A Novel LED Driver with Adaptive Drive Voltage

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Abstract-**This paper presents an LED driver circuit consisting of a voltage pre-regulator and multiple linear current regulators with an adaptively-controlled supply voltage. The proposed driver circuit powers all LEDs in a string with a constant current and provides consistent illumination and optimal operating efficiency at low cost. The performance of the proposed driver was verified experimentally.**

I. INTRODUCTION

Currently, high-brightness light-emitting diodes (LEDs) are increasingly finding new applications in LCD backlighting, automobiles, traffic lights, and general-purpose lighting, because of their superior longevity, low maintenance requirements, and improved luminance. The brightness of LEDs is directly related to their current. An effective way to ensure that each LED produces similar light output is to connect them in series. However, a major drawback of a series connection of LEDs is their cumulative voltage drop that eventually limits the number of LEDs in a string. On the other hand, simple paralleling of LEDs or LED strings is not desirable because of current sharing problems related to the LED's exponential voltage-current characteristic with a negative temperature coefficient of the forward-voltage [1].

There are several methods of driving multiple LED strings connected in parallel. A straightforward approach is to employ a current regulator for each string, as shown in Fig. 1. Generally, the current regulator can be of linear or switch-mode type. The approach employing linear regulators offers a low cost, but suffers from a poor operating efficiency because the voltage drop across the linear regulator, i.e., the voltage difference between the input and output voltage of the linear regulator, cannot be minimized under all operating conditions. Namely, the input voltage of the linear current regulators needs to be set based on the worst-case condition, i.e., for the maximum LED string voltage drop, to ensure that the current of every LED string is regulated in the entire temperature and current range. As a result, the linear regulators driving LED strings that have a below-maximum voltage drop operate with reduced efficiencies. This drawback of the linear-current-regulator LED driver can be overcome by employing a more efficient switch-mode current regulator to drive each LED string [2]-[5]. Although this approach offers a higher operating efficiency compared to its linear counterpart, it also has a higher component count and cost.

For LED drivers employing linear current regulators, the drive voltage is typically provided by a switch-mode pre-regulator [6], as shown in Fig. 2. In the implementations shown in Fig. 2, the fixed output voltage of the pre-regulator is set by a voltage feedback at the level which ensures that current regulators for each string are capable of providing the desired current for the worst-case condition, i.e., for the maximum forward voltage drop of LED strings. In this LED driving approach, the only way to maintain high efficiency operation of the linear regulators is to use LEDs with matched forward voltages, which inevitably increases the cost.

The efficiency of linear-regulator LED drivers with a pre-regulator can be improved by sensing and regulating the minimum voltage of the linear regulators as shown in Fig. 3. In this method, which was proposed in [7] and implemented with digital technology in [8], the lowest voltage drop across the linear regulators (V_{MIN}) is detected through the sensing diodes and compared with reference voltage V_{REF} so that the output voltage of the pre-regulator is automatically adjusted to keep the minimum linear-regulator voltage to $V_{MIN} = V_{REF} - V_F$, where V_F is the forward voltage drop of the sensing diodes. The efficiency performance of this approach is strongly affected by the selection of reference voltage V_{REF} and characteristics of the sensing diodes, primarily their temperature dependence. Because of the tolerances of minimum voltage drops of linear current regulators, i.e., tolerances of dropout voltages, reference voltage V_{REF} must be selected above the anticipated worst-case voltage, which is the highest dropout voltage expected. As a result of an increased reference voltage required to provide the worst-case design margin, the efficiency of the driver in Fig. 3 is always lower than the possible maximum efficiency. Moreover, because of the strong temperature dependence of the forward voltage of the sensing diodes, the actual sensed minimum voltage drop across the linear regulators varies with the operating temperature causing a significant variation of the power loss. The detrimental effects of the non-optimal reference voltage V_{REF} and temperature dependence of the forward voltage drop of the sensing diodes are progressively more pronounced as the number of LEDs in a string decreases.

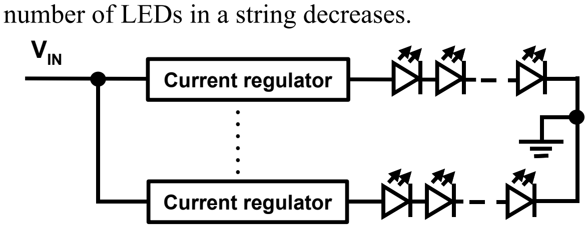

Figure 1. LED driver with current regulator in each string. Current regulator can be either linear or switch-mode type.

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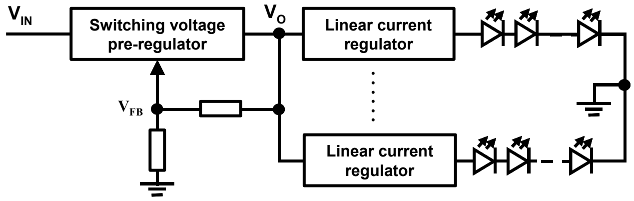

Figure 2. LED driver with linear current regulator in each string and switch-mode pre-regulator.

