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Concept of Intelligent Solid-State Street Lighting Technology

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***Abstract*—Street and road lighting consumes about ~2 % of global electric power and the trade-off between energy saving and social needs for traffic safety, crime prevention, aesthetic comfort, etc. has to be established. A wide range investigation of an intelligent solid-state street lighting system prototype equipped with LED-based luminaires, motion sensors and microcontrollers with power-line-communication interfaces was performed under real outdoor conditions. The two-level and two-zone street illumination method was implemented basing on psychophysical investigation. The decrease of efficiency under the dimming conditions and significant electromagnetic interference in the frequency range of tens and hundreds MHz were identified as limiting factors of conventional current regulating ICs and the necessity of further improvement was pointed out.**

***Index Terms*— Light emitting diodes, energy consumption, algorithm design and analysis, electromagnetic interference.**

I. INTRODUCTION

The main scope of outdoor lighting is the extension of an acceptable human life quality for the dark period of the day. Life quality comprises the accessibility of social activities, crime prevention, traffic safety, aesthetic impact, and human behaviour. On the other hand, outdoor lighting is connected to energy saving and related environmental issues. In particular, street and road lighting consumes about ~2 % of global electric power and is responsible for the annual exhaust of more than 300 million tons of carbon dioxide (CO_2) in the European Union and USA.

The first attempts of public outdoor lighting can be dated as early as to the IVth century AD in Arabia but only the XVIIth century can be considered as a beginning of the street lighting in Europe [1]. In the XIXth century the first generation of street lamps (oil lamps) were replaced by gas lamps as more cost efficient and maintenance friendly light sources. Gas lamps were used for about one hundred years until electrical light sources, mercury and low-pressure sodium (LPS) discharge lamps, were implemented. The necessity of street illumination always was contradicted by huge public expenses for energy consumption (oil, gas or electricity) and maintenance. Therefore modern, more cost and energy efficient lighting technologies are welcomed in this area.

Since the first demonstration of a light-emitting diode (LED) based street lamp [2], solid-state technology is treated as energy-efficient and reliable lighting technology that promises a significant reduction of cost for public lighting. However, the straightforward replacing of conventional luminaries with solid-state ones offers marginal economic benefits. The main reason is that LEDs have to compete with either low-pressure sodium or high-pressure sodium (HPS) lamps, which are the most efficient conventional sources of light and only recently are caught up with the most advanced LEDs in terms of photometric efficiency [3]. Another reason is a relatively high price of LED luminaires that considerably counterweights the reduced maintenance cost. Actually, unique properties of solid-state lighting, such as versatility in composing spectral power distribution, instantaneous and lossless dimming, intelligent control, and improved directionality are the key features allowing for energy-savings based on the novel street lighting technology.

Intelligent street-lighting control was demonstrated for conventional discharge lamps powered by dimmable ballasts [4], [5]. Solid-state systems have more sophisticated and advanced controllability [6]. The main principles of intelligent control involve individual luminaire dimming, which is implemented by two-way power line and/or wireless communication between the luminaires and central computer [7], [8], traffic sensors, luminance/illuminance meters, and meteorological station. However, since sodium lamps are slow in varying the output and significantly lose efficiency when dimmed [5] the LED based technology becomes unbeatable. LEDs respond to the variation of driving current on the nanosecond time scale and the efficiency and even effective lifetime of LEDs increase with reducing the average driving current due to the reduction of junction temperature [9]. The power loses in LED driving circuits due to the dimming option can be minimized by employing advanced switch-mode current regulation circuits [10]. The first two-level illuminance lighting system employing a presence sensor has been introduced together with the first prototype solid-state street lamp [2]. The further development and world-wide implementation of LED based intelligent street lighting systems relies on explicit investigation and enhancement of dimmable LED driving circuits, reliable short distance communication systems, as

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well as on psychophysical optimization of the trade-off between energy saving and social needs for traffic safety, crime prevention and aesthetic comfort.

