Sohel UDDIN, Hussain SHAREEF, Azah MOHAMED, Mahammad A HANNAN

Dept. of Electrical, Electronic & Systems Engineering, Universiti Kebangsaan Malaysia

Harmonics and thermal characteristics of low wattage LED lamps

***Abstract**. This paper presents harmonics and thermal characteristic of Light Emitting Diode (LEDs) Lamps which are used in residential and commercial applications as energy efficient lighting bulbs. It is done by performing experimental tests on various LED lamps available in the market. The current drawn by several LED lamps are first measured to investigate the electrical characteristics. These measurements provide current harmonic characteristic of individual lamps. Then various configurations of LEDs were connected to a laboratory scale feeder to analyze the diversity factors. Furthermore, heat generation levels of the tested LED lamps are investigated to measure the thermal characteristics of LED lamps. The results show that individual LED bulbs produce considerable amount of harmonics but it could be reduced by combining various types of LED bulbs. Furthermore, the diversity factor could be improved if LED lamps are mixture with Compact Fluorescent Lamps (CFLs). Results also shows that the thermal characteristic of LED lamps is much better compare to the performance of CFLs.*

***Streszczenie.** W artykule przedstawiono analizę harmonicznych oraz charakterystyki termiczne żarówek z diodami LED, stosowanymi komercyjnie w lampach. Badania przeprowadzono na losowo wybranych lampach dostępnych na rynku. Wskazano rozwiązania mogące zredukować ilość generowanych harmonicznych. (**Charakterystyka harmonicznych i termiczna żarówek małej mocy z diodami LED**)*

Keywords: LEDs, CFLs, Harmonic Distortion, Diversity factors, Power quality.
Słowa kluczowe: LED, CFL, zakłócenia harmonicznymi, jakość energii, współczynnik niejednoczesności.

Introduction

Recent research reports highlight that, Light Emitting Diode Lamps (LEDs) has almost 2 times better efficiency compared to Compact Fluorescent Lamps (CFLs) and 8 to10 times more efficient then incandescent lamps. Also the life time of LED is much longer than other types of lamp and they are environmentally friendly due to absence of mercury inside the LED lamps.

However, like CFLs, a compact AC/DC converter should be used in the lighting fixture to supply DC current to LED chips which introduce nonlinearity to the system. Due to the non-linear characteristic, LED bulbs produce highly distorted currents [1]. This distorted current can penitrate into the power system network. Although the input power of a single LED bulb is quite low, a large number of customers using LED bulbs and CFLs per premises could create significant power quality problems [2].

A large number of studies were conducted on LED lamps as an energy efficient lamp but most of the researchers pay their attention on the internal ballast circuit design and enhancing their performance [3-6]. Several other researchers have concentrated on light distribution and visual performance of LED lamps [7-10]. A few contributions focus on harmonic emissions of LEDs lamps [1], [11]. It is found that most of the new design of LEDs with lower power rating (<25 Watt) have a power factor (PF) up to 0.6 and current total harmonic distortion (THD_I) between 100-140 % [1], [11]. Even if the individual effect is very small on a distribution feeder, a large number of LED lamps connected to a single feeder may introduce considerable harmonic current distortion and power quality problems. But it should be noted that arithmetic sum of individuals may lead to wrong estimation of current harmonic distortion levels. Therefore it is necessary to measure the diversity factors to know the impact of large number of LED lamps on power quality. Diversity factor is defined as [12],

(1) $$DF_n = \frac{\textit{Vector sum of current harmonic (as measured)}}{\textit{Aretmetic sum of current harmonic (as calculated)}}$$

where: DF_n – Diversity factor.

Among other issues of LED, the heat dissipation and thermal degradation of efficiency are probably the two most important ones [13]. It is also known that the efficiency and reliability of LED strongly rely on successful thermal dissipation due to it’s inherit low junction temperature in the LED chip. For this reason, several studies have been reported in the thermal design and management of LED bulbs [14-15]. Since, the junction to thermal resistance is an important factor, [13] have discussed about junction thermal resistance and configuration of heat sinks. In a related work in [16], a LED junction temperature measurement technique was introduced for LED lighting system which can measure accurate junction temperature for LEDs. These measurements are important to know the reduction of device luminosity and extra power consumption due to heat generation in air-conditioned buildings [13]. Therefore, a quantitative understanding of the heat dissipation of LED will be helpful for designers to determine if LED is suitable for a particular application and compare LEDs and CFLs, in terms of their thermal and luminous performance.

