Comparison of the EMI performance of LED PWM Dimming Techniques for LED Video Display Application

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***Abstract*— Light emitting diode (LED) video display enclose thousands of LEDs which create the resulting image. LED intensity is regulated using pulse-width-modulation (PWM). Though the individual LED current is small, the total current consumed is large. Simultaneous switching of a large number of LEDs dimmed by PWM can cause serious electromagnetic interference (EMI). Three LED PWM dimming techniques have been studied for potential EMI. Techniques represent different current pulse positioning in time: the aim of study was to compare the spectrum of current produced in LED video display power supply circuits when discussed techniques are used for pixel intensity control. It was assumed that the produced EMI is proportional to the power supply current. The power supply filter and transient load decoupling capacitors were not taken into account. The uniform and non-uniform pixels' intensities distribution within an image were assumed. Spectrum has been studied on a single pixel and the video display tile containing 16x32 LEDs. Resulting time diagrams and frequency responses are presented. The results indicate that, despite expected significant advantage of binary PWM methods, in realistic case all methods' performance is similar.**

***Index Terms*— Displays, electromagnetic interference, frequency domain analysis, power system transients, pulse width modulation.**

I. Introduction

LED displays are intended for large scale imaging as long-life device able to work under unforgiving environment and ambient lighting conditions. Such displays are used in signage, advertising and entertainment [1] where video information display on a large scale and a bright and clear image is needed [2]. A pixel generally is formed by at least 3 LEDs of different color [3]. The LED is driven by a DC current [4] which must be constant to ensure the display color gamut stability [5, 6]. The most convenient method for LED dimming without altering the current is the pulse-width-modulation (PWM) [7]. In order to avoid the display image flicker, 400 Hz to 1 kHz image refresh frequencies are required [7]. To mimic human lightness sensation nonlinearity the incoming image is gamma coded [12]. As the LED PWM dimming is inherently linear, an artificial inverse gamma correction should be introduced in LED displays [11]: there is a need for a high dimming resolution. This in turn requires the PWM pulses which are much shorter than in conventional PWM applications e.g. switched mode power supplies (SMPS) or motor control. Pulse durations of order of tens of nanoseconds are expected. Every pixel is formed by 3 to 5 LEDs which have to be dimmed individually, according to the video frame being displayed. This means that for 320×240 resolution 300 000 PWM channels are used. For 720p it will be 3.6 million.

Low operating voltage of the LED turns as a disadvantage of the LED display. The single LED operates at 20 mA current. But in order to power-up the LED tile of 16x32 pixel resolution, 512 pixels shall be powered. Assuming pixel consists of 4 LED a 41 A power supply current will flow. A relatively small 300x200 pixels display contains 240 thousands of LEDs which consume 4800 A of current! In combination with the pulsed nature of PWM this can create the electromagnetic interference (EMI): when large number of LEDs is switched on simultaneously, a significant current spike will be generated on the power supply lines.

There is a plenty of another EMI sources in LED displays: significant amount of data is transported among the modules; SMPS are used; and signal processors are applied. But the PWM dimming is using significant currents and short driving pulses so has a potential for high energy and wide spectrum RF emissions. Therefore the choice of proper intensity modulation techniques is important. have been compared. The aim of investigation was not the absolute value of emission but the comparison of potential EMI between three major PWM techniques, used for LED dimming [9, 10, 11].

II. PWM Techniques

In case of conventional PWM, LED is driven by altering the time LED is lit on [7, 10]. The average LED radiation output is linearly proportional to pulse duration. Just single "on" state pulse with variable duration appears in a refresh period (refer to Fig. 1).

Manuscript received August 6, 2011.
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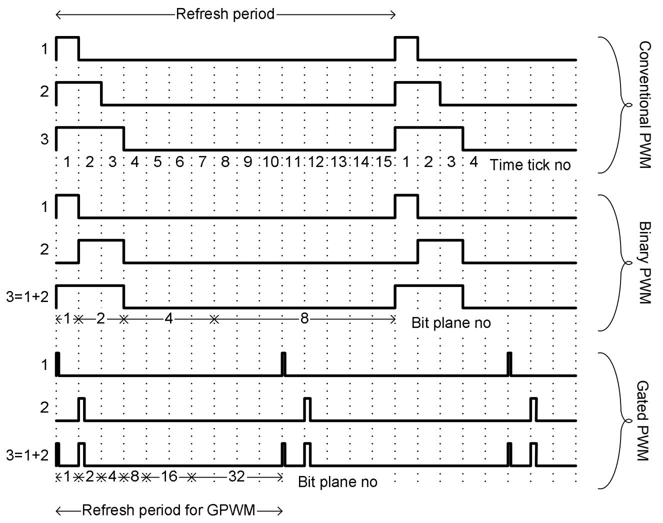

Fig. 1. PWM dimming techniques operation waveforms.

