, “Review of harmonic analysis, modeling and mitigation techniques,” *Renewable and Sustainable Energy Reviews*, vol. 78, pp. 1152–1187, 2017, doi: 10.1016/j.rser.2017.04.121.

[11] A. B. Yildiz and E. Unverdi, “Simplified harmonic model for full wave diode rectifier circuits,” *Automatika*, vol. 55, no. 4, pp. 399–404, 2014, doi: 10.7305/automatika.2014.12.464.

[12] M. McCarty, T. Taufik, A. Pratama, and M. Anwari, “Harmonic analysis of input current of single- phase controlled bridge rectifier,” in *2009 IEEE Symposium on Industrial Electronics & Applications*, 2009, pp. 520–524, doi: 10.1109/ISIEA.2009.5356404.

[13] A. P. Memon, A. Zafar, M. U. Keerio, W. A. Adil, and A. A. A, “Experimental study and analysis of harmonics generation in uncontrolled and controlled rectifier converters,” *International Journal of Scientific & Engineering Research*, vol. 5, no. 1, pp. 1343–1350, 2014.

[14] M. U. Keerio, M. S. Bajwa, A. S. Saand, and M. A. Memon, “Harmonics measurement in computer laboratory and design of passive harmonic filter using MATLAB,” *International Journal of Advanced Computer Science and Applications*, vol. 8, no. 12, pp. 240–247, 2017, doi: 10.14569/IJACSA.2017.081230.

[15] C. Venkatesh and D. S. Kumar, “Modelling of nonlinear loads and estimation of harmonics in industrial distribution system,” *Fifteenth National Power Systems Conference (NPSC), IIT Bombay*, vol. 2, pp. 592–597, 2008.

[16] A. Singhal, D. Wang, A. P. Reiman, Y. Liu, D. J. Hammerstrom, and S. Kundu, "Harmonic modeling, data generation, and analysis of power electronics-interfaced residential loads," in *2022 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2022, pp. 1–5, doi: 10.1109/ISGT50606.2022.9817492.
[17] G. M. -Carvajal, C. F. M. Almeida, C. Duarte, G. O. -Plata, and N. Kagan, "Nonintrusive optimal parameters estimation for a switch mode power supply equivalent circuit model: 120 V 60 Hz CFLs case study," *Energy and Buildings*, vol. 253, p. 111488, 2021, doi: 10.1016/j.enbuild.2021.111488.
[18] G. A. Malagon, J. B. Peña, G. O. Plata, and C. D. Gualdrón, "Analytical and experimental discussion of a circuit-based model for compact fluorescent lamps in a 60 Hz power grid," *Ingeniería e Investigación*, vol. 35, pp. 89–97, 2015, doi: 10.15446/ing.investig.v35n1Sup.53618.
[19] "Modeling and simulation of the propagation of harmonics in electric power networks. I. concepts, models, and simulation techniques," *IEEE Transactions on Power Delivery*, vol. 11, no. 1, pp. 452–465, 1996, doi: 10.1109/61.484130.
[20] F. Z. Peng, "Harmonic sources and filtering approaches," *IEEE Industry Applications Magazine*, vol. 7, no. 4, pp. 18–25, 2001, doi: 10.1109/2943.930987.
[21] A. Skamyin, A. Belsky, V. Dobush, and I. Gurevich, "Computation of nonlinear load harmonic currents in the presence of external distortions," *Computation*, vol. 10, no. 3, pp. 1–15, 2022, doi: 10.3390/computation10030041.
[22] N. R. Watson, T. L. Scott, and S. Hirsch, "Implications for distribution networks of high penetration of compact fluorescent lamps," *IEEE Transactions on Power Delivery*, vol. 24, no. 3, pp. 1521–1528, 2009, doi: 10.1109/TPWRD.2009.2014036.
[23] J. C. -Sola and M. Salichs, "Study and characterization of waveforms from low-watt (<25W) compact fluorescent lamps with electronic ballasts," *IEEE Transactions on Power Delivery*, vol. 22, no. 4, pp. 2305–2311, 2007, doi: 10.1109/TPWRD.2007.899551.
[24] L. Sainz, J. Cunill, and J. J. Mesas, "Parameter estimation procedures for compact fluorescent lamps with electronic ballasts," *Electric Power Systems Research*, vol. 95, pp. 77–84, 2013, doi: 10.1016/j.epsr.2012.09.001.
[25] W. D. Ray, D. R. Brillinger, and P. R. Krishnaiah, "Handbook of statistics, vol. 3: time series in the frequency domain.," *Journal of the Royal Statistical Society. Series A (General)*, vol. 147, no. 5, pp. 697–698, 1984, doi: 10.2307/2981704.
[26] H. Houassine, S. Moulahoum, N. Kabache, H. Houassine, and N. Kabache, "Harmonics generated by compact fluorescent lights : diagnostic and shunt active filtering," *WSEAS Transactions on Electronics*, vol. 8, pp. 91–99, 2017.

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