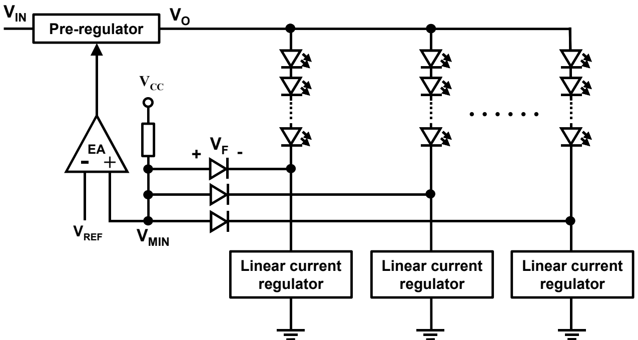

Figure 3. LED driver with switching voltage pre-regulator and detection circuit for the voltage drop of linear regulators.

In this paper, a novel linear-regulator LED driver for paralleled LED strings that employs a voltage pre-regulator with an adaptive output voltage and that offers the maximum efficiency is introduced. In this LED driver, efficiency maximization is achieved by eliminating the sensing of the voltage drops across the linear regulators, i.e., by removing the external voltage feedback for the adjustment of the output voltage of the pre-regulator.

II. PROPOSED LED DRIVER WITH ADAPTIVE DRIVE VOLTAGE

The proposed LED driver shown in Fig. 4 consists of a pre-regulator and multiple linear current regulators connected in series with the LED strings. Current I_{Li} (i = 1,2,···, n) through each LED string is regulated by a corresponding linear current regulator by sensing the string current with sensing resistor R_{Si} and by comparing the sensed voltage with reference V_{REFi}. The error between the sensed and desired current in each string is then processed by corresponding error amplifier EA_i so that error-amplifier output voltage V_{EAi}, which is also gate-to-source V_{GSi} of regulating MOSFET device Q_i, is adjusted to the level necessary to maintain the desired string current V_{REFi}/R_{Si}.

In addition, in the proposed circuit in Fig. 4, the outputs of all error amplifiers are OR-ed via diodes D_1 through D_n to detect maximum error-amplifier output voltage V_{EAMAX} that corresponds to the LED string with the highest voltage drop. Voltage V_E at the cathodes of the OR-ing diodes, which is equal to the difference between V_{EAMAX} and forward voltage drop V_F of the detecting diode, is then applied to the input of the control circuit of the pre-regulator to adjust the output voltage to the optimal level. For a switch-mode pre-regulator, the control circuit in Fig. 4 is a pulse-width modulator (PWM)

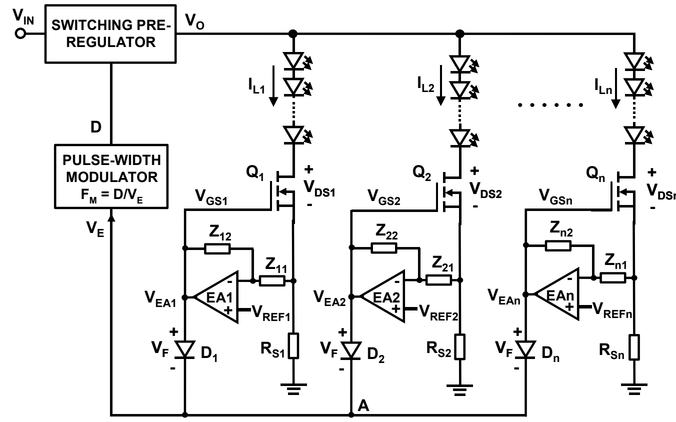

Figure 4. Proposed LED driver with adaptive drive voltage for linear current regulators.

that converts the control voltage V_E to duty cycle D. This modulator is usually implemented inside the pre-regulator as a part of the control IC.

Generally, the switching pre-regulator can be implemented using any non-isolated or isolated topology, depending on the input-voltage range and number of LEDs in a string. Typically, LED drivers employ the boost, buck, or buck/boost topologies.

In the proposed LED driver which does not use any sensing of the voltage across the linear regulators, a proper adjustment of the output voltage of the pre-regulator is achieved by exploiting a relatively strong dependence between drain-to-source voltage V_{DS} and gate-to-source voltage V_{GS} of a MOSFET operating in the linear (ohmic) region. Namely, in the linear region, i.e., when $V_{DS} < V_{GS} - V_{TH}$, drain-to-source current I_{DS} is given by

$$I_{DS} = C_{FET}(V_{GS} - V_{TH} - \frac{V_{DS}}{2})V_{DS} \quad (1)$$

Where C_{FET} is a constant with a unit of A/V^2, V_{TH} is the turn-on threshold of the MOSFET [9].

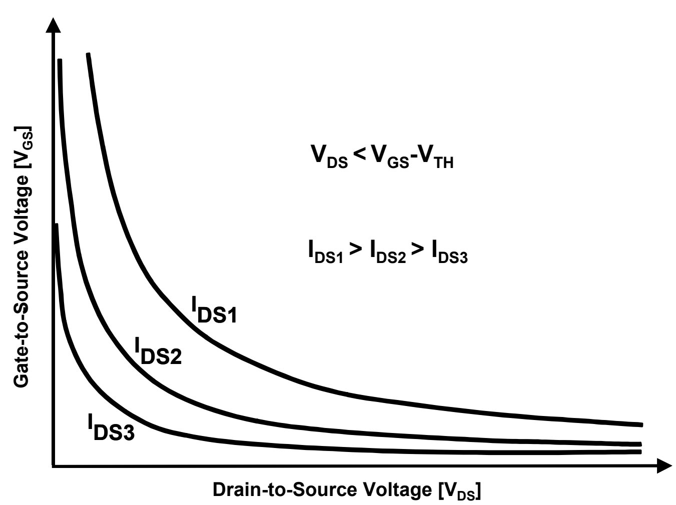

Figure 5. Linear-region dependence of gate-to-source voltage on drain-to-source voltage of MOSFET for different drain-to-source currents.