This paper investigates the electrical and thermal characteristics of LED lamps. This is characterized by measurement tests, using various available LED bulbs in the market. In the investigations, a total of 35 pieces with different ratings from 7 different manufactures (brands) are observed. The electrical tests are carried out to observe their current and voltage waveforms. The characteristics are also compared for their performance with equivalent CLFs harmonics and with IEC 61000-3-2 harmonic standard. This paper also discusses the results of heat measurements obtained from the tested lamps.

Harmonic standard of LED lamps

Similar to any other appliances, LED lamps also must comply with several directives which are applicable to the product. The IEC 61000-3-2 standard assesses and sets the limit for equipment that draws input current ≤16A per phase [17-18]. Harmonic emission limits for lamps are subdivided based on their active power up to 25W and above. Lamps having an active input power less than or equal to 25W must satisfy at least one out of the two following criterions. One of the criteria is that the third harmonic current should not exceed 86% of the fundamental and the fifth harmonic current should not exceed 61%. This gives the value of the current THDi approximately equal to 105%. The recommended voltage distortion limit for class C equipment is 3% and 5% for individual harmonics and total harmonic distortion (THD_V) respectively.

The other criterion is given as a Table 1 for each harmonic order, where limits are expressed as absolute currents per one watt of active power (mA/W).

Table 1. IEC 61000-3-2 limits for class C equipment (P ≤ 25W)

Harmonics [n]	Class C
	[% of fundamental]
3	30 x PF
5	10
7	7
9	5
11	3
13	3
15 ≤n ≤39	3

Experimentation

To analyse the characteristics of the LED lamps, 12 samples of with different power ratings from various manufacture, as shown in Table 2, were tested for harmonics and heat generation. The lamps have build in ballast which is powered using E-27, E-14 or GU-10 type sockets, commonly available in retail stores. All the tested lamps are designed to operate at 220-240 V and have power consumptions rating of 3 W to 8 W.

Table 2. Technical data for tested LED bulbs

Trade name	Type of lamp	Nominal power P [W]	Power factor [PF]	Life span [Years]
Philips Cool Daylight	LED	4.0	0.69	25
Philips Warm Daylight	LED	5.0	0.71	25
Philips Cool Daylight	LED	7.0	0.72	25
Osram Daylight	LED	4.0	0.48	25
Osram Warm White	LED	4.5	0.47	25
Osram Daylight	LED	6.0	0.50	25
Osram Warm White	LED	8.0	0.79	25
Toshiba Cool White	LED	5.5	0.58	30
Bright cool White	LED	5.0	0.46	6
Cash Warm White	LED	7.0	0.48	20
Evenzo Cool White	LED	3.0	0.47	18
Philips Genic	CFL	5.0	0.56	4
Osram Duluxstar	CFL	5.0	0.59	3

Harmonic measurement procedure

To obtain accurate data concerning the exact current harmonic content of LED bulbs, an experimental setup as shown in Fig. 1 is assembled. It consists of four components namely, Fluke 434 power quality analyzer, Fluke i30s current clamp, LED bulb(s) under test, and a personal computer to analyze the signals. Before conducting tests with group of lamps, measurement on individual lamps was performed to obtain harmonic and other characteristic. Each lamp is kept switched on for 10 minutes before the measurements are taken for stabilization. Each lamp is tested for four times to eliminate any error during different period of the day. The captured current waveforms were analyzed by using Fluke 434 and MATLAB software. Similar tests were conducted for group of lamps to calculate the diversity factor of various lamp groups using (1). Furthermore, for comparisons purposes, 2 samples of CFLs indicated in Table 2 are also tested using the same procedure.