Here we report on a wide range investigation of an intelligent solid-state street lighting system prototype equipped with LED-based luminaires, motion sensors and microcontrollers (MC) with power-line-communication (PLC) interfaces. The prototype system consisting of ten fully equipped luminaires on the poles and interconnected by PLC was implemented in the campus of Vilnius University.

II. Experimental results

The schematic design of the proposed intelligent street lighting system is depicted in Fig. 1. The concept relies on the dimming of the luminaires when neither traffic nor pedestrians are present.

The illumination level provided by the luminaires can be defined as High (e.g. 100 %) and Low (e.g. 10-20 %) meaning that when no traffic is present the level is maintained as Low and switched to High only in the adjacent zone of the traffic unit. The adjacent zone is characterized by a particular distance from the detected traffic unit or pedestrian and has High illumination, while the rest of the street is called remote zone and has Low illumination. The psychophysical investigation has revealed that the optimal length of the adjacent zone for pedestrian safety feeling is about 100 m towards the walking direction.

Each LED-based luminaire is controlled by a microcontroller that is responsible for adjusting the power of the LEDs, processing the data obtained from the motion sensors and communicating with the neighbour luminaires and central computer (if any) through the Ethernet/PLC adapter. In contrast to wireless or other control protocols, the PLC method employs AC power lines to transfer digital data at high speed. Such an approach allows the integration of intelligent lighting control without a significant renovation of existing street lighting networks and infrastructure. Furthermore, the high-frequency electrical signals are transferred through the cables and electromagnetic interference (EMI) inherent to wireless communication is avoided.

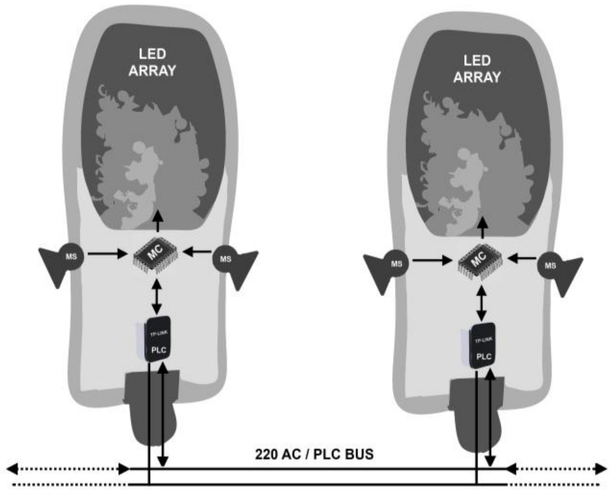


Fig. 1. Schematic design of the proposed intelligent solid-state street lighting system. MC is the microcontroller with Ethernet interface (Propox model MMnet01); MS is the motion sensors (Intelcom model Norma); PLC is the Ethernet power line communication adapter (TP-Link model TL-PA201). Two-wire power line used for both AC power supply and data transfer.

The luminaires are equipped with bidirectional motion sensors that detect the presence of pedestrians and traffic, determine the motion direction, and trigger the MC.

