

# IMPACT OF PULSE MODULATION METHOD OF LED DIMMER FOR STREET LIGHTING ON ITS EFFICIENCY

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## ABSTRACT

Wide utilization of Light Emitting Diodes (LEDs) is one of the most promising tendencies of modern lighting technologies. Implementation of LEDs ensures high efficacy of luminaries, lower power losses and, when equipped with dimmable power supplies, provides also improved functionality of the luminaries that, in turn, in principle reduces amount of energy spent for lighting purposes. However, operation of the LED luminaries depends a lot on the current regulation method implemented in the dimmer. This paper analyzes the impact of pulse modulation methods implemented with MSP430 microcontroller on the losses of the dimmer and luminary and on their efficiency.

## 1. INTRODUCTION

Constantly growing demand for electrical energy and quite questionable prospects of new sources of electrical energy make the problem of energy efficiency very topical nowadays. There are two basic ways of making the energy consumption efficient: increasing the self-efficiency of electrical equipment and avoiding its unnecessary operation (making it “smart”).

One of the most significant energy consumers is lighting. According to [1] about 19% of the electrical energy produced over the world is spent to lighting. For particular objects this percent is even higher. For example, lighting consumes about 30-40% of electrical energy in commercial buildings [2]. So it is quite reasonable to improve efficiency of lighting system. Like it was previously mentioned there are two ways: utilization of the lighting technologies that produce more light per power unit and making lighting systems smart.

Utilization of Light Emitting Diodes (LEDs) successfully combines these two ways. On the one hand modern LEDs have efficacy of several tens lumens per watt (for instance, W724C0 from “Seoul Semiconductor” ensures 700lm at 10W or 70lm/W [3]) that is comparable with high pressure sodium lamps (up to 140lm/W [4]). Of course, these data are given for stand-alone LEDs. LED luminaries produce less light, but they are still good. On the other hand it is possible to effectively dim (adjust) light of LED lamps with no negative impact on LEDs.

Amount of light produced by an LED is proportional to its current. This brings forward two light control methods: 1) fluent regulation of LEDs current and 2) Pulse Width Modulation (PWM) of the current. The second method is

undesirable because the light produced by the LED follows its current at a very high rate ([5] and [6]) which leads to flickering and stroboscopic effects. Another light regulation method is possible because of the rather low power of LEDs. Then LED luminary includes a number of LEDs and it is possible to divide them into groups and control each group separately utilizing some kind of Pulse Code Modulation (PCM). This method, however, ensures less dimming levels and lower accuracy. The above mentioned data gives preference to the current regulation.

LED itself is a low voltage DC element. Moreover, as has already been mentioned, it is better to feed LEDs with constant current of controllable value. This mostly requires DC/DC stage even if the LED luminary is fed from AC line. For this reason various DC choppers are used as the current regulators [7]: buck, boost, buck-boost and Cuk [7]. Each of these topologies is suitable for particular application. For example, for street lighting, when AC-line of rather high value is available, buck converter is suitable as a dimmer. Each of these converters may be driven in different ways. This research tries to find one ensuring the lowest losses in the dimmer.

## 2. CONFIGURATION OF MULTISECTIONAL STREET LUMINARY WITH LEDS

Very often (and in this research too) luminaries contain several strings of LEDs whose lighting has to be controlled independently. Then each section of such luminary requires its own dimming module. On the other hand, street luminaries require a rectifier and, nowadays, power factor corrector (PFC) for better quality of the input current. Then from the point of view smaller volume, mass and cost with the same functionality, it is reasonable to have one rectifier and PFC for all dimmers. This approach produces two stage power supply for the luminary (Figure 1). This paper deals with the second stage of this cascade – the dimmer.

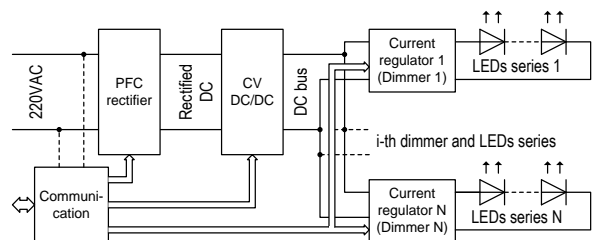


Figure 1 – Power supply for multi-sectional LED luminary.