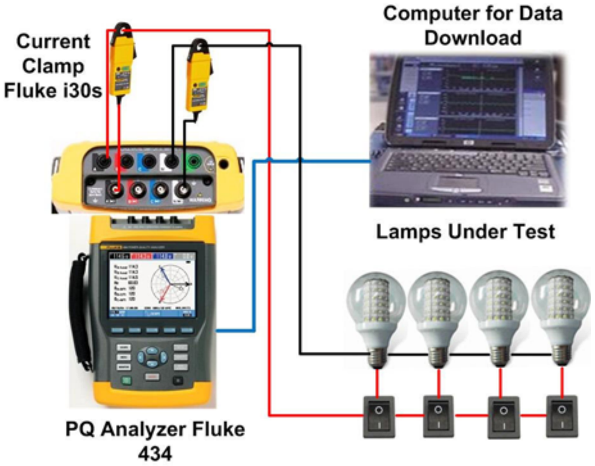

Fig.1. Experimental setup for harmonics

Heat measurement procedure

To measure heat generation from LED lamps, an experimental setup as shown in Fig. 2 is designed. It contain a fluke thermal imager (TI-32 model) and the test lamp placed at a distance of 1 meter apart. The lamp was switch on for 1 hour before take data for stabilization. The surrounding temperature is kept at 27 ^{o}C initially. Each lamp is tested for three times to eliminate any error during day and night.Then the capture image by the thermal imager is possessed by Microsoft Visio. In the images, the temperature scale is indicating on the right side of each figure. Part indicated without the colormapping in the image means maximum temperature and the colures show different level of lower temperatures.

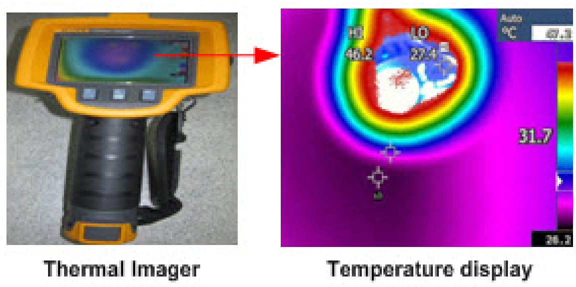

Fig.2. Experimental setup for thermal characterization

Results

In this section, measurements of various test conducted on LED lamps and CFLs are analyzed and discussed. The lamp current waveforms were analyzed using the Fourier Theorem. It provide frequency spectrum of the lamp currents represented by the fundamental sinusoidal component and a series of higher order harmonic components at frequencies that are integer multiples of the fundamental frequency. The square roots of the sum of the amplitudes of the harmonic present the total harmonic distortion (THD).

Harmonic characteristic of individual lamps

The purposes of these tests are to get an insight about the harmonic generation levels from different LED lamps. The typical current waveforms illustrated in Fig. 3 are obtained from different lamps tested. From the figure it can be noted that the current waveforms is not sinusoidal. It means that they inject harmonic into the power system. Furthermore the figure also indicates that dissimilar LED bulbs use different filtering methods to reduce harmonic generation. For example, most of the Phillips brand LED bulbs tested utilize the Valley-filled circuit, the Toshiba 5.5 W lamp contains a passive filter, Osram 8 W sample embed an active filter, and some other tested lamps does not implement any filtering technique.

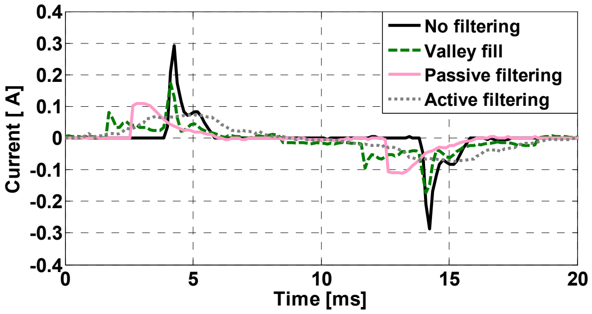

Fig.3. Various types of current waveforms obtained from different tested LED bulbs

To demonstrate further, relative harmonic currents of all tested lamps are presented in Table 3. Note that some of the tested LED bulbs generate quite a high level of harmonic which produce unacceptable limits of harmonics when referred to IEC 61000-3-2 standard described earlier. From Table 3, it can be noted that lamps having the trademark of Philips, have THD_I values between 63 to 65, while Osram brand LED bulbs with power rating less than 6 W produce high levels of harmonics which is in the range of 173 to 175 % THD_I.

