LED Current Balance Using a Variable Voltage Regulator with Low Dropout $v_{DS}$ Control

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Abstract: A cost-effective light-emitting diode (LED) current balance strategy using a variable voltage regulator (VVR) with low dropout $v_{DS}$ control is proposed. This can regulate the multiple metal-oxide-semiconductor field-effect transistors (MOSFETs) of the linear current regulators (LCR), maintaining low dropout $v_{DS}$ on the flat $v_{GS}$-characteristic curves and making all drain currents almost the same. Simple group LCRs respectively loaded with a string LED are employed to implement the theme. The voltage $V_{V_{dc}}$ from a VVR is synthesized by a string LED voltage $Nv_{D}$, source voltage $v_{R}$, and a specified low dropout $v_{DS} = V_{Q}$. The $V_{V_{dc}}$ updates instantly, through the control loop of the master LCR, which means that all slave MOSFETs have almost the same biases on their flat $v_{GS}$-characteristic curves. This leads to all of the string LED currents being equal to each other, producing an almost even luminance. An experimental setup with microchip control is built to verify the estimations. Experimental results show that the luminance of all of the string LEDs are almost equal to one another, with a maximum deviation below 1% during a wide dimming range, while keeping all $v_{DS}$ of the MOSFETs at a low dropout voltage, as expected.

Keywords: linear current regulator; variable voltage regulator; LED; low dropout voltage

1. Introduction

The improving of lighting efficiency is one of the direct ways to contribute to energy-saving and green environment initiatives. Furthermore, mercury-free requests for avoiding the release of pollution into the environment also form part of the vital work at present. Accordingly, light-emitting diodes (LEDs) have become the necessary option in the lighting environmental renovation. Even the power LED has advantages, including a high-fidelity, high rendering, and low power consumption. Currently, the most urgent task is to understand how to make LED luminance become a surface light source, such as a fluorescent lamp. The most effective way to do this is by using a much lower-power LED to implement the surface source. To date, effective control strategies for balancing LED currents only include the linear balancing way and the digital pulse balancing way, such as is shown in Figure 1 [1–10]: in which Figure 1a,b demonstrate linear balancing ways and Figure 1c illustrates the digital pulse balancing way. In Figure 1a, all LED strings are supplied by a constant voltage source (CVS). In this situation, the LED current balance can be easily determined by a voltage detected from a sense resistor. However, this technique may cause a sense voltage change, especially for the CVS supply, since the LED forward voltage will vary with the ambient temperature [11]. As shown in Figure 1b, a shunt current balance configuration is built with a constant current source (CCS) supply, in which all of the string LED currents are collected into the controller and then individually compared with the reference current. This can achieve more accurate current balancing between adjacent LEDs, in order to emit uniform light. In Figure 1c, a digital pulse shunt current balance circuit is implemented with a supply of either voltage source (VS) or current source (CS). In this case,
To improve this problem, the luminance’s area should be fed back to adjust the adjacent string currents, producing correspondingly similar results [19]. On the specified almost-equal saturation-level curves, all string LEDs are then driven by almost constant drain currents to produce an equal luminance. In fact, the cost-effective way to perform a large scale lighting display is by using a shunt current balance configuration by linear current regulators (LCR) with a single voltage source [13,18]. Above all, the MOSFET of LCR may dissipate more conduction loss, due to an uncertain drain-to-source voltage on the $i_{DS}$-$v_{DS}$ plane [19]. Besides, many balance cells for LEDs directly using versatile dc/dc converters or resonant converters have been successively developed [18,20–25]. However, in terms of application for a large scale display, it is difficult to implement a large lighting area using such a large amount LED cells, needed to acquire a balanced luminance. In fact, the cost-effective way to perform a large scale lighting display is to use multiple shunt current balance configurations, controlled by multiple linear current regulators (LCR) with only a single voltage source. In this paper, to improve the characteristics of LCRs for driving the string LEDs, all operation points of the MOSFETs are separately placed on their $v_{GS}$-controlled characteristic curves; curves which are produced from an array of IC values and which are expected to present correspondingly similar results [19].

