LETTER

Linear current module adaptive to wide operating voltage range based on automatic series/parallel conversion

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Abstract A new method based on adaptive series/parallel conversion to realize linear current output in a wide operating voltage range is presented in this paper. According to the load state, a switch array is employed to perform adaptive series/parallel conversion control on load segments and corresponding constant current branches to ensure constant current in each load segment and constant power of the total load in wide operating voltage range. The proposed design combines the advantages of switch mode current source and linear constant current source. The correctness and feasibility of the proposed method are verified by experiments of a LED driver.

Keywords: linear current, constant current sources, adaptive control, wide operating voltage range, LED driver

Classification: Circuits and modules for electronic instrumentation

1. Introduction

Current source, which includes switch mode and linear mode, is widely used in electric appliances, communications facilities, portable devices, etc. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11]. In switch mode, power devices work in on-off state with the control of a high frequency (~kHz or ~MHz) signal [4, 10, 12, 13, 14, 15, 16, 17, 18, 19]. So, the switch mode current source facilitates high conversion efficiency and small volume. However, ripple, electromagnetic interference (EMI) and relatively complex control circuit are drawbacks of switching power supply [18, 19]. Whereas, in linear mode, power devices usually work in constant current state with the control of feedback signal [20, 21, 22, 23, 24]. The advantages of linear current source are small ripple of output current, high accuracy of constant current and simple circuit, etc. But the continuous conduction of power devices will result in low conversion efficiency [8].

In this paper, combining the advantages of switch mode and linear mode current sources [25], a novel linear current module with wide operating voltage range based on adaptive series/parallel conversion is proposed. As the operating voltage changes from low to high, the connection of load branches changes from parallel to hybrid, and finally to series. And the number of parallel constant current branches is correspondingly gradually increasing. The current in each

load branch is constant. And the power of total load is constant, too. The adaptive conversion of connection of current branches and load branches is controlled by a switch array. LED driver is one of the main applications of constant current source [23, 24, 26, 27, 28, 29, 30, 31]. Based on the proposed linear current module, a four-segment LED driver is designed and experimentally verified. Four LED segments and four constant current branches are connected in parallel, respectively, and constant current connects LED block in series at lower operating voltage. At middle operating voltage, two parallel constant current branches connect two parallel LED branches in series. Two LED segments connect in series in each LED branch. And a constant current branch connects four series LED segments in series at higher operating voltage. During the whole operating voltage range (15-60V), the current in each LED segment is nearly the same and stable, and the total power of LEDs is invariable.

2. Design and analysis

Conventionally, switch mode current sources provide relatively large current to load. Several branches of load driven by a switch mode current source are connected in parallel. The output current of linear constant current modules is always relatively lower. Loads driven by a linear constant current source are always connected in series. The voltage drop on the linear constant current module will change greatly due to the wide range of operating voltage. In order to reduce the variation of voltage drop on the linear constant current module, the connection between constant current branches and load branches can be adaptively changed from parallel to hybrid, and finally to series as the operating voltage changes from low to high.

The block diagram of the proposed linear current module adaptive to wide operating voltage range is shown in the dashed box in Fig. 1. In this module, constant current block and load are connected in series. The linear current block is averagely divided into n branches (n is even number). And correspondingly, load is averagely divided into n segments. According to the controlling vector EN_1 , EN_2 , to EN_n from the comparison of voltage reference V_{ref_1} to V_{ref_m} and the detection of the input DC voltage V_d , the switch array controls n load segments connect in series, hybrid and parallel, and the number of constant current branches correspondingly increase according to the number of load branches in parallel, during the operating voltage changes from low to high. When the input DC operating voltage is lower (as-

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Fig. 1 Block diagram of linear current module adaptive to wide operating voltage range.

suming the threshold voltage is V_{T1} , $V_{DC} < V_{T1}$) all constant current branches and all load segments are connected in parallel, respectively. And then the constant current block and the load are connected in series. Setting this mode as *parallel mode*.