As can be seen from Fig. 5 which shows a plot of (1), for a given drain-to-source current I_{DS}, drain-to-source voltage V_{DS} decreases as gate-to-source voltage V_{GS} increases and vice versa. This dependence is exactly what is required in the LED driver in Fig. 4 to properly adjust the output voltage of the pre-regulator so that the maximum LED driver efficiency is achieved.

This self-adjusting feature of the proposed circuit can be further understood by considering its behavior in the presence of various disturbances. For example, if the voltage of the LED string with the highest voltage drop which controls the output voltage of the pre-regulator is increased, voltage V_{DS} of the corresponding current-regulating MOSFET that already has the lowest V_{DS} will decrease causing a decrease in its drain-to-source current I_{DS}. As a result, the error between reference voltage V_{REFI} and current-sensing-resistor voltage will increase causing the output of the error amplifier, which is also gate-to-source voltage $V_{GS,}$ to increase to maintain the desired LED current. At the same time, the increased error-amplifier voltage that is also applied to the input of the modulator increases the duty cycle of the pre-regulator so that the pre-regulator voltage is also increased to compensate for the LED voltage change.

The proposed driver also rejects changes of the pre-regulator input voltage. For example, if input voltage V_{IN} is increased, output voltage V_O will also increase causing an equal increase of the voltage V_{DS} of the linear regulators. As a result, current I_{DS} will also increase decreasing the error between reference voltage V_{REFi} and current-sensing-resistor voltage, causing the output of the error amplifier, i.e., gate-to-source voltage $V_{GS,}$ to decrease to maintain the desired LED current. Since the decreased error-amplifier voltage is also applied to the input of the modulator, the duty cycle of the pre-regulator will decrease which will reduce the output voltage of the pre-regulator so that the input-voltage changes are effectively rejected.

In should be noted that in this sensorless, adaptive drive-voltage method, the drive voltage is always self-adjusted to the minimum voltage required to maintain the desired current through the LED string with the maximum voltage drop. As a result, all linear current regulators in the proposed LED driver operate with minimized voltage drops, which makes the efficiency of the driver maximal.

III. DESIGN CONSIDERATIONS

To achieve the optimal performance of the proposed LED driver, i.e., to minimize the power loss of the linear regulators, a critical design step is to determine the required gain of the pulse-width modulator of the pre-regulator because the modulator gain determines the regulation performance of the voltage loop that self-adjusts the LED drive voltage. Of course, the performance optimization of the switching pre-regulator power stage and the linear current regulators is still crucial for the overall driver performance. However, since the optimization methods for switch-mode and linear regulators are well known and understood, they will not be addressed in this paper.

Generally, to ensure that the proposed LED driver works properly, i.e. that its linear current regulators operate with a minimum voltage drop, the output voltage of the pre-regulator has to be designed with a proper output-voltage adjustment range. This voltage adjustment range is determined by the number of LEDs in a string and the forward-voltage-drop range of the LEDs. Typical forward-voltage-drop V_{FLED} of a red-color LED is between 2.5 V to 3.5 V. For a driver intended to be used for driving LED strings with a high number, as well as low number of LEDs, including a single LED string, the output voltage range of the pre-regulator has to be relatively wide. Specifically, for a driver that can drive strings that have between 1 to 10 LEDs, the pre-regulator must be able to provide a voltage adjustment in approximately 2-40 V range. Generally, to achieve such a wide voltage adjustment range, the duty cycle of the pre-regulator must be able to vary in a wide range, too. For example, for a buck-boost type pre-regulator operating from a 12 V input, the output voltage variation from 2 V to 40 V requires a duty cycle variation from 14% to 77%.

Since in the proposed LED driver the pulse-width modulator is driven by the output of the error amplifier with the highest voltage and since this voltage is only a diode-voltage drop lower than the gate-to-source voltage of the corresponding current regulating MOSFET, modulator input voltage V_E is relatively high. Typically, it is in the 6 V to 15 V range. As a result, modulator gain $F_M = D/V_E$ is relatively low. For example, for gate-to-source voltage $V_{GS} = 10$ V, modulator gain F_M that can provide a duty cycle in the 14% - 77% range must be lower than 0.014 because $F_M = 0.14/10 = 0.014$. An implementation of the modulator with such a low gain may not be practical. In addition, a low modulator gain has also a detrimental effect on the performance of the driver, as will be discussed later.

A more accurate relationship between modulator gain F_M, input voltage of the pre-regulator V_{IN}, LED current I_{LED}, and voltage drop across the LED string V_{LED}, can be derived by recognizing that in the proposed circuit in Fig. 4, the output voltage of the pre-regulator is approximately equal to the voltage drop of the LED string with maximum voltage drop, i.e.,

$$V_O = V_{LED} + V_{DS} + V_{RS} \approx V_{LED} \tag{2}$$

Because for linear current regulators with the current-regulating MOSFET operating in the linear region $V_{DS} \ll V_{LED}$, whereas current-sensing resistor value R_S can always be selected so that $V_{RS} = R_S I_{LED} \ll V_{LED}$.