On the specified almost-equal saturation-level curves, all string LEDs are then driven by almost constant drain currents to produce an equal luminance, even though the $v_{DS}$’s are scattered under the curves. Successively, an approach to place all MOSFET $v_{DS}$ with a low dropout voltage on the specified flat curve in the saturation region is revealed [26]. Accordingly, a variable voltage regulator (VVR) is then proposed to perform the idea, such that all MOSFETs operate on the specified flat saturation curve with low dropout $v_{DS}$. The output voltage $VV_{dc}$ of the VVR is synthesized by a string voltage $Nv_{PD}$ of N-LED, detected source voltage $v_{R}$, and a specified low dropout $v_{DS} = V_{Q}$. With the supply of $VV_{dc}$ to LCRs, all string LEDs can be biased at almost the same saturation-level curves, respectively, whose currents will then be almost equal and can excite all string LEDs to produce an almost even luminance. Modeling the multiple LCRs for regulating constant string currents is conducted. An experimental setup for assessing the control strategies of balancing the multiple string LEDs is built. An aspect of the LCR for the string LED drives is described in Section 2. Using a variable voltage regulator (VVR) as the LCR supply, to excite the string LEDs for the production of a current balance, is explored in Section 3. The design and experiment for verifying the predicted estimations is discussed in Section 4. Final comments are concluded in Section 5.

LED current balancing mainly uses a PWM duty cycle control, such as sequential phase-shift duty control [12,13], burst mode [14,15], self-adaptive control [16], and series-connected mode [17], etc. In this case, the LED driven by the pulse to emit luminance for a human is based on the persistence of vision. Although the LED current balance by pulse drives can be conducted by multiplexing, it is difficult to make all of the string LED currents balanced for obtaining a uniform light source. To improve this problem, the luminance’s area should be fed back to adjust the adjacent string currents, producing a uniform light source. In spite of the fact that the mentioned current balance strategies are available, an uncertainty of the balance between the adjacent string LEDs always exists, mainly due to temperature variation and the dimming process. Further, the cost-effective way to perform a large scale lighting display is by using a shunt current balance configuration by linear current regulators (LCR) with a single voltage source [13,18]. Above all, the MOSFET of LCR may dissipate more conduction loss, due to an uncertain drain-to-source voltage on the $i_{DS}$-$v_{DS}$ plane [19]. Besides, many balance cells for LEDs directly using versatile dc/dc converters or resonant converters have been successively developed [18,20–25]. However, in terms of application for a large scale display, it is difficult to implement a large lighting area using such a large amount LED cells, needed to acquire a balanced luminance. In fact, the cost-effective way to perform a large scale lighting display is to use multiple shunt current balance configurations, controlled by multiple linear current regulators (LCR) with only a single voltage source. In this paper, to improve the characteristics of LCRs for driving the string LEDs, all operation points of the MOSFETs are separately placed on their $v_{GS}$-controlled characteristic curves; curves which are produced from an array of IC values and which are expected to present correspondingly similar results [19].

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Figure 1. Commonly-used LED drives: (a) Voltage control or individual current control by constant voltage source supply; (b) Shunt current control with current source supply; (c) Digital PWM duty control using shunt current balance.

2. Aspect of Linear Current Regulator for LEDs

2.1. Linear Current Regulator

Figure 2a shows the commonly-used LCR, which is a current-series feedback configuration composed of a MOSFET, an operational amplifier (OPA), and a sense resistor $R_s$. A string LED is widely loaded on the MOSFET in application. We define the symbols herein such that $v_{DS} = V_{DS} + v_{ds}$, where $v_{DS}$ is for the total signal, $V_{DS}$ is the dc component, and $v_{ds}$ is the small signal. The small-signal model of the LCD is depicted in Figure 2b, in which the output current (drain current of MOSFET) $i_{DS}$ is given by [17]. If $A_v >> 1$ and $g_m A_v R_s >> 1$, this yields:

$$i_{DS} \approx \frac{V_+}{R_s},$$

(1)

Presuming that the MOSFET operates in the saturation region, $i_{DS}$ in (1) is almost a constant current, varying with the input voltage $V_+$. This drain current can also be directly found from the characteristic curve of the MOSFET, guided by a certain $v_{GS}$. 