As the input DC operating voltage rises, the switch array adaptively parallels appropriate constant current branches and correspondingly transfers the load into hybrid connection. With the increase of DC operating voltage, the number of segments connected in series is gradually increased and the number of parallel load branches is correspondingly gradually reduced. The number of connected constant current branches in parallel is consistent with the number of parallel branches in the load of hybrid connection. Setting this mode as *hybrid mode*. Taking $n = 12$ for example, five threshold voltages (V_{T1} , V_{T2} , V_{T3} , V_{T4} , V_{T5}) are needed. setting a is the number of load branches, b is the number of segments connected in series in a load branch, and c is the number of constant current branches in parallel. In *hybrid mode*, when $V_{T1} < V_{DC} < V_{T2}$, $a = 6$, $b = 2$, and $c = 6$. When $V_{T2} < V_{DC} < V_{T3}$, $a = 4$, $b = 3$, and $c = 4$. When $V_{T3} < V_{DC} < V_{T4}$, $a = 3$, $b = 4$, and $c = 3$. When $V_{T4} < V_{DC} < V_{T5}$, $a = 2$, $b = 6$, and $c = 2$.

While the input DC operating voltage is high enough (assuming the threshold voltage is V_{Tm} , $V_{DC} > V_{Tm}$), a constant current branch is connected in series with all series connected load segments. Setting this mode as *series mode*.

The design described above is verified by a LED linear current driver. In linear constant current drivers of LED, segmented linear constant current source, such as lighting LED segments up one by one as the operating voltage goes from low to high [28, 29, 30], or turning on LEDs on the opposite arm of a rectifier bridge composed of LEDs in each half cycle of the city electricity [31], is a driving method with obvious advantages in voltage operating range, conversion efficiency, etc.. However, at present, the significant drawback of commercial segmented linear constant current driving methods of LED is that the lighting of LEDs is not stable within the whole operating voltage range.

Fig. 2 shows the LED driving circuit based on the proposed linear current module adaptive to wide operating voltage. The constant current block is composed by four branches. A constant current branch is a 20mA current regulative diode (CRD). The LED load are divided into four segments. In each segment, there are three LEDs. The power of a LED is $3.2V \times 20mA$. During the full range of the DC power voltage (15-60V), the detection voltage V_d

Fig. 2 LED linear current driving circuit based on adaptive series/parallel conversion for wide operating voltage range.

obtained by resistance voltage divider is compared with two voltage references V_{ref_1} and V_{ref_2} obtained by a simple circuit based on Zener diode to generate control signal EN_1 , EN_2 , EN_3 and EN_4 to control the status of switches in switch array. Under low DC power voltage (15V-24V), switches S1, S2 and S3 are off, and others are on. Four parallel connected constant current branches provide 80mA current to drive four parallel connected LED segments. As the DC power voltage rises to 24V-48V, switches S1, S3, S5 and S8 are on, and others are off. Two parallel connected constant current branches provide 40mA current to drive two parallel connected load branches. In each load branch, two LED segments connect in series. While the DC power voltage is in 48V-60V, switches S1, S2 and S3 are on, and others are off. One constant current branch provides 20mA current to drive four series connected LED segments. MOSFETs Q1-Q6 correspondingly provide floating control for S1-S6, respectively.

3. Experimental verification

In the experimental circuit, constant current voltage range of CRDs is 4.5-40V. Setting $V_{ref_1} = 4V$, $V_{ref_2} = 2V$, $R1 = 1k\Omega$, $R2: R3: R4 = 3: 1: 1$, $R5: R6: R7 = 10: 1: 1$. Testing results show that V_{DD} varies from 10.18V to 10.91V for V_{DC} in the range of 15-60V. Power supply voltage regulation rate of V_{DD} is 16.2mV/V.