Assuming a buck-boost type pre-regulator, i.e.,

$$V_O = \frac{D}{1-D} V_{IN} \tag{3}$$

and using modulator input-to-output relationship

$$D = F_M (V_{GS} - V_F) \tag{4}$$

to eliminate D from (4), the gate-to-source voltage that is required to provide desired output voltage can be obtained as:

$$V_{GS} = \frac{V_{LED}}{V_{LED} + V_{IN}} \frac{1}{F_M} + V_F \tag{5}$$

Since the range of gate-to-source voltage V_{GS} is constrained between minimum value V_{GSMIN}, which is above threshold voltage V_{TH}, and maximum value V_{GSMAX} that is below the gate-to-source breakdown voltage, the range of modulator gain F_M is also constrained. From (5), the modulator gain range can be calculated as:

$$\frac{V_{LED}}{V_{LED}+V_{IN}}\frac{1}{V_{GSMAX}-V_F} < F_M < \frac{V_{LED}}{V_{LED}+V_{IN}}\frac{1}{V_{GSMIN}-V_F} \quad (6)$$

Minimum gate-to-source voltage V_{GSMIN} required to provide desired LED current I_{LED} and at the same time maintain the MOSFET operation in the linear region can be calculated from (1) by recognizing that at the boundary of the linear and saturation regions, $V_{DS} = V_{GS} - V_{TH}$ so that relationship (1) can be written as:

$$I_{DS} = \frac{1}{2}C_{FET}(V_{GS}-V_{TH})^2 \quad (7)$$

so that

$$V_{GSMIN} = \sqrt{2\cdot\frac{I_{LED}}{C_{FET}}} + V_{TH}, \quad (8)$$

$$F_M \le \frac{V_{LED}}{V_{LED}+V_{IN}}\cdot\frac{1}{\sqrt{2\frac{I_{LED}}{C_{FET}}}+V_{TH}-V_F}. \quad (9)$$

Relationship (6) is shown in Fig. 6 as a plot of an allowable modulator gain range as a function of LED-string voltage V_{LED} for a current-regulating MOSFET employing IRF540 device (V_{TH} = 2.90 V, C_{FET} = 6.41 A/V^2) and operating in the linear region with $I_{DS} = I_{LED}$ = 0.7 A, assuming input voltage V_{IN} = 24 V, and OR-ing diode voltage drop V_F = 0.7 V. In Fig. 6, any modulator gain above F_{MMAX} will lead to an undesirable operation in the saturation region of the MOSFET, whereas for a modulator gain below F_{MMIN}, the maximum desirable gate-to-source voltage will be exceeded. For example, for a string voltage in the range from 56 V to 80 V, which corresponds to a string of 16 LEDs, a modulator gain of around 0.2 can be chosen. However, for a string voltage range of 3.5 V to 5 V that corresponds to one LED, the modulator gain should be kept below 0.05, i.e., around 0.04.

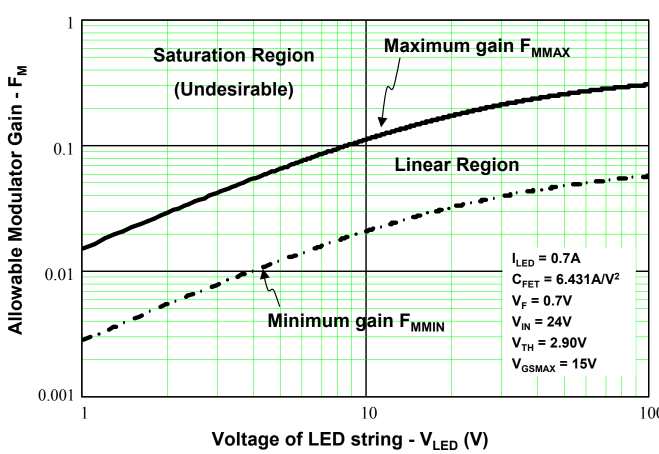

Figure 6. Plot of allowable range of modulator gain F_M as function of LED string voltage.

The selection of a lower modulator gain results in a lower power loss in the linear current regulators because a lower modulator gain requires a larger gate-to-source voltage V_{GS} and, therefore, reduces drain-to-source voltage V_{DS}. A very low modulator gain is not desirable due to several reasons. First, the requirement for a modulator gain below 0.2 excludes the use of internal modulators that are an integral part of today's PWM control ICs since the modulator gain of the majority of these controller ICs is greater than 0.2. Second, the implementation of a discrete modulator with a very low gain may not be practical. Namely, because the gain of the commonly employed saw-tooth modulator is given by $F_M = 1/V_{RAMP}$, where V_{RAMP} is the height of the ramp [10], a modulator gain of 0.04 requires a ramp of 25 V, which may not be practical in an LED driver that operates from an input voltage of 24 V or below. In addition, a low modulator gain has a detrimental effect on the voltage self-adjustment performance because it reduces the loop gain of the voltage loop.