![Diagram of Linear Current Regulator](image-url)
2.2. LED String Module in LCR

Bias Situation for a Single String LED

An LED is essentially a family of diodes, whose current is temperature-dependent and varies, approximately in exponential form, in its forward bias [19]. The relation of the general LED current $i_D$ and the voltage $v_D$ can be simply expressed by the Shockley equation; for a single LED, this is presented as:

$$i_D(v_D) = I_s(e^{v_D/V_T} - 1), \quad (2)$$

and

$$v(i_D) = v(i_{DS}) = \eta V_T \ln \left( \frac{i_{DS} + I_s}{I_s} \right), \quad (3)$$

where $I_s$ is the leakage current in reverse bias, $V_T$ is the thermal voltage, $\eta$ is the ideality factor, $v_D$ is the forward voltage, and $v_{DS}$ is the drain-to-source voltage of MOSFET. For a number of $N$ LEDs connected in a series to form the string $N$-LED, the voltage $v_{DN}$ of the forward bias can be given by:

$$v_{DN} \equiv Nv_D = \eta N V_T \ln \left( \frac{I_s + L_s}{I_s} \right), \quad (4)$$

where $i_{DS} = i_D$ is due to the series connection of $N$-LED, and $N$ is an integer. With the assumption of the diode ideality factor $\eta = 1$ in standard fabrication, and if $i_D >> I_s$, we can simplify Equation (4) as:

$$v_{DN} \approx Nv_T \ln \left( \frac{i_D}{I_s} \right) \approx NV_T \ln \left( \frac{i_D}{I_s} \right), \quad (5)$$

In Figure 2a, the loop equation for the LCR loaded with the string $N$-LED can be given by:

$$V_{dc} = v_{DS} + Nv_D + i_{DS}R_s, \quad (6)$$
where $V_{dc}$ is the dc supply voltage. The drain-to-source voltage of the MOSFET can be given by:

$$v_{DS} = V_{dc} - Nv_D - i_{DS}Rs,$$

$$= V_{dc} - v,$$  \hspace{1cm} (7)

where we let $v$ be the voltage sum, i.e.,

$$v = Nv_D + i_{DS}Rs,$$  \hspace{1cm} (8)

Form (6), the drain current of the MOSFET in the LCR can also be given by

$$i_{DS} = f(v_{DS}) = \frac{1}{2c}(V_{dc} - Nv_D - v_{DS}),$$  \hspace{1cm} (9)

For the convenience of analysis, point $M$ is set to measure the drain voltage of the MOSFET, $v_M$, and Equation (6) can then be modified as:

$$v_M = V_{dc} - Nv_D = v_{DS} + i_{DS}Rs,$$  \hspace{1cm} (10)

If a small variation of $v_D$ is neglected, $V_M$ instead of $v_M$ is given by:

$$V_M = V_{dc} - NV_D = V_{DS} + i_{DS}Rs,$$  \hspace{1cm} (11)

Equation (11) represents a LCR loaded with one string $N$-LEDs and supplied by a voltage $V_M = V_{dc} - NV_D$. The combined characteristics of the one string $N$-LED and MOSFET of the LCR for bias and load-line descriptions, is shown in Figure 3a.

![Figure 3](https://example.com/figure3.png)

**Figure 3.** Predicted bias situation of a LCR loaded with one string $N$-LEDs by a constant voltage $V_{dc}$ supply: (a) Combined characteristics of the one string $N$-LED and MOSFET of a LCR for bias and load-line descriptions; (b) Bias situation of the LCR for $T_+ > T_0 > T_-$.
In this study, only the three kinds of temperature variations \( T_+ > T_0 > T_ - \) for the string N-LED are considered. Because of temperature-dependence, the voltage change of the N-LED will lead to a change in \( V_M \), resulting in a move of the load line of MOSFET on the \( i_{DS}-v_{DS} \) plane, which is clearly explored in Figure 3a. Correspondingly, the characteristics of N-LED on the \( i_D-v_D \) plane for the mentioned temperature variation are also depicted. In addition, the bias situation in the LCR with a constant \( V_{dc} \) supply is predictively shown in Figure 3b under temperature variation \( T_+ > T_0 > T_- \), including the sense voltage \( v_{GS} = i_{DS}R_s, Nv_D, v_{DS} \), and the voltage sum \( v \) etc., all are presented with respect to the current \( i_{DS} = i_D \).