Table 3. Harmonic contents of single LED lamps

Tested lamp	Harmonic [%]				
	Fund	3^{rd}	5^{th}	7^{th}	THD_I
Philips 4 W	100	34.61	6.28	22.27	63.05
Philips 5 W	100	36.92	7.16	19.81	63.83
Philips 7 W	100	32.34	11.60	23.40	64.23
Osram 4 W	100	89.24	70.65	51.19	173.92
Osram 4.5 W	100	91.72	77.47	59.43	157.76
Osram 6 W	100	91.96	77.05	58.51	174.37
Osram 8 W	100	22.25	15.04	2.34	30.94
Evenzo 3 W	100	90.70	77.34	58.89	164.45
Bright 5 W	100	86.65	75.92	61.75	167.25
Cash 7 W	100	91.23	74.81	56.41	168.22
Toshiba 5.5 W	100	73.40	45.40	35.62	106.34

This is because these LED bulbs do not use any filter in their ballast circuit. However, in case of 8 W Osram LED lamps, it produce the lowest THD_I which is in the rage of 30 to 35 %. The current wave form and harmonic spectrum of tested Phillips and Osram lamps are shown in Figs. 4 and 5 respectively. From Fig. 4, it is clear that the current waveforms of different wattage lamps have same characteristics although the magnitude of current increases with the increase of power rating. This also observed for the case of Osram lamps in Fig. 5, if the lamp uses same ballast circuit. Fig. 5(b) depicts the harmonic spectrum of these lamps. It is noticed that the magnitude of harmonic current is decreased with increasing harmonic order and their magnitudes are comparable with each other for different wattage lamps. All other tested lamps have similar observation and their THD_I values are greater than 100 as seen in Table 3.

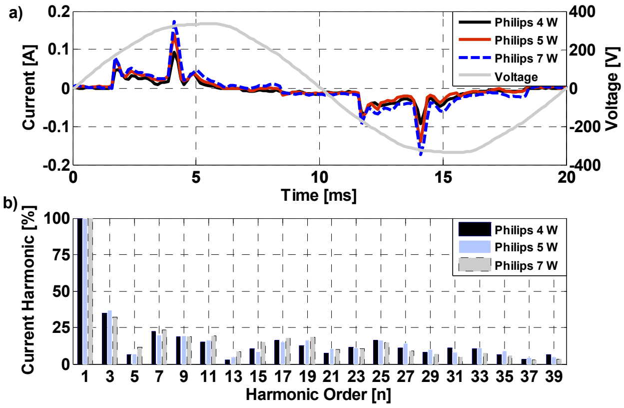

Fig.4. Test results of Philips 4 W, 5 W, 7 W LED bulbs: (a) Lamp current and voltage waveforms (b) Individual harmonic spectrum

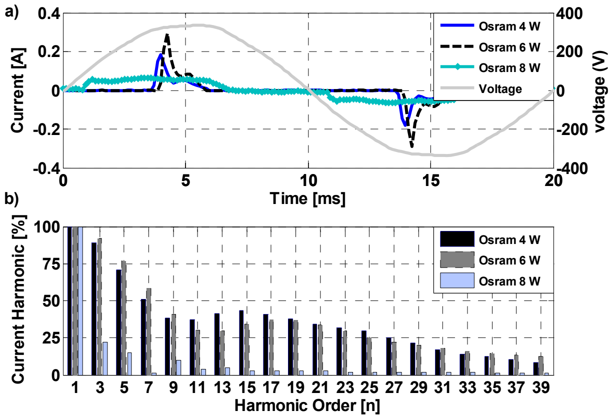

Fig.5. Test results of Osram 4 W, 6 W, 8 W LED lamps: (a) Lamp current and voltage waveforms (b) Individual harmonic spectrum

Harmonic characteristic of multiple lamps

The aim of these tests is to investigate the effect of harmonic characteristic from group of LED lamps. For this purpose, the diversity factors of various groups of lamps are measured. A small value of diversity factor indicates that a significant amount of cancellation occur because of superposition of individual current wave shapes. The diversity factors of different group of LED lamps are presented on Table 4. From Table 4, note that Combination-A have a diversity factor of 0.83 while combination-D shows much lower diversity factor which is equal to 0.72. That means combination-A with 3 lamps produces more harmonic than Combination-D with 7 lamps. This shows that the diversity factor decreases with increasing number of lamps.

To further investigate, diversity factors of individual harmonic orders are plotted for Combination-A and D as shown in Fig. 6 and 7. In this case, only odd order harmonic are presented because even order harmonic are almost zero. From Fig. 6, it can be noted that diversity factor for all harmonic orders are greater than 0.5 for Combination-A while for the Combination-D shown in Fig 7, diversity factors for individual harmonic orders are much lower and falls below 0.5 starting from 19^{th} order harmonic. Therefore, Combination- A is more problematic than Combination-D.