To examine the effect of the modulator gain on the voltage loop regulation performance, Fig. 7 shows a small-signal block diagram of the proposed driver. In Fig. 7, K_{DS} and K_{GS} are small-signal gains of the MOSFET operating in the linear region defined as:

$$K_{DS} = \left.\frac{\Delta I_{DS}}{\Delta V_{DS}}\right|_{\Delta V_{GS}=0} \quad (10)$$

and

$$K_{GS} = \left.\frac{\Delta I_{DS}}{\Delta V_{GS}}\right|_{\Delta V_{DS}=0}. \quad (11)$$

Using relationship (1), K_{DS} and K_{GS} can be derived as:

$$K_{DS} = C_{FET}(V_{GS}-V_{TH}-V_{DS}) \quad (12)$$

and

$$K_{GS} = C_{FET}V_{DS}. \quad (13)$$

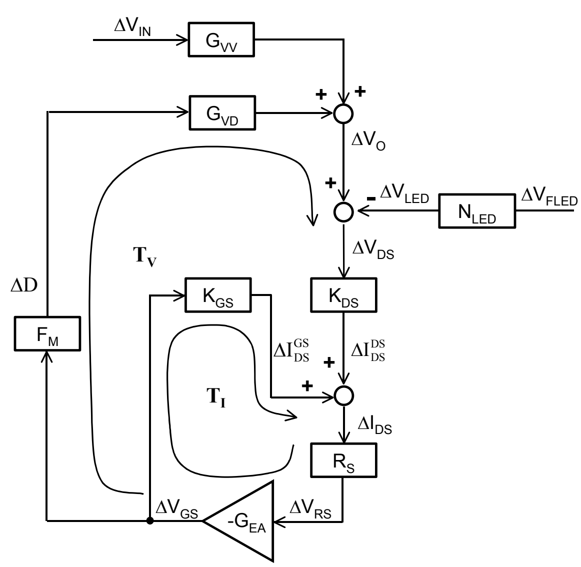

Figure 7. Small-signal block diagram of proposed driver.

Blocks G_{VD} and G_{VV} in Fig. 7 represent the control-to-output and audio-susceptibility transfer function of the switching pre-regulator, respectively, [10]. For a buck-boost converter operating in CCM, these two transfer functions at low frequencies are given by:

$$G_{VD} = \left.\frac{\Delta V_O}{\Delta D}\right|_{\Delta V_{IN}=0} = \frac{V_{IN}}{(1-D)^2} \tag{14}$$

and

$$G_{VV} = \left.\frac{\Delta V_O}{\Delta V_{IN}}\right|_{\Delta D=0} = \frac{D}{1-D}. \tag{15}$$

From Fig. 7, current loop gain T_I and voltage loop gain T_V are defined as:

$$T_I = G_{EA} K_{GS} R_S \tag{16}$$

and

$$T_V = \frac{F_M G_{VD} K_{DS} R_S G_{EA}}{1+T_I} = \frac{F_M G_{VD} K_{DS} R_S G_{EA}}{1+K_{GS} R_S G_{EA}} \tag{17}$$

Since for a properly designed current regulation loop T_I>>1, voltage loop gain can be expressed as:

$$T_V \approx F_M G_{VD} \frac{K_{DS}}{K_{GS}} \tag{18}$$

Finally, voltage adjustment ΔV_O of the proposed LED driver with respect to changes in the LED string voltage ΔV_{LED} and input voltage ΔV_{IN} are, respectively, given by:

$$\frac{\Delta V_O}{\Delta V_{LED}} = \frac{1}{\frac{1}{T_V}+1} \tag{19}$$

and

$$\frac{\Delta V_O}{\Delta V_{IN}} = \frac{G_{VV}}{T_V+1} \tag{20}$$

As can be seen from (18), for a given power stage and linear current regulator, the voltage loop gain can only be adjusted by the selection of modulator gain F_M. For good loop regulation performance, F_M needs to be as high as possible. Namely, if modulator gain F_M is high enough so that voltage loop gain T_V>>1, any change in LED-string voltage V_{LED} would be exactly compensated with a corresponding change of output voltage V_O, i.e., the change of LED-string voltage V_{LED} would not affect the efficiency performance of the driver. Furthermore, when T_V>>1, according to (20), any change in input voltage V_{IN} would result in essentially no change of output voltage V_O, i.e., the change of input voltage V_{IN} would also not affect the efficiency performance of the driver. However, in the proposed LED driver, voltage loop gain T_V is relatively low in order to achieve linear region operation of the MOSFET and maximize the efficiency, especially for LED strings with a low number of LEDs. For example, for V_{LED} = 3.5 V, I_{LED} = 0.7 A, V_{IN} = 24 V, D = 0.127, according to Fig. 6, F_M needs to be below 0.05. If F_M = 0.04, V_{DS} is 0.118 V and V_{GS} is 3.875 V so that voltage loop gain T_V = 9.15. With this voltage loop gain, a 1-V decrease of the LED-string voltage would cause only a 0.90-V decrease of output voltage, resulting in a 0.1-V increase of the voltage drop and 70-mW (or 84.7%) loss increase of the MOSFET. In addition, a 5-V change in the input voltage would cause a 71.66-mV change in the drain-to-source voltage of the MOSFET, leading to 50-mW (or 60.73%) power loss increase.