1) Ambient Temperature at \( T = T_0 \)

In this situation, \( T = T_0 \), we presume that the MOSFET is initially biased at \( v_{GS2} \). A thick-green dc load line of the MOSFET on the \( i_{DS}-v_{DS} \) plane is presented by (11), and the corresponding string N-LED characteristic curve on the \( i_D-v_D \) plane is given by (2), as respectively shown in Figure 3a.

In other words, the operation point of MOSFET is at \( (i_{DS20}, V_{DS20}) \) and that of the N-LEDs is at \( (I_{D20}, V_{D20}) \), where \( I_{DS20} = I_{D20} \), while we presume that the point \( q_{20} \) has a low dropout voltage \( V_{D20} \). For the load line on the \( i_{DS}-v_{DS} \) plane in this situation, the supply to the drain of the MOSFET is equivalent to \( V_{M2} \) under the gate drive of \( v_{GS2} \) in (11) and the \( V_{DS2} = (V_{M2} - V_{Rs}) \).

2) Temperature falling to \( T = T_- \)

Once the environmental temperature \( T \) falls to \( T_- \) from \( T_0 \), where \( T_- < T_0 \), the string N-LED voltage will increase to \( V_{D2} = Nv_{D-} \), due to the negative temperature-dependent coefficient, and results in the \( V_{M2-} \) decreasing to \( V_{dc} - NV_{D-} \). In this situation, the green-thick dc load line will move to the left, as a red line, leading the operation point \( q_{20} \) moving left to \( q_{2-} \) while \( v_{DS} = V_{DS2-} \), and while the MOSFET operates in the triode region and its drain current is \( i_{DS} = I_{2-} \); correspondingly, when the string N-LED current decreases, reducing its luminance, even its voltage \( V_D \) is slightly increasing. Accordingly, it may happen to push the operation point from the saturation region into the triode region, due to the increase of N-LED’s voltage in a lower temperature situation.

3) Ambient Temperature rising to \( T = T_+ \)

If the temperature increases to \( T_+ \) from \( T_0 \), where \( T_+ > T_0 \), the green-thick dc load line will move right, as a blue line, due to \( V_{M2+} \) increasing to \( V_{dc} - NV_{D+} \), which leads the operation point \( q_{20} \) to move right to \( q_{2+} \) on the flat \( v_{GS2+} \) characteristic curve. Accordingly, the \( i_{DS} = I_{2+} \approx I_{20} \) and even the \( v_{DS} \) increases to \( V_{DS2+} \); meanwhile, the string N-LED current is \( i_D = I_{2+} \approx I_{20} \), which keeps its luminance at almost the same value as that produced at \( I_2 \).

4) Bias Situation for the MOSFET with Constant \( V_{dc} \) Supply for \( T_+ > T_0 > T_- \)

In order to explain the drain-to-source voltage of the MOSFET for \( T_+ > T_0 > T_- \) under a constant voltage \( V_{dc} \) supply, a voltage sum \( v = Nv_D + i_{DS}R_s \) is introduced in Figure 3b. The voltage \( v \), as the dark brown line, clearly displays the variation of \( v_{DS} \) between saturation and the triode regions, due to the temperature effect, where \( v_{DS} = V_{dc} - v \).