Table 4. Diversity factors of several groups of LED lamps

Combination	Lamps	Diversity factors
A	Philips 4 W, Osram 4 W, Bright 5 W	0.83
B	Philips 7 W, Osram 4.5 W, Osram 6 W, Bright 5 W, Evenzo 3 W	0.77
C	Philips 7 W, Osram 4.5 W, Bright 5 W, Cash 7 W, Evenzo 3 W	0.78
D	Philips 7 W, Osram 4.5 W, Osram 6 W, Bright 5 W, Toshiba 5.5 W, Cash 7 W, Evenzo 3 W	0.72

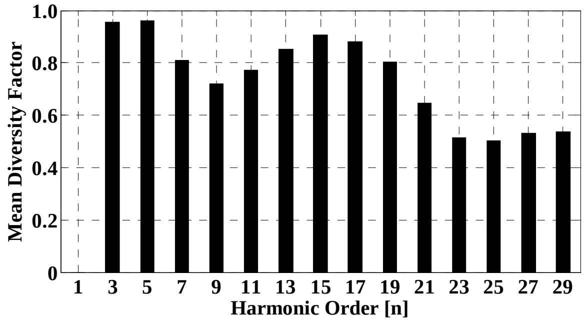

Fig.6. Diversity factors of different harmonic orders for Combination-A

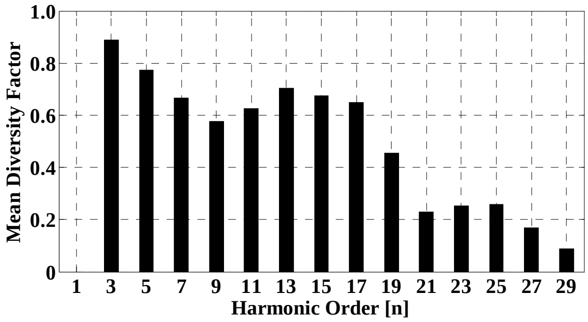

Fig.7. Diversity factors of different harmonic orders for Combination D

A second test is conducted to observe the effect of same wattage LED lamps with same trademark when they are connected in groups. Tables IV and V show the results of a group of 5 W and 4 W LED lamps from Phillips and Osram. From Tables V and VI it can be observed that, there is no effect of adding more LED lamps in the circuit on harmonic generation. This is because the wave shapes generated by adding similar lamps is unaffected except the magnitude of current drawn from the system. Similar observation is obtained when the lamps with different power is combined from the same manufacturer considering the type of ballast used. As a result, diversity factor is not affected for those cases and the diversity factor will be close to 1.

Table 5. Harmonic contents of group of 5 W LED lamps from Philips

No. of lamps	Power P [W]	Harmonic [%] Fund	3^{rd}	5^{th}	7^{th}	THD_I
1	5	100	35.3	11.0	18.5	64.1
2	10	100	35.7	11.2	17.0	64.5
3	15	100	35	12.1	18.7	62.3

Table 6. Harmonic contents of group of 4 W LED lamps from Osram

No. of lamps	Power P [W]	Harmonic [%] Fund	3^{rd}	5^{th}	7^{th}	THD_I
1	4	100	91.4	74.2	54.9	174.1
2	8	100	92.1	77.8	59.9	174.6
3	12	100	89.1	70.8	51.0	173.2

Since CFLs are the most commonly used energy efficient lamps today, it is important to compare the performance of new LED lamps with CFLs in terms of diversity factor. Therefore, a third test is conducted to observe the effect of combinations of various LED lamps with CFLs. For this purpose, two additional CFLs are connected to Combination-B and C shown in Table 4. Table 7 shows the results of adding the CFLs with LED lamps to the test feeder. From Table 7, it can be noted that the diversity factor for Combination-B reduced to 0.64 from 0.77 as shown in Table 4. The same property is seen from Table 7 for combination-C. Therefore, it can be concluded that large number of lamps together with CFLs and LED bulbs can reduce the diversity factor and harmonic injection the power system.

