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Original article

Demand side management perspective on the interaction between a non-ideal grid and residential LED lamps

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ABSTRACT

Lighting industries across the world are witnessing a rapid shift towards energy efficient LED (Light Emitting Diode) lightings. These lighting technologies can be seen as an alternative tool to the DSM (Demand Side Management) in residential, commercial as well as industrial sector. DSM has a strong linkage with the reliability and quality of power supply and any variations in supply conditions may significantly affect DSM strategies. As LED lighting technologies are penetrating the lighting market at a rapid pace, it is important to assess the different impacts of distribution grid conditions on the power quality and energy consumption performance of LEDs. This paper presents an extensive analysis of the consequences of sustained abnormal voltage, supply voltage harmonics, and supply frequency variations on LED lamps and its overall effect on the popular "LED lighting DSM Program" – being adopted worldwide. It was observed that under the variable grid conditions, some lamps' technologies offer DSM like advantages without being actively engaged in DSM. Several parameters have been evaluated, analyzed and, recommendations have been made for LED-based passive DSM strategies which may encompass the LED manufacturers, the utilities, and the governments.

Introduction

Continuously increasing demand of world's energy consumption has attracted the significant attention of researchers and policymakers. Electricity consumption is the fastest growing end-use energy consumption, and therefore, this area has recently been the top priority for its efficient transmission, distribution, and utilization. According to IEA, lighting sector consumes around 20% of global building electricity consumption which was around 7 exajoule (EJ) in the year 2013 [1]. This sector offers an enormous potential for electricity savings by 2030 [1]. LED-based lighting technologies are gaining popularity and acceptance as it has significant advantages over traditional lighting sources [2]. It has become one of the most common energy-efficient solutions of this era, and a number of strategies from technical to policy level are being seen to make this technology worth to the different users. It is expected that global LED lighting market share will reach around 70% by 2020 which was just around 18% in 2013 and therefore, it is important to assess this technology from different perspective before it is highly penetrated in the global lighting market.

The basic problem arising in the mass usage of LEDs is the voltage distortion in the grid network that arises because of the poor power quality of the LED lamps generated by the non-linear devices used in developing these technologies. An adverse effect is expected on the electric grid as a result of this mass replacement [3–7]. LEDs are generating high current harmonics and that are creating a significant level of voltage distortion, and therefore, it is necessary to check the LED lamps' performance when the distorted voltage being applied. In addition, it is also expected that there are several other grid conditions which can further affect the power quality and energy consumption performance of LED lamps.

The global electricity sector is transitioning towards a more sustainable future. On the way to this transition, the electricity sector is facing the two major challenges: meeting the ever-mounting demand and the fight against continuously increasing carbon emissions. The world's electricity demand is increasing at a very fast rate which was almost doubled from 1990 to 2011, and it is further expected to grow by at least 81% in the current policies scenario and 69% in the central new policies scenario from 2011 to 2035 [8]. The electricity demand is particularly increasing with the Asia, which is expected to increase by 4% per year until 2035 [8]. For instance, the current electricity demand pattern of India, the third largest economy in Asia, is still suffering from the demand-supply mismatch problem. The actual power supply position of India in the financial year 2015–16 is shown in Table 1 [9]. A deficit in terms of energy, as well as peak, could be noticed which was recorded much higher in some of the regions. This demand-supply mismatch is leading to severe low voltage problem in India [10] and, in

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Table 1
Actual power supply position of India (2015–16).

Parameter	Energy (MU)	Peak (MW)
Requirement	1,114,408	153,366
Availability	1,090,851	148,463
Shortage	23,557	4903
Deficit (%)	2.1%	3.2%

fact, some of the states are totally unreliable in terms of the standard voltage level. Some of the other countries are also suffering from low voltage problems because of increasing demand of electricity [11]. On the other hand, increased penetration of distributed generation is creating high voltage problems at the consumer end especially for the renewable-rich countries [12,13].

Finally, it is an undeniable fact that any mismatch between the demand and supply of electricity creates not only a high or low voltage problem but, an under frequency or over frequency condition at the grid level also occurs. In essence, increased demand has stressed the power system network which results in fall in frequency while on the other hand, exceeding supply than the required demand results in an increase of supply frequency and grid has to operate other than the standard operating frequency of 50 HZ or 60 HZ. Table 2 shows the operating frequency in the Northern regional grid of India where the highest variation was observed for the FY 2015–16 [14] and it suggests the need for consideration of these frequency variations while pushing the technologies like LED lighting.