Linear PWM offers a convenient and simple intensity control mechanism: only the amount of the available duration steps limits the dimming resolution.

But the conventional PWM has an inherent disadvantage: for any pixel intensity the start of the "on" status pulse is in the same temporal position (time tick number 1 in Fig.1). At this time instance all the LEDs are turned "on" and a large current spike will occur on power supply line, causing an EMI problem.

The binary-weighted PWM (BPWM) or Bit Angle Modulation (BAM) [10] dimming technique is using several pulses in a period. The width of each separate pulse is proportional to the weight of the bit in the corresponding binary code of the required intensity. Together, these pulses form the required pulse duration so the total pulse width is the same as for the conventional PWM. This type of dimming should produce less EMI thanks to spreading of the current consumed in time (Fig.1).

But both conventional PWM and BPWM have a drawback: the shortest pulse is defined by loading time. Additional gating of the LED lighting is used in Gated PWM (GPWM) [11] technique. Here "on" pulse duration is limited only by LED luminescence response speed [7]: The LED is turned "on" (Fig.1) for a duration that is much shorter than the data loading time (time tick positions is Fig.1).

III. EMI IN LED DISPLAY

In our study we concentrate on the spectral content of driving current waveforms. If driving waveform $i(t)$ is known then, assuming the signal is with period T, its spectral components I_k can be obtained using complex Fourier series:

$$I_k = \frac{1}{T}\int_{-T/2}^{T/2} i(t)\cdot e^{-jk\omega_1 t}dt\,, \tag{1}$$

where ω_1 is the angular repetition frequency of image refresh. With an assumption that signal $i(t)$ has been sampled at sufficiently high frequency, its discrete counterpart i_n can be used in a discrete Fourier transform (DFT):

$$I_k = \frac{1}{T}\sum_{n=0}^{N-1} i_n \cdot e^{-\frac{jkn2\pi}{N}}\,. \tag{2}$$

Fourier coefficients a and b can be obtained as

$$a_0 = \frac{2I_0}{N}, a_k = real\left(\frac{2I_k}{N}\right), b_k = imag\left(\frac{2I_k}{N}\right). \tag{3}$$

The magnitude of the current spectrum for 1 A current spike of 1 kHz repetition frequency PWM at 3/127 duty cycle (127 levels of the PWM) is presented in Fig. 2.

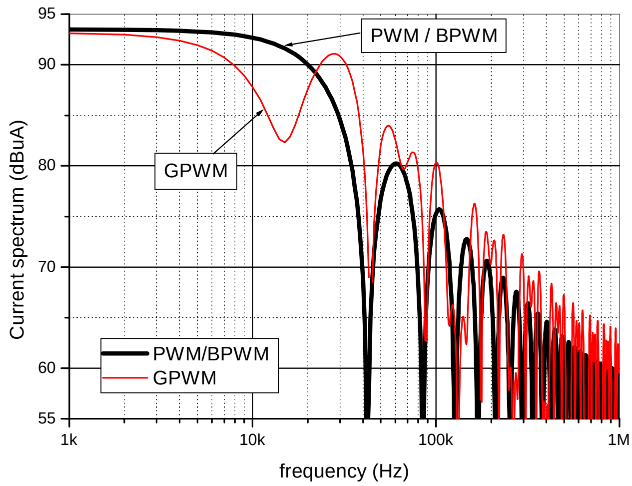

Fig. 2. Power supply current spectrum for code 3.

Results of the BPWM waveform for code 3 would be similar (refer to Fig. 1), but the GPWM signal with a two levels gating gave different spectral response. The reason for the different response is triple: (i) GPWM contains two pulses; (ii) period was slightly adjusted [7]; (iii) pulses are narrower.

IV. EMI OF REAL IMAGES

In the exercise above it was assumed that 50 LEDs are dimmed with the same code. But in the real image various LED intensities can occur. Now, with the individual LED spectral responses available we can calculate the spectral response for any image pattern by summing the individual LEDs currents. Such an assumption is valid provided that the three following conditions are met: (i) power supply is fed to a single junction on the LED tile; (ii) wavelengths are large enough compared to PCB size; (iii) power supply traces are assumed to go in one direction. The last condition will not be fulfilled in the real PCB: despite the prevailing direction in the LED tile PCB for power traces, it is unavoidable (and preferable for EMI reduction) that power supply traces will go in a random direction. But the assumptions above significantly simplify the analysis of PWM techniques' potential EMI. With these assumptions in mind, a uniform intensity distribution image was analyzed first. The results for 511 levels PWM, BPWM and GPWM are presented in Fig. 3.