### 3. FEATURES OF TESTBENCH

#### 3.1 Power Circuit

In the case of the two-stage configuration of the street lighting luminary it is reasonable to build the dimmer based on a step-down DC/DC converter. This converter has linear regulation characteristic that makes control loop more stable and reduces the amount of the required calculations. On the other hand, if supplied from AC grid through PFC rectifier such dimmer may ensure output voltage high enough to feed a string of LEDs (usually few tenths of volts).

Basic configuration of the step-down converter (Figure 2-a) is not convenient for direct practical utilization because the source (emitter) of its transistor has a different potential than the common wire (ground). At the same time, from a practical point of view it is convenient to tie all controls and measurements to the same common wire. For this reason the basic topology is rearranged in respect to the source of the transistor. Then it is easy to provide local power supplies to the microcontroller (MCU), driver and to a simple current measuring resistor.

However, the described approach has one significant drawback – if the current measuring resistor is also tied to the common wire it is only possible to measure current in the transistor (when it is on). This makes estimation of the output current more complicated and implementation of some control strategies inconvenient. For this reason a Hall sensor has been installed in the testbench. Altogether all the above mentioned considerations produces the configuration of the testbench shown in Figure 2-b.

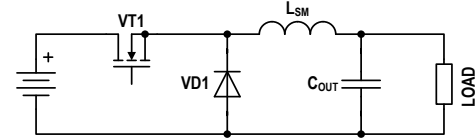
The converter has been designed to supply 7 10W LEDs (Seoul's W724C0). This string has rated voltage of about 25V at current 2.8A. Then the reasonable input voltage is 25...30V and, taking into account typical safe operating area the transistor and diode must be able to operate at 50...60V and 5...6A. The final choice of these elements, however, was determined by their availability in the laboratory. That is why oversized switches were chosen.

The most significant passive components – the current smoothing coil  $L_{SM}$  and output capacitor  $C_{OUT}$  have been chosen taking into account the ripple considerations. The coil  $L_{SM}$  has been chosen to keep discontinuous mode of operation of the converter at 80kHz and 5% of load in the worst case (with duty cycle  $D=0.5$ ). Then current's ripple is two times higher than the output current and:

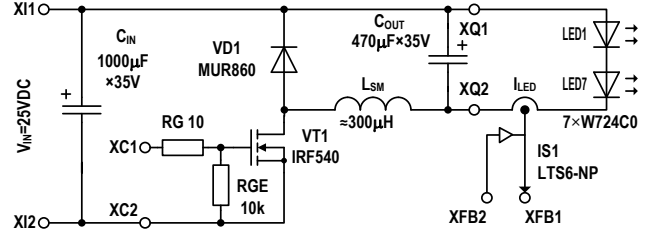
$$L_{SM} > \frac{V_{L_{max}} \cdot \Delta t_{max}}{\Delta I_{min}} = \frac{\frac{V_{IN}}{2} \cdot \frac{T}{2}}{0.1 \times I_{LED_{max}}} = \frac{12.5 \cdot 6.25}{0.28} \approx 280 \mu H .$$

The output capacitor  $C_{OUT}$  has been chosen to keep the changes of the output current  $I_{LED}$  below 5% of its maximum (0.14A) within all switching period. Since in the rated operation point slope of the volt-ampere curve of the LEDs is 1A/V the voltage pulsations must be 0.14V. Then:

$$C_{OUT} > \frac{I_{C_{max}} \cdot \Delta t_{max}}{\Delta V_{min}} = \frac{I_{LED} \cdot T}{0.14} = \frac{2.8 \cdot 12.5}{0.14} \approx 250 \mu F .$$



a) basic topology;



b) buck converter of the testbench;

Figure 2 – Buck (step-down) converter in dimming application.

#### 3.2 Control unit and measurement circuit

The above described dimmer is a pulse mode converter whose operation is defined by the duty cycle of control impulses. This impulse sequence could be formed by various pulse generators – either digital or analogue. However, implementation of a closed loop includes also measurements of analogue signals and data processing that, in turn, require some advanced digital devices – a microprocessor or a programmable logic array. A microprocessor system with MSP430 has been utilized because of availability and as equipment that is widely utilized in the author's department for training purposes and is well studied for this reason.