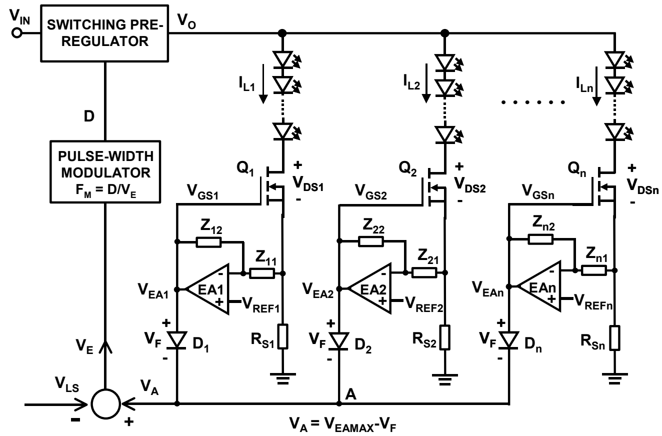

Figure 8. Block diagram of proposed LED driver with level shifter.

The voltage loop performance of the proposed LED driver can be improved by employing a level shifter to reduce the voltage at the input of the modulator, as illustrated in Fig. 8. By subtracting a fixed voltage V_{LS} from voltage V_E, the gain of the modulator can be increased without adversely affecting the current regulation or efficiency performance of the LED driver.

Following the same derivation procedure as for the case without voltage level shifting, the maximum modulator range can be derived as:

$$F_M \le \frac{\frac{V_{LED}}{V_{LED}+V_{IN}}}{\sqrt{2\frac{I_{LED}}{C_{FET}}}+V_{TH}-V_F-V_{LS}} \quad (V_{LS} < V_{LSCRIT}) \tag{21}$$

where critical voltage shift level V_{LSCRIT} is defined as:

$$V_{LSCRIT} = \sqrt{2\frac{I_{LED}}{C_{FET}}} - V_F + V_{TH} \tag{22}$$

When $V_{LS} \geq V_{LSCRIT}$, V_{GS} is always greater than required V_{GSMIN} to maintain desired I_{LED}, regardless of modulator gain F_M.

Minimum F_M that is constrained by the maximum gate-to-source breakdown voltage is given by:

$$F_M > \frac{V_{LED}}{V_{LED}+V_{IN}} \frac{1}{V_{GSMAX}-V_F-V_{LS}} \tag{23}$$

Finally, the maximum voltage shift level for a given gain F_M is limited to:

$$V_{LS} \le V_{GSMAX} - \frac{V_{LEDMIN}}{V_{LEDMIN}+V_{IN}} \frac{1}{F_M} - V_F \tag{24}$$

where V_{LEDMIN} is the minimum LED-string voltage.

Figure 9 shows the plot of allowable range of modulator gain F_M as a function of the LED-string voltage with a level shifter. Compared to the plot shown in Fig. 6 for the case without a level shifter, the maximum gain is increased significantly for the whole range of LED-string voltage under the same conditions. For example, with a 2.4 V level shift and for a string voltage in the range from 56 V to 80 V, a modulator gain of around 2 can be chosen, whereas for a string voltage range of 3.5 V to 5 V, the modulator gain can be as high as 0.4. These two gains are about ten times the gains for the case without a level shifter.

Since level shifting affects the gate-to-source voltage V_{GS}, it also affects the power loss of the MOSFET, as illustrated in Fig. 10. For the same modulator gain F_M and LED current I_{LED}, a higher voltage shift level gives a lower drain-to-source voltage, i.e., a lower power loss. For a target power loss, a higher shifting level allows a higher modulator gain. For an LED string with a voltage range from 32 V to 46 V, and with F_M = 0.4, V_{GSMAX} = 15 V, V_F = 0.7 V, and V_{IN} = 24 V, the maximum shifting level is 12.87V, so a shifting level of 4.3 V can be chosen, V_{GS} will range from 6.43 V to 6.63 V. The power loss of the MOSFET is about 20 mW for I_{LED} = 0.7A.

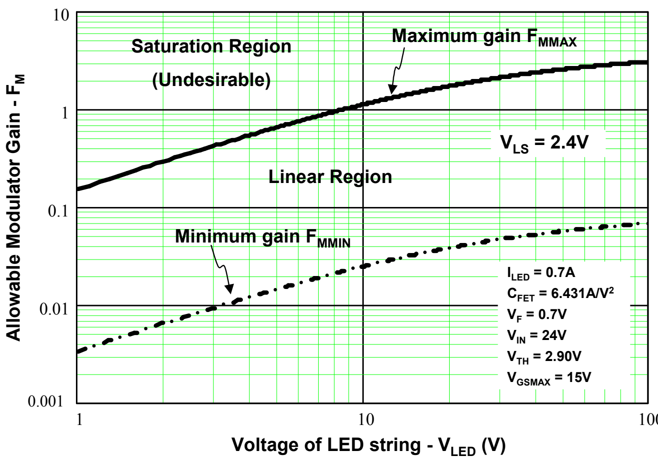

Figure 9. Plot of allowable range of modulator gain F_M as function of LED string voltage V_{LED} with a 2.4-V level shifter.