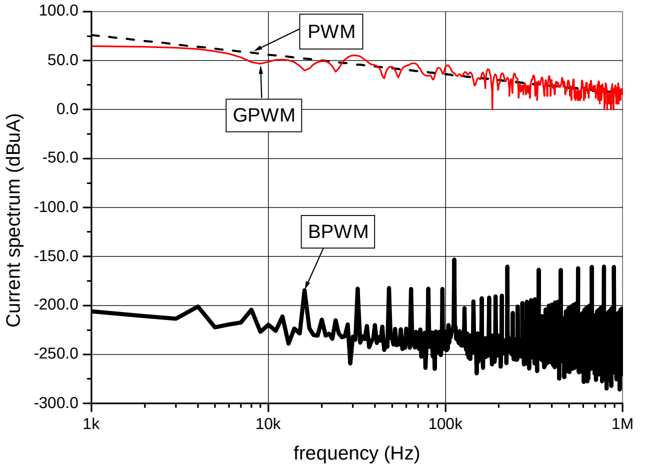

Fig. 3. Power supply current spectrum for the image with uniform histogram.

It has been assumed that pixel intensities are uniformly distributed in an image histogram. The PWM waveform will always start at time instant zero, therefore, accumulation of all possible uniformly distributed combinations should result in a saw-tooth-like spike. Spectral response of the saw-tooth-like signal is an exponential pulse. Hence, this result is as expected. However, for BPWM the resulting signal is almost zero: the spectral response is close to calculation errors rather than some reasonable curve. This phenomenon can be explained by availability of opposite waveforms: the waveform presenting code 1 has an opposite waveform with code N_{max-1} and so on. Therefore with all possible code combinations distributed evenly we have very low EMI as the result for BPWM.

Unfortunately, this does not hold true for the GPWM signal waveform. At a first glance, it seems that the result should be similar to the BPWM, since it also has opposite codes, but closer examination of waveforms on Fig. 1 reveal that opposite waveforms are available only for a few codes, which do not use gating feature. Gating level defines which bit planes, or levels, are allowed for longer duration. Gating level also defines the total duration for lower bit planes. Fig.1. is illustrating gating level 4 for GPWM: total duration for levels (bits) 0,1,2 and 3 (corresponding to weights 1, 2, 4 and 8) is the same, though "on" duration differs accordingly.

In the simulation of the GPWM power supply current behavior presented in Fig. 3, gating level 4 was used. This means that the first four bit planes are gated, i.e. durations thereof are narrower than that dedicated for a bit plane (refer to Fig. 1 for explanation). Distribution of similar intensities has been used for the larger amount of LEDs (256 pieces), whereas spectral peaks of the power supply current have been identified and summarized in Table 1.

The number of the PWM levels used (511) calls for 9 bit planes, therefore, just five of nine bit planes are the same as the BPWM. But it is interesting to note that the GPWM is effectively spreading the signal over the wide frequency range. This has resulted in moderate EMI levels (7.5 mA peak for the GPWM compared to 25.5 mA peak for the PWM). Note that for low resolution, GPWM performance is worse than that of the PWM.

TABLE I
SPECTRAL PEAK HEIGHT VS. MODULATION TECHNIQUE AND PWM RESOLUTION

	Number of available levels						
PWM resolution	7	15	31	63	127	255	511
Modulation	Spectral peak height, mA						
PWM	25.5	25.5	25.5	25.5	25.5	25.5	25.5
BPWM	~0	~0	~0	~0	~0	~0	~0
GBPWM2*	33.1	21.3	12.2	6.3	3.1	1.6	0.8
GBPWM3*	61.7	33.9	27.2	18.7	10.1	5.2	2.6
GBPWM4*	78.2	57.4	34.1	34.5	24.7	14.3	7.5
GBPWM5*	88.6	73.9	55.4	38.7	39.7	30.1	18.2
GBPWM6*	91.4	82.7	72.3	54.0	43.5	44.5	35.1

*The numbers next to GPWM indicate the gating level used.

Driving current spectrum was studied for real images, where uniform intensities distribution is not common. Well-known image "Lena" and image featuring the scenery named "Concert" have been studied. Previous investigation did not use inverse gamma correction coding which is needed to account for the human lightness sensation nonlinearity [12]. Next investigation used artificial inverse gamma corrected images: before coding into a waveform, gamma correction of power 2.5 [12] have been introduced. The resulting power supply current waveforms are presented in Fig. 4.

