Study of Digital LED Driving Technology based on Auto-Identifying Open Strings in LEDs Array

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***Abstract*-A novel two-stage digital control driver for the high bright LEDs is proposed. The front stage is a PFC circuit controlled by the chip MC33262, the DC/DC stage is a half bridge circuit controlled by the micro-controller. The output current of the controller is adjusted according to the number of the strings in the open-circuit state, so the current of a single LED ring is always nearly constant even when several LED rings are in the open-circuit state. In the paper, the design process of the system is presented, an 112W prototype is presented in the laboratory, and the experimental results verify the control method proposed in the paper.**

I. INTRODUCTION

With the development of the LED encapsulation technology and the manufacturing process, the high bright LED begins to be greatly used. The project " Ten Thousands in Ten Cities" that started in 2009 in China replaced 10000 HPS lamps for LEDs in each ten city and the LEDs will be widely used in many other fields, especially in the street lighting. Many cities have the demonstration road for the LED lighting.

The power of the LED street light is mostly between 100W to 200W. The power of each LED lamp is low so it is necessary to use the LED array by series and parallel connections. The best driving mode for the LED is the constant current control, rather than the constant voltage driving mode, which was harmful to the useful time of the LED lamp[1-2].

A common failure case in LED lighting is the open circuit state. Once a LED in a series is broken, all of the LEDs in this series will stop working. Because the LED lighting system has many parallel branches, it's complicated to use independent driver for each branch, which means that we must provide a constant current control circuit and an open circuit protection circuit for each branch, the volume of the driver is big and the costs are also high. It is also difficult to control and adjust the current in each branch in the case of driving all paralleled branches with a single converter, although the total current of the LED arrays can be controlled.

If the total current is controlled to be constant with a single driver, once a branch in the LED array is in the open-circuit state, the current of other branches will increase, the LEDs in other branches will be damaged by the over current, and other branches will be broken successively.

In order to solve this problem, a novel LED driver strategy is proposed base on auto-identification of the number of open circuit rings in the LED lighting system, the design methods of the power circuit and the controller are presented. Experiment results are also given for verifying the validation of the proposal driver.

II. CIRCUIT ANALYSIS

Fig.1 shows the proposed lighting system. The full power for the LED driver shown in Fig.1 is 112W. The system consists of eight parallel branches, with 12 LEDs in each branch. The driver has two power stages. The former is the power factor corrector circuit, which can realize the power factor correction function and provide a stable bus voltage for the latter stage [3-4]. The latter is a resonant half bridge DC/DC current source converter, which supplies a constant total current for the LED array by adjusting the switching frequency.

MC68HC908KX8 by Freescale is adopted here to control the LED lighting system. The open-circuit signals are detected by the MCU, and the MCU can adjust the working frequency to keep the total current constant. The eight open-circuit signals are named as A, B, C, D, E, F, G, H. A sampling circuit consists of a current transformer, a rectifier and a low-frequency pass filter. The average current is sampled here to obtain the information of the total driving current for the array. With ADC module of the MCU, the value of the total current for the system is obtained by the MCU.

A. Design of the active power factor corrector

The boost circuit working in the CRM mode is usually adopted to be the PFC circuit with 400V bus voltage. However, the input voltage for the LED array is usually 48V, which makes the voltage transfer ratio of the resonant half bridge DC-DC converter very low. So there is too much reactive power exchange in the half bridge and the output capacitor, and it also makes the adjustment frequency ranging scope for different open-circuit number too broad, which makes it difficult to design the EMI filter of the system. In this article, we mainly study the driving of LED array, so in spite of the problems, the boost CRM mode APFC circuit is still adopted. In the future work, some other PFC converter with lower bus voltage will be used to replace the boost CRM mode APFC.

B. Resonant DC-DC current source converter

Resonant DC-DC current source converter is consisted of a class-D resonant converter, a rectifier, a filter inductor and the LED array as the load.

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In the process of the current adjustment, the voltage change for the LED load is very little, so the LED array can be assumed as a constant voltage load, whose value is set to 46V. We can also assume that the rated current of each LED is 330 mA. The equivalent impedance of each LED string can be approximated as 140Ω, so 8 strings can be equivalent to 17.5Ω.