2.3. Dimming with a Constant Voltage Supply to LCR

When using a LCR loaded with one string LED, with a constant supply of \( V_{dc} \), for example, in the dimming process, the operation point of the MOSFET under different drives \( v_{GS} \)’s will change dramatically, since the voltage drop \( v_R \) on the source resistor \( R_s \) will vary far more than the voltage \( NV_D \). In this description, three kinds of gate voltages \( v_{GS} \)’s are explored, to dim the string N-LED. As mentioned previously, the operation of LCR is initially placed at point \( q_2 \) under normal temperature \( T_0 \), as shown in Figure 4, in which the N-LED current \( i_D = I_{D2} \) under the MOSFET is driven by \( v_{GS2} \). If the gate voltage changes from \( v_{GS2} \) to \( v_{GS1} \) while \( v_{GS1} < v_{GS2} \), the operation point \( q_2 \) will move to
point $q_1$ on the flat $v_{GS1}$-characteristic curve, since the voltage $N\Delta v_D$ will decrease due to the decrease of $i_D$, lowering the LED luminous output. On the other hand, if the gate voltage varies from $v_{GS2}$ to $v_{GS3}$ for example, as well as $v_{GS3} > v_{GS2}$, the voltage $v_{DS} = V_{DS3}$ will move left, to point $q_3$ on the triode region of the $v_{GS3}$-characteristic curve. In this instance, the drain current $i_D$ will increase to $I_{DS}$ since the voltage drop on $R_s$ and $N\Delta v_D$ will increase, leading to the decrease of $v_{DS}$. Therefore, although an increase of the $N$-LED current $i_D = I_{DS}$ will raise the luminance, the luminance change may not be proportional to the dimming level, disturbing its uniform distribution variation.

Figure 4. Bias situations for MOSFET and a single string LED during dimming process at $T = T_0$, where the LCR is supplied with constant $V_{dc}$.

3. Variable Voltage Regulator for LCRs to Balance the String LED Currents

3.1. $VV_{dc}$ Synthesized to Clamp Low-Dropout $v_{DS}$ in the MOSFET

As mentioned in Figures 3 and 4, for a LCR with constant voltage $V_{dc}$ supply, the drain-to-source voltage $v_{DS}$ is not only dependent on the forward voltage of the string LED, but is also subject to the voltage drop $v_R$ of the source resistor $R_s$. Accordingly, the $v_R$ will increase, due to the increase of $i_{DS}$; the $v_{DS}$ may fall dramatically to enter into the triode region of the MOSFET. On the contrary, the $v_{DS}$ will be located far away from the triode region, due to the reducing $i_{DS}$, and the operation point will move right. Here, it will be sustained on the flat $v_{GS1}$-characteristic curve, on which the drain current $i_{DS}$ will remain almost constant in a wide variation of $v_{DS}$, resulting in a $N$-LED luminance output which is almost the same. In order to remedy the issue due to a constant voltage $V_{dc}$ supply, a constant low-dropout $v_{DS}$ is initially specified as $V_Q$, close to the boundary of triode region, but on the flat portion of the $v_{GS}$-characteristic curve. Subsequently, all drain voltages at points $M$, $v_{MK}$, are only supplied by a variable dc supply $VV_{dc}$ from a variable voltage regulator (VVR), in which the low dropout $V_Q$ is involved, i.e.,

$$v_{MK} = VV_{dc} - N\Delta v_{Dk},$$

where the footnote “k” denotes the $k$th operation point, and:

$$v_{Rk} = i_{DSk}R_s,$$

Then, the output voltage $VV_{dc}$ of VVR can be estimated as:

$$VV_{dc} = N\Delta v_{Dk} + V_Q + i_{DSk}R_s,$$

$$= N\Delta v_{Dk} + v_{MK},$$
where the $V_Q$ is a constant low voltage placed close to the boundary of the triode region, but in the saturation region, as shown in Figure 5a, i.e.,

$$V_Q = V_{V_d} - v_k$$

$$\equiv \text{constant} \quad (15)$$

where the sum of the voltage $v_k$ is given by:

$$v_k = Nv_D + i_{DS}R_s$$

$$\quad (16)$$

Accordingly, the $VV_{dc}$ can then be synthesized form (14), including $Nv_D$, $i_{DS}R_s$, and the specified low-dropout $V_Q$, as shown in Figure 5b. In Figure 5a, the supply $v_{V_d}$ for different operation points under constant $V_Q$, can be easily found in (12). Remarkably, with a variable supply $VV_{dc}$, the LCR is able to keep the MOSFET operating at the specified $V_Q$ under different $v_{GS}$'s, which are the corresponding dimming levels. In addition, with the low-dropout $V_Q$, the MOSFET can only dissipate low conduction loss, and the string N-LED can emit luminance, proportional to the dimming levels.