The particular control core is based on MSP430F1232 microcontroller (Figure 3). Its clock system is synchronized from an 8MHz crystal for better performance and accuracy of measurements. Connections of the corresponding pins of MCU as well as connections of pins for energy supply, reset and programming (not shown in Figure 3) are typical for these MCUs.

Analogue measurements are provided by internal analogue to digital converter (ADC10). Current signal (taken from a Hall sensor integrated in the power circuit) is connected analogue input A3. Initially it was planned to utilize also some analogue circuitry to adjust voltage levels. However, due to the operation parameters of the utilized current transducer (LTS6-NP by LEM – 2.5V offset and 0.625V span for 3A input current) it is possible to attach it to MCU directly, so that amplifier A1 acts basically as a follower.

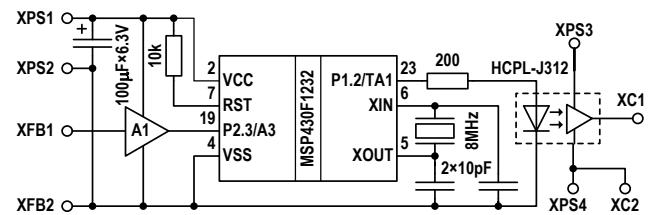


Figure 3 – Control unit of the testbench.

Control pulses may be generated either by the internal timer of MSP (Timer A3) or by the software on general purpose digital output. The pin 23 is shared for these two methods. The generated control signal is passed through a driver HCPL-J312. Almost no extra components are used because the output power of the converter is small and its power switch is MOSFET with small pin to pin capacitances. Pins XPS1 and XPS2 are used to supply MCU with 3V, but XPS3 and XPS4 provide 15V gate voltage for MOSFET.

### 3.3 Generating the control impulse signal

A sole square pulse is characterized only by its period and duty cycle. These parameters define also operation of the controlled converter (amount of transferred energy per cycle, losses, dynamic changes etc.). Although eventually only absolute values of the time parameters have an impact on the operation of the converter, the methodology of calculation of these time intervals as well as principles of pulse sequence generation is also important and may be quite different.

If the required duty cycles are obtained with the same period of all pulses the method is called Pulse Width Modulation (PWM - Figure 4-a). In case of PWM the value of the carrier frequency has significant impact on the losses in the converter. That is way this method has been tested with several values of the frequency (80, 40 and 10kHz).

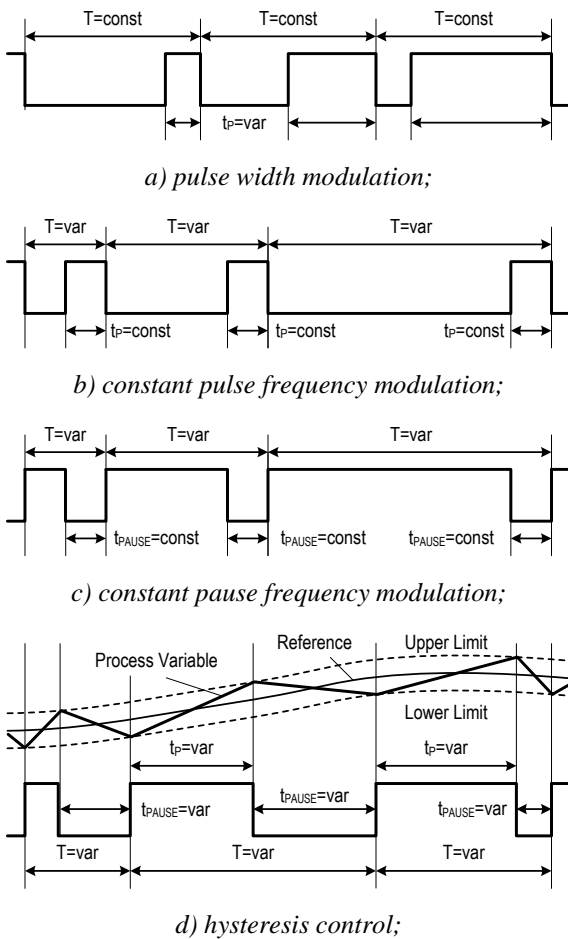


Figure 4 – Approaches to generation of the control pulses.