Table 7. Diversity factors of several groups of CFLs and LED lamps

Combination	LEDs	CFLs	Diversity factors
B	Philips 7 W, Osram 4.5 W, Bright 5 W, Evenzo 3 W	Philips 5 W, Osram 5 W	0.64
C	Philips 7 W, Osram 4.5 W, Bright 5 W, Cash 7 W, Evenzo 3 W	Philips 5 W, Osram 5 W	0.66

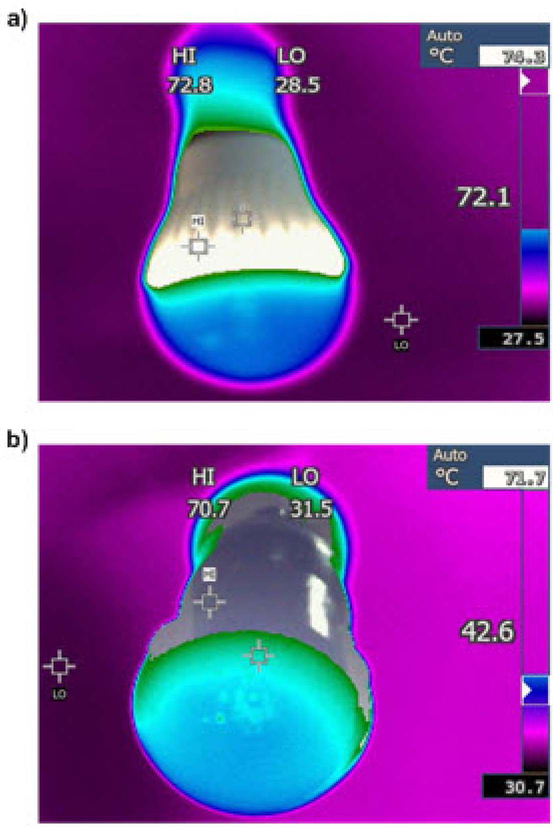

Fig.8. Thermal measurement (a) Philips 7 W (b) Osram 4 W

Thermal measurement of LED Lamps

The purpose of this test is to analyze the heat dissipation from LED Lamps. A sample image obtained from a 7-W Philips lamp is shown in Fig 8 to demonstrate the thermal property of this lamp. From figure, it can be seen that some part of this bulb can reach 72.8^{o}C which is recorded at the surface of the heat sink of the lamp. The ballast circuit is situated inside heat sink and thus may affect the life of the bulb depending upon heat the ballast circuit is subjected to. However, the glass surface enclosing the LED in all tested lamp shows the lowest heat level. Similarly, the same test has been conduct for other lamps and the results are tabulated in Table 8 and Fig 9. It is found that the behavior of all other lamps is similar like the one presented above. From Table 8 and Fig.9, it is clear that, Philips brand LED lamps dissipate less heat than other manufacturers in terms of same wattage rating. Note that all other lamps dissipate heat between 60 to 85 ^{o}C so this indicate that all lamps have efficient heat dissipation mechanisms and thus does not reduce the device luminosity significantly.

Table 8. Compression of heat dissipation of LED lamps

Tested lamp	Temperature [^{o}C]
Philips 4 W	58.0
Philips 5 W	62.7
Philips 7 W	72.8
Osram 4 W	70.7
Osram 4.5 W	55.1
Osram 6 W	73.0
Osram8 W	86.0
Cash 7 W	65.1
Toshiba 5.5 W	60.0
Bright 5 W	73.5
Evenzo 3 W	70.9

Comparison of thermal characteristics of LED lamps and CFLs

Since CFLs are the most commonly used energy efficient lamps today, it is also important to compare the performance of new LED lamps with CFLs in terms of heat generation. For this purpose, two 5 W CFLs namely Philips and Osram brand was tested. Fig. 10 illustrates the thermal characteristic obtained for Phillips lamps. It can be noted from Fig 10 that Philips 5 W CFLs generate 107 ^{o}C while the 5 W LED lamps produce around 63 ^{o}C. Furthermore, it is clear that the maximum heat is generated at the glass surface of the tube in case of CFLs while in LED lamps maximum heat is recorded at the surface of heat sink. Therefore, LED lamps produce less heat and have better mechanism to dissipation heat compare to CFLs.