![Figure 5.](image-url)

3.2. Dimming for Multiple-String N-LEDs

For dimming multiple-string N-LEDs, multiple identical $i_{DS}$-$v_{DS}$ planes, as shown in Figure 6, are simultaneously controlled by multiple LCRs with varying $v_{GS}$ values, in which all $v_{DS}$’s are then placed at a constant low-dropout $v_{DS} = V_Q$. For the convenience of analysis, all components, including MOSFETs, OPAs, LEDs, and source resistor $R_s$, are assumed to be identical in an array of integrated circuits (ICs), in which only one $VV_{dc}$, as shown in Figure 5b, is supplied in the planes of Figure 6. For the ease of analysis, two $i_{DS}$-$v_{DS}$ planes are taken as being the same as each other, for example, in which $V_{Q1}$ and $V_{Q2}$ are the low-dropout voltages. Since the two MOSFETs are identical, the two operation points are almost the same, leading to the two string LEDs having the same currents. However, once there is a deviation from $v_{DS}$, at least one of the MOSFET’s $v_{DS}$ should be maintained at the specified $V_Q$, leaving the rest of $v_{DS}$’s as being greater than $V_Q$, but still remaining on the same flat $v_{GS}$-characteristic curve; on which both of the drain currents of the MOSFETs in this example are almost the same, but are different for the $v_{DS}$. Thus, the two string N-LEDs can still have the same currents, and thus emit the same luminance. This control theme is to be extended to the current balance of multiple string N-LEDs.
The control reference is preset at the master LCR and wires together with the other slave LCRs. Since the devices and components, in practice, can be selected as almost identical to one another, the current balance between the adjacent string LEDs can then be realized as predictions.

3.3. Master and Slave Control for Current Balance of Multiple string N-LEDs

In this study, using an array of ICs to acquire identical MOSFETs for serving multiple-string N-LED control, is vital work. The circuit scheme for the multiple LCRs respectively loaded with one string N-LED, is outlined in Figure 7, in which the master and slave controls for the current balance are built. Since the devices and components, in practice, can be selected as almost identical to one another, the current balance between the adjacent string LEDs can then be realized as predictions.

The control reference is preset at the master LCR and wires together with the other slave LCRs. The $V_{Vdc}$ of VVR is basically synthesized by the loop parameters of the master LCR, as per Figure 5b, including the $v_{DS}$ of the MOSFET, $v_R$ on source $R_S$, $N_{vD}$ on the N-LED, and the specified low voltage dropout $V_Q$. To implement the VVR, a reference voltage $(V_Q + V_k)_{ref}$ is initially preset, where $V_k$ depends on the state of the gate drive $v_{GS}$. After comparing the instantly detected voltage $(V_Q + V_k)_{ref}$ in the master loop, the synthesized $V_{Vdc}$ is then adapted to supply all multiple string LEDs through the LCRs, and results in the same currents for adjacent LEDs, while holding all $v_{DS}$’s positions greater than the lowest $V_Q$. Once the control is finished in the master LCR, all slave LCRs with the updated supply $V_{Vdc}$, can mirror the master drain current on their flat $v_{GS}$-characteristic curves in the $i_{DS}$-$v_{DS}$ planes, and then all slave string LED currents are almost the same as one another.

![Figure 6](image-url) Current balance control for multiple-string N-LEDs using multiple identical $i_{DS}$-$v_{DS}$ planes, where all of the MOSFETs and LCRs are assumed to be identical with $V_{Vdc}$ supply.

![Figure 7](image-url) Configuration of master and slave control for the current balance of multiple string N-LED.
3.4. Digitizing the VVR Controller

Figure 8 shows the digital control architecture used to build the VVR, in which the controller is executed by Microchip dsPIC33FJ06GS202, according to the idea theme in Figure 5b. The mentioned three parameters, \( v_{DS}, v_{R}, \) and \( N_{VD} \), detected from the master LCR are respectively sampled and held before the digitizing process. After combining them, a \( v_{R} + v_{DS} \) through D/A is obtained, to compare with the reference \( (V_Q + V_k)_{ref} \) at the error amplifier (EA). The error signal from the EA will then guide the VVR to provide an updated \( VV_{dc} \) for supplying the master and slave LCRs. This digitizing process makes the \( VV_{dc} \) produced from VVR more accurate and stable against the parameter variations mentioned previously.