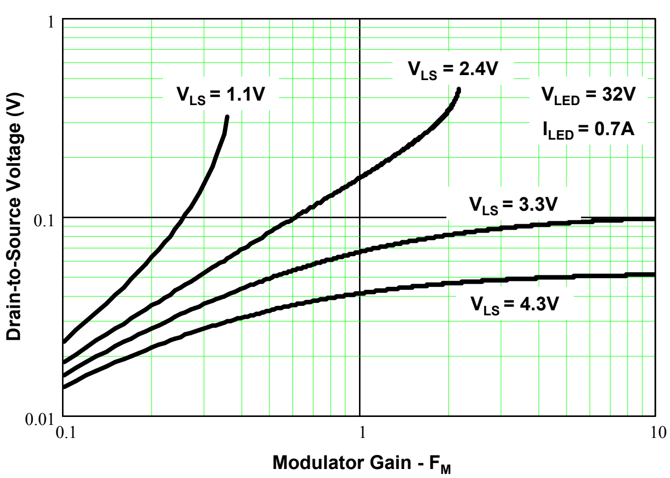

Figure. 10 Plot of drain-to-source voltage V_{DS} as function of modulator gain F_M for different voltage-shift levels V_{LS}.

IV. PERFORMANCE EVALUATION

The performance of the proposed LED driver was verified experimentally by building and testing an LED driver with a 120-kHz SEPIC pre-regulator. The circuit diagram of the experimental circuit is shown in Fig. 11, whereas Table I lists its key components. The SEPIC topology was selected because it can work with an input voltage that is above or below its output voltage, which is advantageous for applications with an input voltage range overlapping the output voltage. Four variable resistive loads were used to emulate LED-string loads and evaluate the performance of the proposed LED driver. The measured overall efficiency of the proposed LED driver with four loads with different voltage drops is shown in Fig. 12. At V_{IN} = 24 V and for R_{LOAD1} = 94.4 Ω, R_{LOAD2} = 92.231 Ω, R_{LOAD3} = 92.857 Ω, and R_{LOAD4} = 92.660 Ω, the overall efficiency is 88.37%. In this case, since R_{LOAD1} has the highest voltage drop of 33.04 V, the error amplifier for transistor Q_1 has the highest output of 5.576 V, as shown in Fig. 13. For V_{IN} = 24 V, this error-amplifier voltage results in a 0.026 V drop across Q_1 and a minimum drive voltage V_O of 33.276 V. MOSFETs Q_2, Q_3, and Q_4 have voltage drops of 0.785 V, 0.566 V, and 0.635 V, respectively, which corresponds to a total power loss of about 0.7 W. The measured output current of each load is shown in Fig. 14 for an input voltage in the range between 20 V and 30 V. The maximum relative error of load currents (preset load current = 350 mA) is 0.45% for all loads over the entire input range. When R_{LOAD1} is closer to the other three loads, e.g., 92.342 Ω, R_{LOAD3} exhibits the maximum voltage and the output voltage of the pre-regulator is adjusted to a lower level, i.e., 32.60 V, to maintain its current regulation. As a result, at V_{IN} = 24 V, the overall efficiency increases to 89.27%, as shown by the upper curve in Fig. 12.

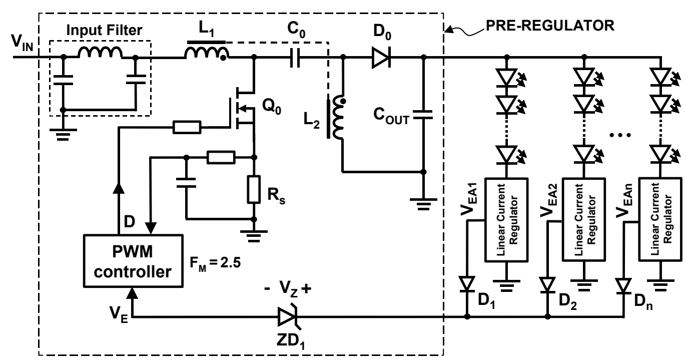

Figure 11. Experimental LED driver with adaptively-controlled drive voltage employing SEPIC pre-regulator.

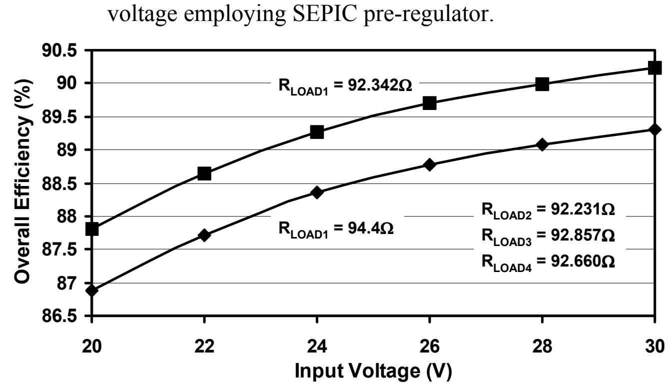

Figure 12. Measured overall efficiency of experimental LED driver.