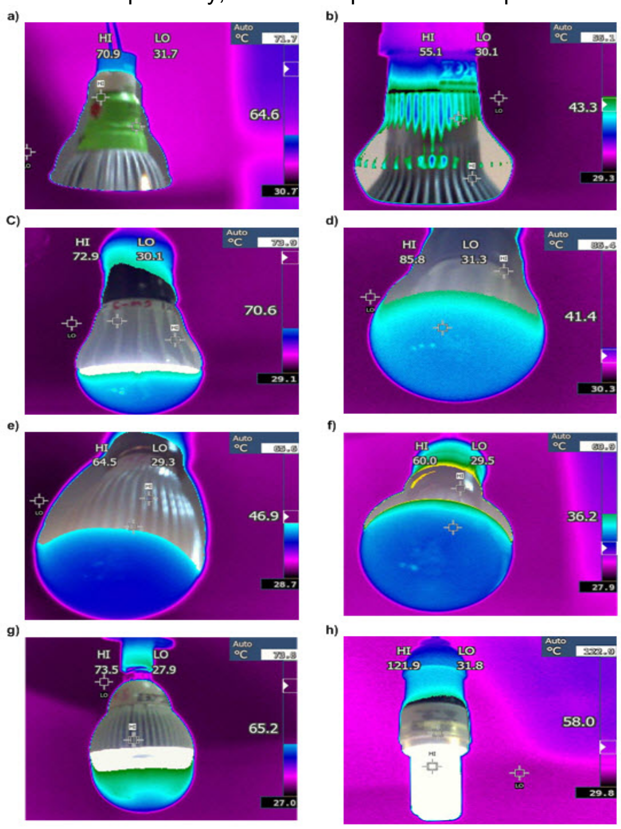

Fig.9. Evenzo 3 W, Osram 3 W, Osram 6 W, Osram 8 W, Cash 7 W, Toshiba 5.5 W, Bright 5 W, CFL-Osram 5 W

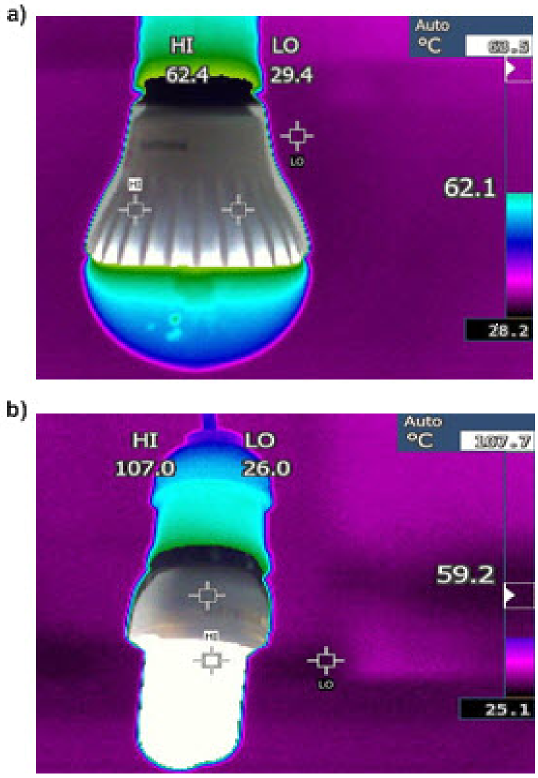

Fig.10. Thermal measurement Philips 5 W(a) LEDs (b) CFLs

Conclusion

This paper has presented several experimental results of current harmonic distortion and analyzes the effect of diversity factors for energy efficient LED lamps. In the experiments various types of LED lamps from different manufactures were tested. It is found that LED lamp's diversity factors become smaller if a larger amount of LED lamps from various brands are connected. Low diversity factor indicates low harmonic injection to the system. However, it is found that group of lamps with same model will not reduce diversity factor and harmonic distortion. Moreover, the comparison of diversity factors of LED lamps with CFLs indicates that a mixture of CFLs with LEDs can further reduce the diversity factor and hence harmonic injection. Therefore it is recommended to use LED lamps and CFLs together in lighting applications to reduce power quality problems. Furthermore, heat generation levels from CFLs and LED lamps were also investigated. It is seen that, all LED bulbs produce heat between 60-85 ^{o}C and highest heat is concentrated at heat sink. On the other hand, CFLs generates heat above 100 ^{o}C and it is observed at the surface of the class tube.

Acknowledgment

This work was carried out with the financial support from the Ministry of Higher Education of Malaysia (MOHE) under the research grant UKM-KK-02-FRGS0193-2010.