![Figure 8](image)

**Figure 8.** The algorithm to implement VVR for supplying the LCRs, executed by Microchip dsPIC33FJ06GS202 with reference to Figure 5b.

4. Design and Experiment

To verify the proposed control theme, a scaled-down simple layout of \( 5 \times 6 \) LEDs are arranged with five string LEDs connected in parallel, in which each string has six LEDs in series. Five LCRs are employed to drive the five string LEDs, respectively, in which MOSFET IRF110 is used as the current regulator in LCR, and the LED EHP-C04/UT01-P01/TR with a rated power of 1 W is adopted. The operational amplifier TL074 with a slew rate of 13 V/μs is used as a comparator. The power LED has a conductance \( (i_{DS}/v_{GS}) \) of approximately 0.42 mA/mV. The transconductance \( (i_{DS}/v_{GS}) \) of the MOSFET is about 2.97 mA/mV under an \( i_{DS} \) varying from 0 mA to 350 mA; correspondingly, \( v_{GS} \) varies from 3.72 V to 4.5 V. The low-dropout \( v_{DS} = V_Q \) is 1.5 V, specified at \( i_{DS} \approx 200 \) mA. The circuit schemes for the experiment are as in Figures 7 and 8, in which the digital controller for synthesizing the VVR is as per the loop parameters of the master LCR, with reference to the estimation profile in Figure 5b. In Figure 7, the \( v_{DS} \) is instantly detected by the differential amplifier (A1) and is controlled at a low dropout \( V_Q \). The voltage \( v_k = f(i_{DSk}) \) in (16) is a function of the \( k \)th current \( i_{DSk} \) detected from a source voltage \( (v_R) \), in which the voltage \( v_k \) is the summation of \( v_R \) and \( N_{VD} \), where the footnote “\( k \)” is used to denote the position of the operation point driven by \( v_{GSk} \). The \( v_Q \) and \( v_k \) are merged at the inverting input of the error amplifier (A2) and compared with a specified reference.
voltage \( (V_Q + V_k)_{\text{ref}} \). After comparing the error output \( V_{ea} \) from A2 with a reference sawtooth at the PWM controller (A3), an updated variable voltage \( VV_{dc} \) from the VVR is acquired through the loop regulation in the master LCR. With the \( VV_{dc} \), the \( v_{ds} \)'s in the five string LCRs can then be kept at a low dropout \( V_Q \) on the five flat \( v_{gs} \)-characteristic curves, respectively. A source resistor \( R_s = 12 \Omega \) which is, estimated for the current sensor is used, the VVR is supplied by a dc source \( V_{dc} = 35 \text{ V} \), and the dimmer control is implemented by a precision variable resistor. The digitizing controller, as shown in Figure 8, is implemented by Microchip dsPIC33FJ06GS202, in which three parameters, including \( v_{ds} \), \( v_{r} \), and \( v_{ds} \), detected from the control loop of the master LCR, are sampled and held for digitizing. Through D/A conversion, the voltage \( v_k \) is acquired. After merging the \( v_k \) and \( v_{ds} \) to compare with the reference \( (V_Q + V_k)_{\text{ref}} \) at the error amplifier (EA), the updated \( VV_{dc} \) from the VVR to supply the five LED strings, is achieved. Consequently, the self-feedback in the control loop of the master LCR for keeping all slave \( v_{ds} \)'s at low dropout is always valid, and indeed the updated \( VV_{dc} \) is able to achieve the current balance in the multiple LED strings.

4.1. Experiment for a Single String 6-LED

The experiment to evaluate the characteristics of a LCR to drive a single string 6-LED and their relative parameters during \( v_{gs} \) changes, is shown in Figure 9. The synthesis voltage \( VV_{dc} \) composed of \( v_{dn} = Nv_{d}, v_{r}, \) and \( v_{ds} \) under the \( v_{gs} \) control, is displayed in Figure 9a, in which all of the parameters measured meet the estimations with an acceptably low dropout voltage. The experiment shows that \( v_{ds} \) varies at around 1.5 V, from 1.77 V to 1.38 V, in all five MOSFETs; correspondingly, their \( v_{gs} \) varies from 3.72 V to 4.46 V.