When V_{DC} varies in the range of 15-60V, tested results of control vector, state of switches, connection mode of LED segments, and voltage drop on each LED segment are given in Table I. For V_{DC} in 15-24V, $EN_1 = EN_2 = 1$, $EN_3 = EN_4 = 0$, switches S4, S5, S6, S7, S8, S9 are turned on to control four LED segments connected in parallel. $V_A = V_B = V_C = V_D = 9.4V$ confirms the *parallel mode* of LED load. When V_{DC} is in 15-24V, $EN_2 = EN_3 = 1$, $EN_1 = EN_4 = 0$, S1, S3, S5, S8 are turned on to control LED_1 connects LED_2 in series, LED_3 connects LED_4 in series, and these two LED branches are connected in parallel. $V_A = V_C = 19.7V$ and $V_B = V_D = 9.4V$ confirms the *hybrid mode* of LED load. While V_{DC} is in 48-60V, EN_1

Table 1 Tested results of control vector, state of switches, connecting mode of LED segments, and voltage drop on each LED segment in the range of 15–60V for V_{DC}

V_{DC} (V)	15~24	24~48	48~60
control signals	$EN_1 = 1$ $EN_2 = 1$ $EN_3 = 0$ $EN_4 = 0$	$EN_1 = 0$ $EN_2 = 1$ $EN_3 = 1$ $EN_4 = 0$	$EN_1 = 0$ $EN_2 = 0$ $EN_3 = 1$ $EN_4 = 1$
on-state switches	S4, S5, S6, S7, S8, S9	S1, S3, S5, S8	S1, S2, S3
off-state switches	S1, S2, S3	S2, S4, S6, S7, S9	S4, S5, S6, S7, S8, S9
LED segments connecting	parallel mode	hybrid mode	series mode
voltage on LED segments (V)	$V_A = 9.4$ $V_B = 9.4$ $V_C = 9.4$ $V_D = 9.4$	$V_A = 19.7$ $V_B = 9.4$ $V_C = 19.7$ $V_D = 9.4$	$V_A = 38.7$ $V_B = 28.7$ $V_C = 19.7$ $V_D = 9.4$

Fig. 3 Current in each LED segment obtained by varying V_{DC} .

$= EN_2 = 0, EN_3 = EN_4 = 1$, S1, S2, S3 are turned on to control four LED segments connected in series. $V_A = 38.7V$, $V_B = 28.7V$, $V_C = 19.7V$ and $V_D = 9.4V$ confirms the *series mode* of LED load.

Fig. 3 indicates that tested current in each LED segment is stable at about 20mA during V_{DC} in 15–60V. The voltage regulation rate for I_{LED_1} , I_{LED_2} , I_{LED_3} and I_{LED_4} is 66.7 $\mu A/V$, 82.2 $\mu A/V$, 77.8 $\mu A/V$, 84.4 $\mu A/V$, respectively. As shown in Fig. 3, current in each LED segment decreases obviously when the input DC voltage is slightly greater than 48V. The reason is as following: When the input DC voltage is slightly greater than 48V, the connection mode of LED segments changes from *hybrid mode* to *series mode*. The voltage drop on LED load increases dramatically, resulting in a sharp decrease of voltage drop on the linear current block.

In Fig. 4, for the conventional constant current driving scheme which contains a CRD and 12 LEDs connected in series, when $V_{DC} < 30V$, the LED power is about zero because the voltage drop on each LED is lower than its on voltage. LEDs do not reach their rate power until $V_{DC} > 40V$. For the proposed linear current driving scheme, in which the connection of load branches adaptively changes from parallel to hybrid, and finally to series as the operating voltage changes from low to high, the LED power is nearly invariable in the whole range of V_{DC} (15–60V), because the

Fig. 4 Tested result of LED power of conventional constant current driving scheme and proposed linear current driving scheme.

current in each LED segment is constant, as shown in Fig. 3 in the whole range of V_{DC} .

4. Conclusion

A novel linear current module adaptive to wide operating voltage range, combining the advantages of switch mode and linear mode current sources, is proposed. A switch array is employed to adaptively convert the series/hybrid/parallel connection mode of load segments according to the change of DC operating voltage. The proposed linear current module can make sure that the current in each load segment and the total power of load is constant, respectively, during wide operating voltage range. A four-segment LED (3 LEDs connect in series in each segment) driver is used to experimentally verify the proposed linear current module. During 15–60V of operating voltage range, the current in each LED segment is stable around 20mA, and the total power of all four LED segments is nearly invariable (0.693~0.804W). Compared with the conventional linear current LED driving scheme which contains a CRD and 12 LEDs connected in series, the operating voltage range of the proposed module is obviously wider.

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