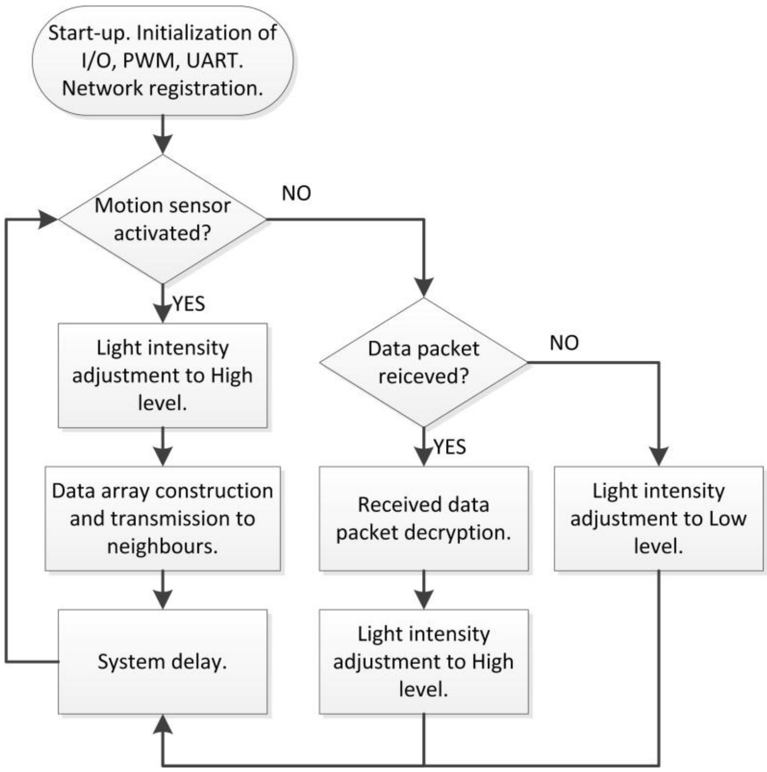


Fig. 2. Block diagram of the microcontroller's internal logical routine.

The internal logical routine of the MC is depicted in Fig. 2. After the start-up procedures, involving the initialization of I/O, network settings, etc., the continuously running loop starts. First of all, the MC checks whether traffic presence data is obtained from the own sensors or neighbour luminaries and switches to High illumination regime if YES received. After some predefined system delay, the loop restarts and continues operating. The key advantage of such a system is the operation without a central computer or central control point. The necessary data from one fixture can be transferred to another one or to several of them in the case of road crossing and *vice versa*. In parallel with traffic data, the luminaires can broadcast additional data packets informing bout the change of weather conditions (for the decrease of High illumination level when the road surface is snowy or wet [5]) or about any technical faults occurred at any point. Additional connection to the control centre through the GPRS, GSM, DSL, etc. can be implemented and used for the monitoring of the system and broadcasting of general instructions, such as weather conditions, on/off signals and etc.

In order to achieve the best economical and energy saving results, the entire street lighting system has to be optimized. Despite the fact that the main energy loses take place inside the LED junction due to non-radiative carrier recombination [9], the efficiency of LED driving circuits are of crucial importance. In contrast to the most of the conventional light sources, LEDs have to be driven by regulated DC power supplies. Usually the driving integrated circuits (ICs) are well optimized for operation in the 100 % load mode, but additional losses occur when dimming is applied. The dependences of efficiency on dimming factor of three commercial switch-mode current regulators are depicted in Fig. 3. The circuits used to measure efficiency had basic configuration recommended in manufacturer's datasheets (see, e.g. the inset in Fig. 3). One can see that each of the ICs exhibit more than 92 % efficiency when run in the full load mode. However, dimming to 50 % of the initial value results in a decrease of efficiency to 83 %, 63 % and 47 % for different ICs, respectively.