![Figure 9](image-url)

**Figure 9.** Characteristics of the master LCR loaded with a single string 6-LED in dimming process by \( v_{gs} \) controlled: (a) The synthesized \( VV_{dc} \) composed of a specified \( V_{ds1} = V_Q \approx 1.5 \text{ V} \), \( v_{r} \), and \( v_{ds} = 5v_{d}; \) (b) LED current \( i_D \) versus \( v_{gs}; \) (c) LED luminance with respect to conduction loss of MOSFET during dimming.

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The LED luminance, with respect to the LED current $i_D$ under the $v_{GS}$ control, is shown in Figure 9b, in which each string 6-LED can emit a luminance from 0 to 62.1 kcd/m$^2$; correspondingly, the string LED current $i_D$ varies from 0 to 357 mA. The string LED luminance is measured vertically, facing the LED display at a distance of 50 cm, by using a luminance-meter type BM-910 TOPCON with a high accuracy. The string LED luminance and the conduction loss in MOSFET are measured in Figure 11. It is clearly seen that the maximum conduction loss in the MOSFET is only 492 mW at $i_{DS} = 357$ mA, due to a low dropout of $v_{DS} \approx 1.38$ V, which actually benefits the MOSFET, dissipating the low conduction loss.

4.2. Experiment for the Multiple String 6-LEDs

In this experiment, the master and the four slave LCRs are supplied by the same $VV_{dc}$, and all of the controls are wired with the same dimmer signal. The $VV_{dc}$ is controlled by the loop of the master LCR. With the $VV_{dc}$, each slave LCR can self-regulate the MOSFET’s $v_{DS}$ to stay at the low dropout $V_Q$, even at a place higher than $V_Q$ toward right-side, where the drain current can always mirror the master current during the dimmer control.

The variations of the five $v_{DS}$’s, with respect to each string’s LED current, are shown in Figure 10a, in which the highest $v_{DS}$ is 1.78 V and the lowest $v_{DS}$ is 1.37 V, and all are located on the flat $v_{GS}$-characteristic curves. With reference to $v_{DS} = V_Q = 1.5$ V, the deviation $\Delta v_{DS}$ above $V_Q$ is 0.28 V and below $V_Q$ is 0.13 V, in which the low deviation is still on the flat $v_{GS}$-characteristic curve in the saturation region of MOSFET. The luminance’s distribution of the 5-group LED strings during the LED current change is displayed in Figure 10b, in which the adjacent luminance values between 6-LED strings are almost the same during a wide dimmer range. In this measurement, the maximum luminance deviation, of about $\pm 0.45$ kcd/m$^2$, occurs at the highest luminance of 62.7 kcd/m$^2$ (where $i_{DS} = 357$ mA) and the minimum deviation of about $\pm 0.01$ kcd/m$^2$ at the lowest 2.65 kcd/m$^2$ (where $i_{DS} = 10$ mA). The measured luminance can be expected to be uniform if the proposed $5 \times 6$ LED layout is equipped in a panel display. This experiment successfully demonstrates the current balance strategy for the multiple string LED; particularly, the control theme, which is easy to implement by using simple LCRs with a microchip control. The experimental setup of a scale-down $5 \times 6$ LED display is shown in Figure 11.

**Figure 10.** The measurements of the five string 6-LEDs connected in parallel during dimming process: (a) Drain-to-source voltage $v_{DS}$’s; (b) Luminance’s emitted from the five string 6-LED, all measures are group-displayed with respect to the string LED currents.
5. Conclusions

In this paper, the synthesized VVR successfully achieves a low dropout $v_{DS}$ for all MOSFETs in the LCRs, and allows their operation points to remain on the flat $v_{GS}$-characteristic curves, on which all of the drain currents are almost the same and actually attain the balance of the multiple string LED currents. In addition, the experiment evidenced that the control strategy is feasible in practice. All measurements, including the current balance behavior, low dropout voltage deviation, and the distribution of luminance between the adjacent string LEDs etc., all meet the estimations. Consequently, the cost-effective LCRs with the proposed control theme can actually achieve the current balance in multiple string LEDs, and it would be suitable to extend their use to a large-scale display that requires multiple string LEDs.

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