TABLE I

KEY COMPONENT LIST

L_1, L_2	Core: MS080125, μ_i = 125 Winding: AWG# 23, N_1 = N_2 = 45 Ts $L_1 = L_2$ = 148 μH
C_0	Electrolytic, 220 uF, 35 V
D_0	MBR2090CT, 90 V, 20 A
C_{OUT}	Electrolytic, 470 uF, 35 V
Q_0 of pre-regulator $Q_1 - Q_4$ of current regulators	IRF540, 100 V, 28 A
ZD_1	1N4731, V_Z = 4.3 V
$D_1 - D_4$	1N4148, 75 V
PWM Controller	UC3843
Current Error Amplifiers	LM358
Switching frequency of SEPIC	120 kHz

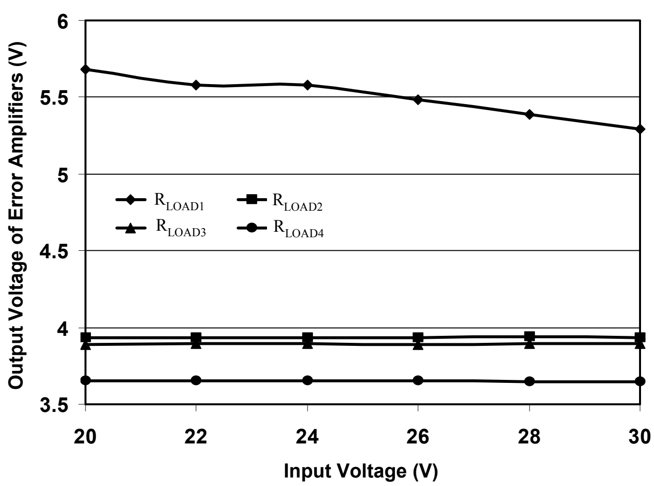

Figure 13. Measured output voltages of error-amplifiers of experimental LED driver.

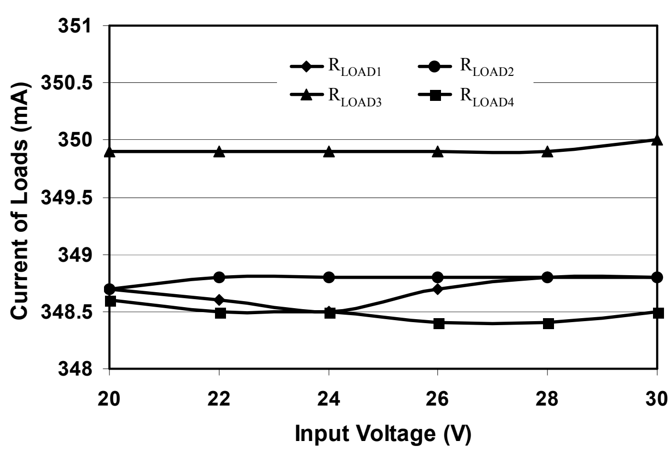

Figure 14. Measured load currents of experimental LED driver.

V. SUMMARY

An LED driver circuit consisting of a voltage pre-regulator and multiple linear current regulators with an adaptively-controlled drive voltage is presented. In this LED driver, the efficiency maximization is achieved by eliminating the sensing of the voltage drops across the linear regulators, i.e., by removing the external voltage feedback for the adjustment of the output voltage of the pre-regulator. The drive voltage adjustment in the proposed driver is implemented by exploiting a relatively strong dependence between gate-to-source and drain-to-source voltages of the current-regulating MOSFET operating in the linear region. Performance of the proposed driver was verified experimentally.

REFERENCES

[1] G. Carraro, “Solving high-voltage off-line HB-LED constant-current control-circuit issues,” *IEEE Applied Power Electronics Conference (APEC) Proc*., pp. 1316 - 1318, 2007.

[2] H. Broeck, G. Sauerlander, and M. Vendt, “Power driver topologies and control schemes for LEDs,” *IEEE Applied Power Electronics Conference (APEC) Proc*., pp. 1319 - 1325, 2007.

[3] T. F. Pan, H. J. Chiu, S. J. Cheng, and S. Y. Chyng, “An improved single-stage Flyback PFC converter for high-luminance lighting LED lamps,” *The 8th International Conference on Electronic Measurement and Instruments*, Vol. 4, pp. 212 - 215. Aug. 2007.

[4] H. J. Chiu and S. J. Cheng, “LED backlight driving system for large-scale LCD panels,” *IEEE Transactions on Industrial Electronics,* Vol. 54, No. 5, pp. 2751 - 2760, Oct. 2007.

[5] G. Spiazzi, S. Buso and G. Meneghesso, “Analysis of a high-power-factor electronic ballast for high brightness light emitting diodes,” *IEEE Power Electronics Specialists Conference (PESC) Proc.,* pp. 1494 - 1499, 11 - 14 Sept. 2005.

[6] Y. H. Fan et al, “A simplified LED converter design and implement,” *The 9th Joint Conference on Information Sciences (JCIS)*, Taiwan, Oct. 8 - 11, 2006.

[7] L. Burgyan and F. Prinz, “High efficiency LED driver,” *United States Patent* 6690146, Feb. 10, 2004.

[8] M. Doshi and R. Zane, “Digital architecture for driving large LED arrays with dynamic bus voltage regulation and phase shifted PWM,” *IEEE Applied Power Electronics Conference (APEC) Proc*., pp. 287 - 293, 2007.

[9] S. M. Sze, *Semiconductor Devices: Physics and Technology*, John Wiley & Sons, New York, 1985.

[10] R. W. Erickson and D. Maksimovic, *Fundamentals of Power Electronics,* The 2nd Edition, Kluwer Academic Publishers (KAP), Massachusetts, 2001.