If the required duty cycles are obtained with the same length of pulses (Figure 4-b) or with the same length of pauses (Figure 4-c) the method is called Frequency Modulation (FM). Since the range of working values of the duty cycle of step-down converters with LEDs is narrow and lies in the area of big values (regulation curve basically follows the volt-ampere characteristic of LED and practical changes of current happen at higher duty cycles – [6]) the second modification of FM (constant pause) is preferable and it has been investigated.

It is also possible to form the control pulses both of variable frequency and of variable pulse lengths. The most popular modification of this method is hysteresis regulation. In this case the control unit does not calculate the duty cycles but compares a reference curve with the feedback of the system. Switching happens when the feedback is outside of the predefined reference (Figure 4-d). Unfortunately, due to the high nonlinearity of the volt-ampere curve of LEDs this method is not compatible with this particular application and has not been investigated.

In practice the duty cycle is not a constant. It undergoes dynamical changes at start-up, changes of the setpoint, input voltage of the converter etc. Then the practical pulse sequence depends on the modulation method and is different even for the same duty cycles. An example of start-up process for the reference current 1A obtained with PWM or FM is given in Figure 5 (in this example the rate of change of the duty cycle and, hence, current overshoot are chosen rather high for demonstration purposes).

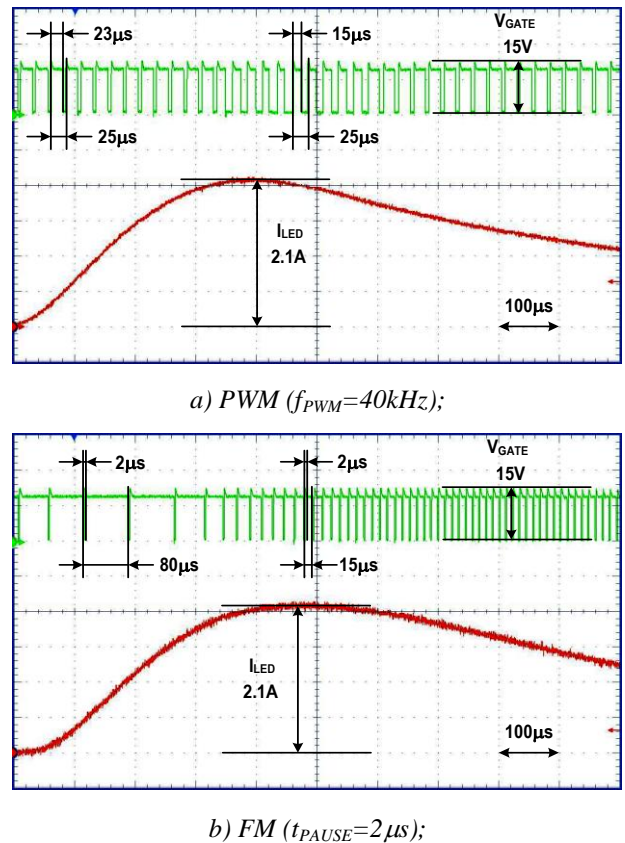


Figure 5 – Dynamic performance of modulation methods.

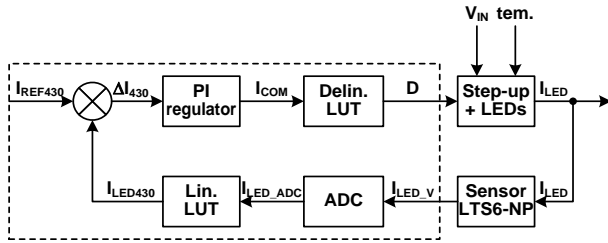


Figure 6 – Closed loop for stabilization of LED's current.

### 3.4 Software

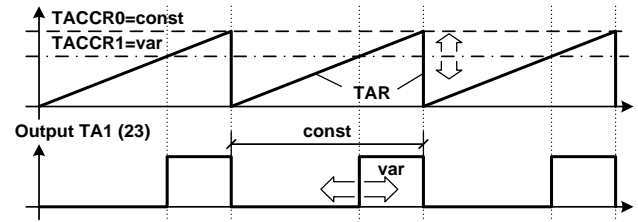
MSP430F1232 provides plenty of automatically functioning hardware for measurements and pulse generation. That is why the main functions of the developed software are initial tuning of the MCU's hardware, processing of the obtained measurements and calculation of the duty cycle, as well as run-time reprogramming of the hardware. In conjunction with external equipment MCU's hardware and software implement a classical closed loop with proportionally-integral (PI) regulator for automatic stabilization of current in LED string (Figure 6).