To understand the effect of abnormal grid conditions, three different reputable international brands of LED lamps have been tested. Firstly, the current waveform and harmonic emissions of these lamps were analyzed. The results suggest that these three brands use different filtering techniques as part of the LED driver circuit and it can be classified into three different categories in accordance with their filtering operation which is summarized in Table 3.

Finally, three-different non-ideal grid conditions have been identified for analyzing its interaction with the three-different variety of LED lamps are: **s**ustained abnormal voltage, supply voltage harmonics and **s**upply frequency**.** These three non-ideal grid conditions have been emulated through a grid emulator. The LED lamps were connected to this emulated grid for measurement of energy consumption and, power quality performance. This study will address the lack of data and its analyses on the linkage of grid conditions, power quality, and energy consumption performance of reputable international brands of LED lamps.

The rest of the paper is organized into five different sections. Section 'Literature review' reviews the previous related work followed by a brief on the laboratory setup and emulated grid conditions in Section 'Laboratory test setup & emulated grid conditions'. Section 'Results and discussions' explains the experimental results which are followed by Section 'Analysis & Discussion from DSM perspective' where the results from the demand side management perspective have been discussed. Section 'Conclusions' is devoted the conclusion of the work.

Table 2
Operating frequency in Northern Region (2015–16).

Frequency (Hz)	% of time FY 2015–16
Maximum Instant Frequency	50.55
Minimum Instant Frequency	49.50
> 50.20	0.53
> 50.10	5.36
50.05–50.10	13.96
49.90–50.05	67.19
< 49.9	13.48
< 49.8	1.83
< 49.7	0.18

Table 3
Three different brands of LED lamps and their characteristics.

Filtering Technique	Approximate THDI Range (%)	Tested Brand of LED Lamps	Actual THDI (%)
Passive filter	100–130	B	100–120
Valley fill filter	25–40	A	30–55
Active filter	5–10	C	4–10

Literature review

Power quality issues with CFL lamps and the performance of CFL against a range of grid conditions have been undertaken by many researchers [15–21]. Power quality characteristics of demand side management with CFL lamps were first highlighted in 1993 and it was recommended that power quality should be given significant consideration in the implementation of DSM programs [17]. The energy saving benefits and the harmonic issues of CFL lamps were presented in [18]. A strong linkage has also been reported between the change in grid parameters and the performance of CFL lamps. An increase in supply voltage increases the total harmonic distortion (THD or THDI) of the lamp current [18]. The performance of CFL lamps has also been measured with the distorted voltage waveform and reported in [20]. Effect of different level of supply voltage THD as well as changing the supply wires length has been assessed on a range of CFL lamps [19]. The effect of various influence factors such as input voltage magnitude and input voltage harmonic distortion levels on CFL's performance has been examined in detail and it highlights that high-power factor CFLs are more sensitive to input voltage magnitude as compared to standard CFLs [15]. Further, the implications on the distribution lines due to high penetration of CFLs has also been studied and presented in [21]. A study on phase angle of the harmonic emission of different type of lightings also highlights that phase angle could be a part of future harmonic emission standard which will help manage the overall harmonic emissions [16].

Now, when there is a major transition towards LED lighting, a variety of research in different areas of this technology is being considered. Recent studies in LED lighting have been mainly focused on reliability, thermal output, light quality, and light distribution [22–27]. Some of the researchers have also highlighted the problem of harmonics and other power quality related issues with LED lightings [6,28–33]. LED lighting technology is also a non-linear load, and the currently available LED lamps are creating significant power quality issues. Few studies have also conducted the evaluations based on modeling of the harmonic emissions by LED lamps in distribution systems and reported that poor quality LED lamps can cause significant harmonic distortion in the distribution systems [34,35]. Similar to CFL lamps, the power quality and energy consumption performance of the LED lamps can also get affected by the variation in the grid supply conditions and therefore, it is an interesting study which needs to be carried out as there is no literature available which can fill this significant gap. The previous work in this area examines the effect of input voltage magnitude on combined CFL and LED harmonics performance and presents that the transition towards LEDs is a better option for the lighting sector [36,37]. Another work highlights the effect of voltage sag and swells on LEDs performance and explains how it could create a detrimental effect on LEDs [38]. This article is mainly focused on evaluating the performance of LED lamps against non-ideal grid conditions such as abnormal supply voltage, supply harmonics, and supply frequency variations.

Laboratory test setup & emulated grid conditions

A full test setup using the grid emulator was made in the Power System Research Laboratory of the University of Auckland, New Zealand. The setup includes the California Instruments AMETEK MX15-