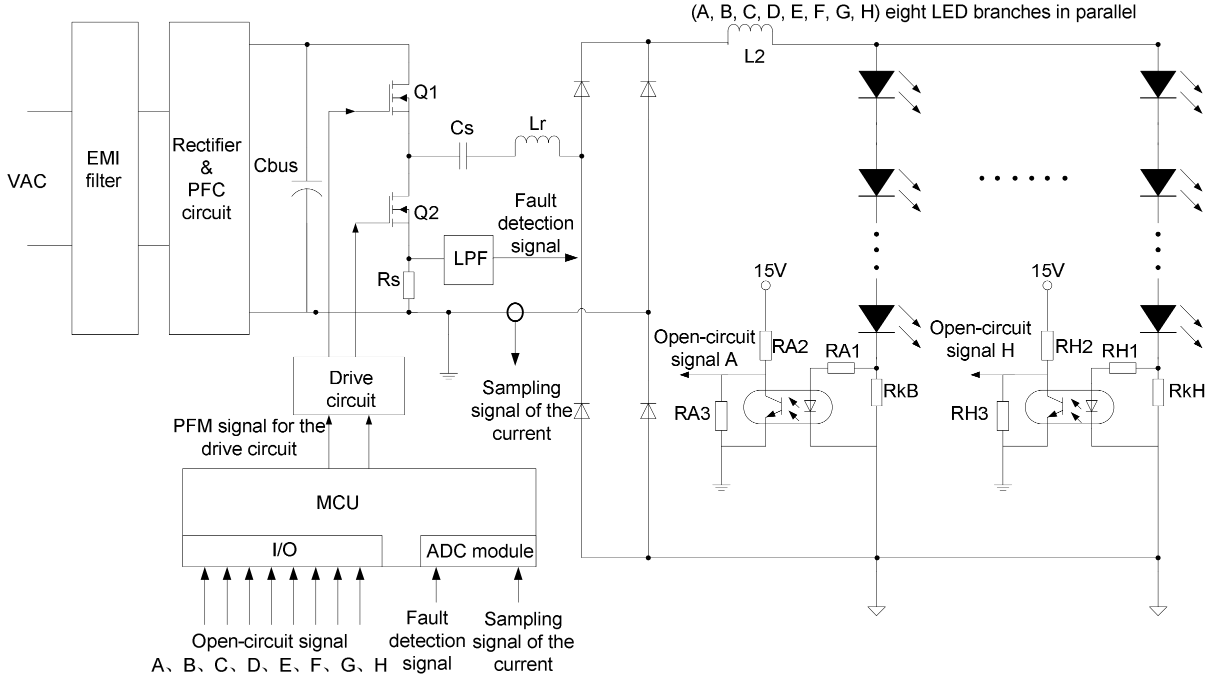

Fig.1 Proposed LED lighting system

The equivalent circuit is shown in Fig.2. The DC bus voltage is 400V, therefore the RMS value of the fundamental component of the voltage for the half-bridge midpoint is $\sqrt{2}U_{BUS}/\pi$ =180V[5].

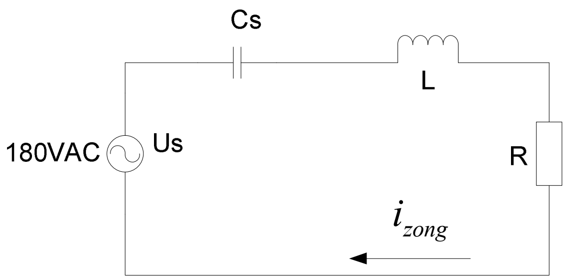

Fig.2 Equivalent circuit of the LED driver

Considering the characteristics of the series resonance with *LC* type, with the increase in the number of the broken LED rings, the total parallel equivalent impedance increases and the total current decreases step by step. We can find that the frequency will increase greatly.

To reduce the noise, the lowest switching frequency must be higher than the highest acoustic frequency, which is 25 kHz. The switching frequency under the full load is set to 35 kHz. In order to limit the high switching frequency, when 5 branches are all in the open-circuit state, the switching frequency is set to100 kHz.

Therefore the resonant inductor *L* and capacitor *Cs* can be designed under 35 kHz when 8 branches operate normally.