The developed software is interrupt driven – channel 0 capture/compare interrupts are utilised. One more capture/compare channel 1 is used to program pulse length. Basic operations of this interrupts are: initiation of new AD conversion, linearization of the measured non-linear data  $I_{LED\_ADC}$  and converting them into linear  $I_{LED430}$ , calculation of the current command  $I_{COM}$  in correspondence with the parameters/state of PI regulator and based on the current deviation  $\Delta I_{COM} = I_{REF430} - I_{LED430}$ , de-linearization of  $I_{COM}$  and finding the required duty cycle  $D$ , programming the capture/compare modules in correspondence with modulation method and obtained duty cycle  $D$ .

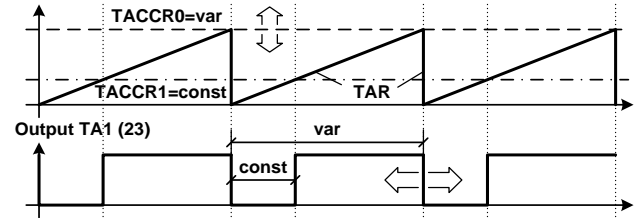
Linearization and de-linearization operations are performed utilizing the corresponding Look-Up Table (LUT). The data for these LUTs has been found from a special experiment made with an open loop system.

PWM signal is generated in a typical way for TA by compare/compare module 1 running in the output mode 6 – toggle/set mode (Figure 7-a). Pulse lengths are defined by the content of register TACCR1, while its content is taken from a de-linearization LUT based on the output of the PI regulator ( $I_{COM}$ ). PWM generating does not assume changes of the period and the content of TACCR0 remains constant (99 – for 80kHz PWM, 199 – for 40kHz and 799 – for 10kHz at 8MHz timer clock).

FM signal is also generated by compare/compare module 1, but running in the output mode 2 – toggle/reset mode (Figure 7-b). Pauses generated with this method are constant and they are defined by the content of register TACCR1 (always 16 for 2μs at 8MHz clock). Frequency and period of the impulses generated with this method are changing and depends on the content of TACCR0. This data, in turn, are taken from a de-linearization LUT based on the output of the PI regulator ( $I_{COM}$ ). The content of this LUT is, of course, different if compared to the PWM method.



a) PWM pattern generation;



b) FM pattern generation;

Figure 7 – Timer TA as PWM and FM signal generator.

## 4. COMPARISON OF RESULTS

The above described LED dimmer and its control have been assembled and tested. A series of experiments with the dimmer has been provided. During these experiments input/output voltages ( $V_{IN}$  and  $V_{LED}$ ) and currents ( $I_{IN}$  and  $I_{LED}$ ) have been measured. Then the input and output power ( $P_{IN}$  and  $P_{LED}$ ) have been calculated. Based on the power values the overall efficiency of the system has been found:

$$Ef = 100 \times (P_{LED} / P_{IN}) = 100 \times (V_{LED} \cdot I_{LED}) / (V_{IN} \cdot I_{IN})$$

The efficiency of the dimmer obtained in this way is presented graphically in Figure 8. For PWM control these curves look quite traditional - certain drop at the ends that can be explained by off state losses at the left end and rapidly increasing conduction losses – at the right end). One less expected phenomenon is the reduction of efficiency for 10kHz modulation frequency of PWM and more significant drop of the ends of this curve.

The efficiency obtained with FM seems more constant over all power range (except its low power and low frequency part) which could make the power balance of the operating dimmer more predictable.