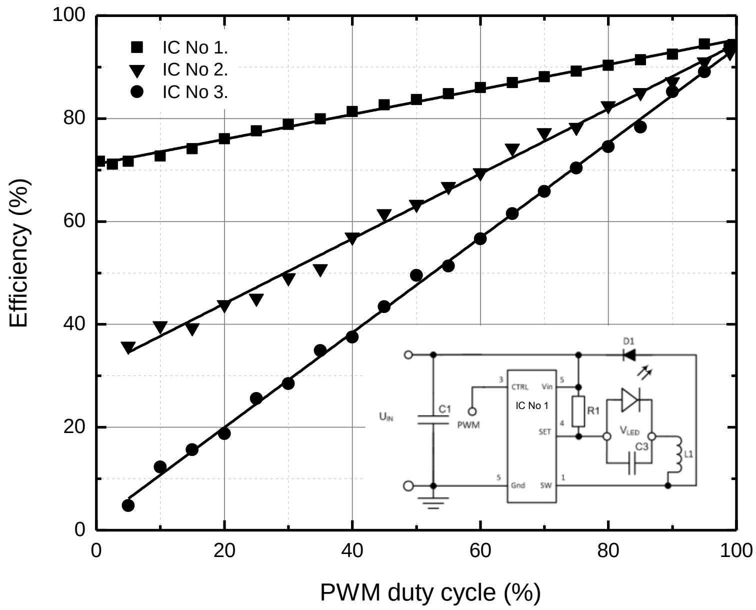
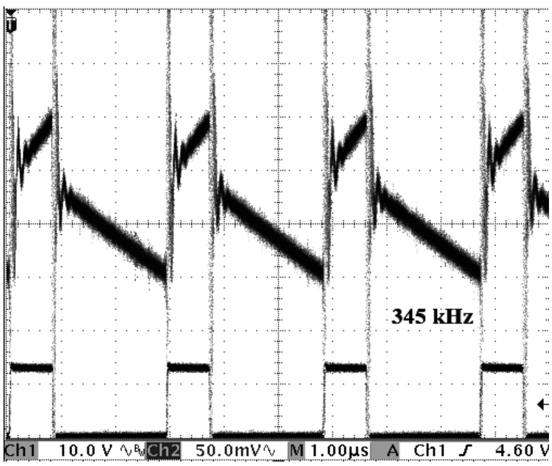


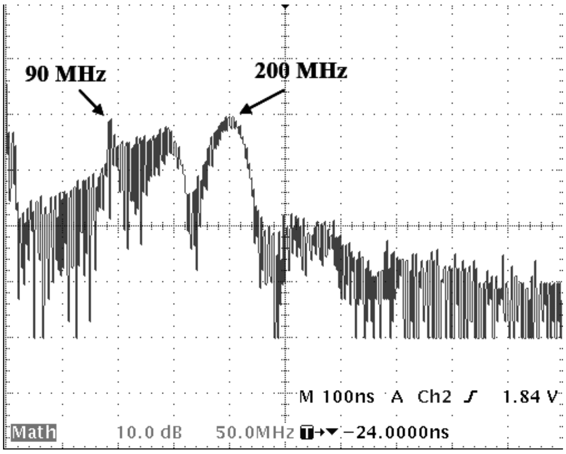
Fig. 3. Efficiency of the current regulating ICs as functions of PWM dimming duty cycle. Solid point – experimental data; dashed lines – linear eye guides; inset – circuit diagram for an IC recommended by the manufacturer.

Consequently, it is obvious that the first sample is preferential for using in the present configuration for dimmable applications with moderate efficiency, while the other two circuits have to be significantly improved and optimized.

On the other hand, the undesirable EMI is an inherent feature of switch-mode power circuits and has to be treated seriously in order to meet international regulations and standards [10]. The output oscillogram of current for the first investigated IC is depicted in Fig. 4(a) and the fast Fourier transformation (FFT) spectra of harmonics is sown in Fig. 4(b). One can see that the internal chopping frequency is in range of hundreds of kHz, while the EMI spectrum is rather wide covering tens and hundreds of MHz.



a)



b)

Fig. 4. Switching diagram of an IC LED current regulator (a) and FFT spectra (b).

Such frequencies of EMI can parasitically interact with radio broadcasting and communication signals including PLC used for luminaire control therefore it is strictly regulated by EU standards EN 61000 and EN 61326. It is believed that the implementation of proper external elements can result in a significant reduction of EMI [10], however a high attention has to be paid to the EMI issues when designing the switching LED power supplies.

III. Conclusions

A concept of an intelligent solid-state street lighting system was demonstrated in real outdoor conditions. The two-level and two-zone illumination method was implemented basing on psychophysical investigation. The limitations of conventional current regulating ICs were identified and the necessity of further improvement was pointed out.

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