According to the equivalent circuit schematic shown in Fig. 2, the total current can be calculated by the equation as follows.

$$i_{zong}(t)=\frac{u_S(t)}{Z}=\frac{u_S(t)}{R+j\left(\omega L-\frac{1}{\omega C_S}\right)} \tag{1}$$

Where

$i_{zong}(t)$ is the instantaneous value of the total current, Z is the equivalent impedance of U_S, R is the equivalent impedance of the LED array, ω is the switch angular frequency.

Here $u_s(t)=\frac{2}{\pi}U_{bus}\sin(\omega t)=U_s\sin(\omega t)=180\sqrt{2}\sin(\omega t)$

If all 8 branches operate normally, the RMS value of the total current can be set as follows:

$$I_{zong}=330mA\times 8=2640mA \tag{2}$$

According to (1) and (2), the complex impedance including inductor *L* and capacitor *Cs* can be obtained as follows.

$$\omega L-\frac{1}{\omega C_S}=\sqrt{\left(\frac{U_s}{I_{zong}}\right)^2-R^2} \tag{3}$$

Where U_s =180V, I_{zong} =2640mA and R =17.5Ω, the complex impedance can be calculated as follows.

$$\omega L-\frac{1}{\omega C_S}=\sqrt{\left(\frac{180}{2.64}\right)^2-17.5^2}=65.9\Omega \tag{4}$$

Here *Cs* has little effect on the result and can be selected to 100 μF, thus the value of the inductance can be calculated as follows.

$$L=\frac{\mathrm{Im}(Z)+\frac{1}{\omega C_S}}{\omega} \tag{5}$$

$$=\frac{65.9+\frac{1}{2\pi\times35\times1000\cdot100\times10^{-9}}}{2\pi\times35\times1000}=507uH$$

If there are only three normal operating branches, then I_{zong} =0.99mA and R =46.67Ω, the complex impedance under this condition can be calculated as follows.

$$\omega\big|_3\cdot L-\frac{1}{\omega\big|_3\cdot C_S}=\sqrt{\left(\frac{180}{0.99}\right)^2-46.67^2}=175.7\Omega \tag{6}$$

The equation of the switch angular frequency can be obtained as follows.

$$LC\omega\big|_3^2-175.7C\omega\big|_3-1=0 \tag{7}$$

Then the switching frequency when there are only three normal branches can be obtained.

$$f\big|_3=63.2\text{kHz}。$$

According to (6) and (7), the switching frequency under different open-circuit number can be calculated and listed in Tab.1.

Tab.1 Calculated parameters with different open strings

Number of branches operated normally	Total current (mA)	Equivalent impedance of LED array (Ω)	Calculated switching frequency （kHz）
8	2640	17.5	35
7	2310	20	37.1
6	1980	23.33	40.1
5	1650	28	44.4
4	1320	35	51.2
3	990	46.67	63.2

C. *Protection circuit for the open-circuit fault*

The detection circuit for the open-circuit fault for each branch is shown in Fig.3, a opticalcoupler is adopted for sampling the open-circuit state of the LED ring, the opticalcoupler can also realize the isolation of the output side and the input side.

As shown in Fig.3, if there is no LED in the open-circuit state in a branch, the diode of the opticalcoupler is turned on, the transistor of the opticalcoupler is also turned on, then the corresponding I/O is in the low level condition. In this circuit, the parameters are shown as follows.

Rkx = 5Ω, *Rx1* = 200Ω, *Rx2*=20kΩ, *Rx3*=10kΩ.

When the LED in the branch is in the open-circuit state, the diode of the opticalcoupler is turned off, and the transistor is also turned off. The open circuit detecting signal for MCU Kx changes to high level.

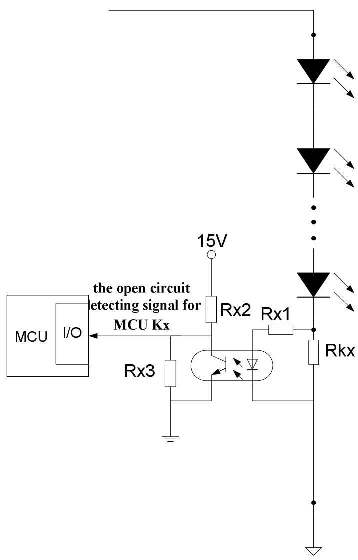

Fig.3 Circuit for detecting open LED strings

The open circuit detecting signals for MCU Kx (x=A,B,C,D,E,F,G,H,I) are connected to eight pins of MCU. Once the level of one pin changes to high level, the number of the open-circuit branches will plus 1. Through detecting number of the pins in the high lever state, the MCU will know the number of the branches that are in the open-circuit state.