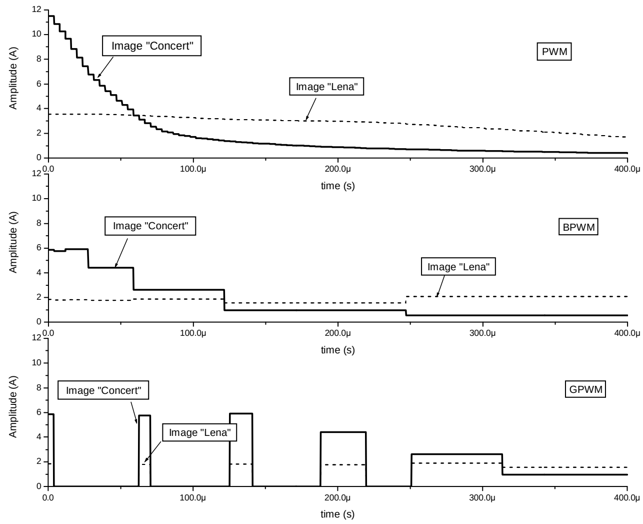

Fig. 4. Power supply current waveforms for a 256 LED tile.

The same amount of the driven LEDs was used: the tile was assumed to have 256 LEDs. Intensity histograms have been obtained for aforementioned images and histogram data has been normalized to be spread over 256 LEDs. Fractional LEDs contribution was allowed in order to reduce the required computation time.

Despite that the resulting current waveforms for two indicated images were different (Fig. 4), the resulting spectral performance was similar to all PWM techniques (Fig. 5 and Fig. 6).

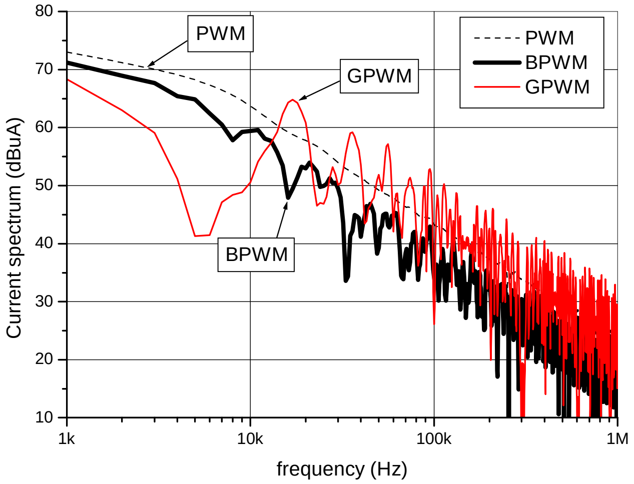

Fig.5. Power supply current spectrum for image “Concert”.

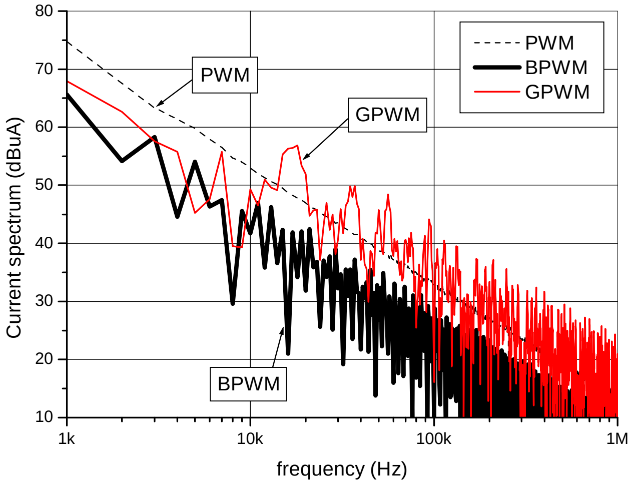

Fig.6. Power supply current spectrum for image “Lena”.

In all the cases studied, PWM techniques produced similar results. The low frequency component was higher for the PWM technique. BPWM had slightly better performance in the high frequency region: about 3-4 dB lower than PWM and 8-12 dB lower than GPWM. This could be expected: i) in BPWM some waveforms still cancel each other; ii) GPWM use much shorter pulses, so corner frequency for worst case decay is higher. However, the BPWM technique no longer holds the significant advantage noted in the case of uniform image intensities distribution which was demonstrated in Fig.3. This can be explained by disproportion in opposite waveforms which was the case in a uniform distribution image.

V. Conclusions

Three major LED PWM dimming techniques have been studied with the aim to compare the possible EMI levels. The BPWM and GPWM techniques possess the switching pulses spreading in time so could be expected to produce much less EMI than the conventional, linear PWM. The investigation with uniform pixel intensities distribution indicated that only BPWM exhibits such an advantage. But uniform pixel intensities distribution could never be expected on video display, because of gamma correction and non-uniform nature of images' histograms. The investigation with real gamma-corrected images indicated that all techniques have much closer than expected EMI performance. Due to inherent codes cancelation BPWM has around 4 dB improvement over PWM and 12 dB over GPWM. The GPWM techniques is using shorter pulses so higher EMI is naturally expected. Hence, it may be concluded that EMC potential for all the three PWM techniques studied is similar. Though, in some cases slight differences indicated could be essential in passing the product's EMC tests. Worst case analysis over several test movies should give more definitive comparison.

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