REFERENCES

[1] Blanco A.M., Parra E.E., Effects of High Penetration of CFLs and LEDs on the Distribution Networks, *14th International Conference on Harmonics and Quality of Power* (*ICHQP),* (2010), 1-5

[2] Dwyer R., Khan A.K., McGranaghan M., Tang L., McCluskey R.K., Sung R., Houy T., Evaluation of harmonic impacts from compact fluorescent lights on distribution systems, *IEEE Trans. Power System.,* 10 (1995), No. 4, 1772-1779

[3] Qu X., Wong S.C., Tse C.K., Resonance assisted buck converter for offline driving of power LED replacement lamps, *IEEE Trans. Power Electron*, 26 (2011), No. 2, 532-540

[4] Chen N., Chung H.S.H., A Driving Technology for Retrofit LED Lamp for Fluorescent Lighting Fixtures With Electronic Ballasts, *IEEE Transactions on Power Electronics*, 26 (2011), No. 1, 588-601

[5] Gu L., Ruan X., Xu M., Yao K., Means of eliminating electrolytic capacitor in AC/DC power supplies for LED lightings, *IEEE Trans. Power Electron*, 24 (2009), No. 5, 1399-1408

[6] Wojtkowski W., Step – up converters for power LED power supply, *Przeglad Elektrotechniczny*, 4 (2011), 71-72

[7] Balsky M., Bayer R., Comparison of real street lighting with sodium lamps and LEDs, *Przeglad Elektrotechniczny*, 4 (2011), 17-19

[8] Kiyak I., Topuz V., Oral B., Modeling of dimmable High Power LED illumination distribution using ANFIS on the isolated area, *Expert Syst. with Application*, 38 (2011), No. 9, 11843-11848

[9] Reyes M.A., Gallagher S., Sammarco J., Evaluation of visual performance when using incandescent, fluorescent, and LED machine lights in mesopic conditions, *Annual Meeting of IEEE Industry Applications Society (IAS),* (2009), 1-7

[10] Pabjanczyk W., Sikora R., Markiewicz P., Gabryjelski Z., The influence of a road LED luminaires on the electrical power quality in a power networks, *Przeglad Elektrotechniczny*, 4 (2011), 120-123

[11] Cuk V., Cobben J.F.G., Kling W.L., Timens R.B., An analysis of diversity factors applied to harmonic emission limits for energy saving lamps, *The 14th International Conference on Harmonics and Quality of Power (ICHQP),* (2010), 1-6

[12] Mansoor A., Grady W.M., Chowdhury A.H., Samotyj M.J., An investigation of harmonics attenuation and diversity among distributed single-phase power electronic loads, *IEEE Trans. Power Delivery*, 10 (1995), No. 1, 467-473

[13] Qin Y., Lin D., Hui S.Y., A Simple Method for Comparative Study on the Thermal Performance of LEDs and Fluorescent Lamps, *IEEE Trans. Power Electronics*, 24 (2009), No. 7, 1811-1818

[14] Cheng H.H., Huang D., Lin M.T., Heat dissipation design and analysis of high power LED array using the finite element method, *Journal of Microelectronics Reliability*, in press.

[15] Luo X.B., Liu S., A microjet array cooling system for thermal management of high-brightness LEDs, *IEEE Trans. Advanced Pack.*, 30 (2007), No. 3, 475-484

[16] Qu X., Wong S.C., Tse C.K., Temperature Measurement Technique for Stabilizing the Light Output of RGB LED Lamps, *IEEE Trans. Instrumentation and Measurement*, 59 (2010), No. 3, 661-670

[17] IEEE Std 519-1992, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems, (The Institute of Electrical and Electronics Engineers, 1993)

[18] IEC Std 61000-3-2, Limits for Harmonic Current Emissions (Equipment Input Current ≤ 16A Per Phase), (Ed. 3.2, 2009)

Authors*: Sohel Uddin is a Masters student at the Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), E-mail: sohel_091@yahoo.com.*

Dr. Hussain Shareef is a senior lecturer of Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), E-mail: shareef@eng.ukm.my.

Prof. Dr. Azah Mohamed is a professor of Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), E-mail: azah@eng.ukm.my.

Dr. M A Hannan is an Associate professor of Department of Electrical, Electronic and Systems Engineering, Universiti Kebangsaan Malaysia (UKM), E-mail: hannan@eng.ukm.my.