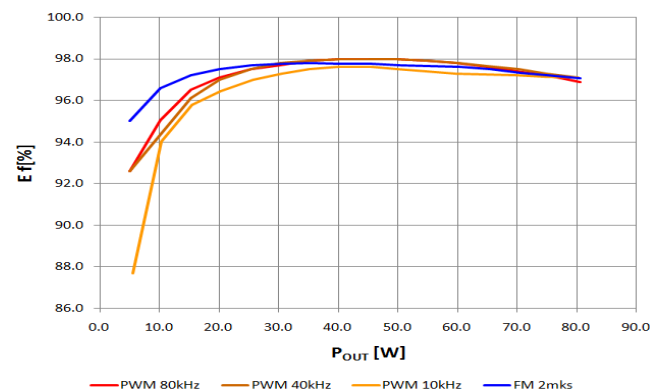


Figure 8 – Efficiency of step-down LED dimmer.

## 5. ANALYTICAL ESTIMATION OF LOSSES

Some calculations were done in order to explain the impact of control method on losses. There are three major sources of losses in buck converter: power MOSFET VT1, freewheeling diode VD1 and smoothing inductor  $L_{SM}$ . Losses in semiconductor devices can be divided in two parts: switching and conduction losses. Inductor losses are similarly divided into copper and core losses. If skin effect is ignored then the copper losses are proportional to average current, but its ripple defines the core losses. Switching losses of MOSFET is proportional to switching frequency and can be calculated from:

$$\Delta P_{VT1_{sw}} = \left( \frac{V_{DC} \cdot I_{L_{SM}} \cdot (t_{d(off)} + t_f)}{2} + V_{DC} \cdot I_{L_{SM}} \cdot (t_{d(on)} + t_r) \right) + V_{DC} \cdot Q_{rVD1} \cdot f_{sw}$$

where  $V_{DC}$  is input voltage,  $t_d$ ,  $t_f$  and  $t_r$  are switch parameters but  $Q_{rVD1}$  is diode stored recovery charge. Transistor conduction losses:

$$\Delta P_{VT1_{cond}} = \frac{I_{L_{SM}}^2 \cdot R_{ds} \cdot t_{on}}{T},$$

where  $R_{ds}$  is on state resistance and  $t_{on}$  is conducting time. Conduction losses in the freewheeling diode:

$$\Delta P_{VD1} = \frac{V_F \cdot I_{L_{SM}} \cdot (1 - t_{on})}{T},$$

Copper losses in smoothing coil winding:

$$\Delta P_{L_{SM}} = R_{Cu} \cdot I_{L_{SM}}^2,$$

where  $R_{Cu}$  is winding resistance.

Calculation of coil core losses is complicated due to inductance dependency on magnetizing force and AC flux density. Increase of magnetizing force leads to lower inductance, but AC flux density can increase it. For these reasons magnetizing force in Oersted's is calculated first:

$$H = \frac{0.4 \cdot \pi \cdot N \cdot I_{L_{SM}}}{l}$$

$N$  is number of turns, but  $l$  is length of magnetic path. Inductance reduction is determined from manufacturer data sheet based on calculated magnetizing force, but inductor current ripple – from these new inductance values:

$$\Delta i = \frac{(U_{DC} - U_{LED}) \cdot t_{on}}{L_{SM}}$$

If the ripples are known, AC flux (in Gauss) can be found:

$$B = \frac{\Delta i \cdot L_{SM} \cdot 10^8}{2 \cdot S_{Core} \cdot N},$$

where  $S_{Core}$  is core cross section area in  $cm^2$ . After analysis of obtained results it was concluded that increase in inductance based on AC flux is around 10% and can be neglected. Inductance values should be recalculated in case of bigger inductance increase. Core loss can be now determined from manufacturer data sheets taking into account switching frequency and AC flux.

The calculations made with the above methodology for different PWM frequencies and FM generally corresponds to the experimentally obtained data but have significantly different pattern at low power.

## 6. CONCLUSIONS

The obtained experimental and analytical data show that the efficiency of the above described dimmer is high with all tested control techniques. The experimentally obtained efficiency at FM regulation is more constant for wider range of power that could be explained with opposite dependency of the losses in active and passive elements of the converter on its switching frequency, but such assumption does not have analytical confirmation. For this reason the FM regulation has to be investigated in more details utilizing improved measurement technique and paying more attention to analytical background.

It has also been stated that the constant pause FM method provides better static accuracy of regulation. At the same time, it may have negative impact on electromagnetic compatibility of the converter, its dynamic performance and size/weight of its reactive components. These questions, as well as impact of modulation method on the other converters and investigation of hysteresis control require an extended research that is planned for the nearest future.

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