D. *Current sampling and the design of closed-loop controller.*

With the increasing of the branches in the parallel circuit, it is difficult to make each of the branches with independent constant current control, so it's suitable to make the total current of LED rings constant.

As shown in Fig.1, a current transformer(CT) is used to sampling the current, the AC current passes through the half-wave rectifier with a diode, then the current signal is changed to the voltage signal, the voltage signal passes through a RC type low pass filter, then we can get the information of the total current through all the 8 LED branches. This analog signal is send to MCU, and a digital value which is used as the practical total current signal for the total current close-loop control is gotten by the use of the ADC module of the MCU.

During the close-loop control processing, the reference of current value is redefined according to the number of the branches in the open-circuit state, then through comparing the practical total current with the defined reference value the suitable switching frequency is obtain to adjust the total current of the branches which are still working. The control diagram is shown in Fig.4.

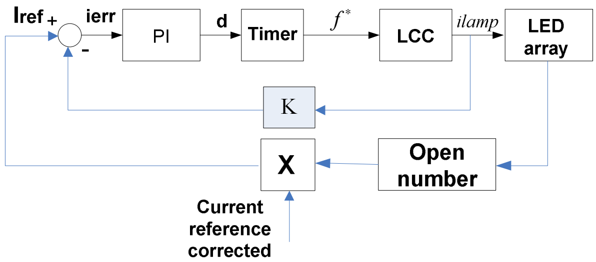

Fig.4 Block graph of the closed loop current control

III. EXPERIMENT RESULT AND ANALYSIS

Fig.5 shows the prototype used in the laboratory. The waveforms of the voltage and the current for one branch are shown in Fig.6 when 8 branches work together. The waveforms of the voltage and the current are shown in Fig.7 when 3 branches work together. It is evident that with the increase in the number of the branches in the open circuit state, the current of every branch keeps constant and the voltage of the parallel circuit is with little change. The Lissajous figure of one branch is shown in Fig.8. It is evident that the LED load is not a pure resistive load.

Fig.9 shows the voltage of Q2, the voltage of the rectifier in the input side, and the total current of the system when all of the 8 branches operate normally. It's evident that there is a certain phase shift between them. The different is decided by the load network consisted of Cs, L, the rectifier and the LED load. Fig.10 shows the voltage of Q2 and the voltage of the rectifier in the input side when only 3 branches operate normally. It is evident that with the increase in the number of the branches in the open-circuit state, the load is lower and the switching frequency is higher while the phase shift between them is with little change, and the total current gets smaller and changes step by step.

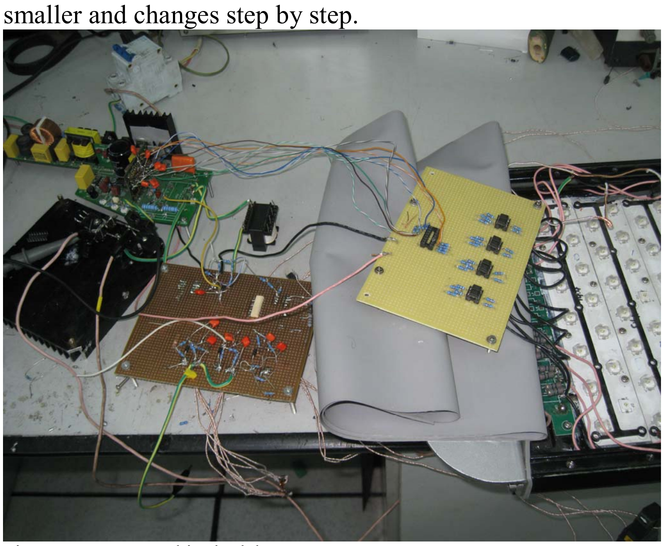

Fig.5 Prototype used in the laboratory

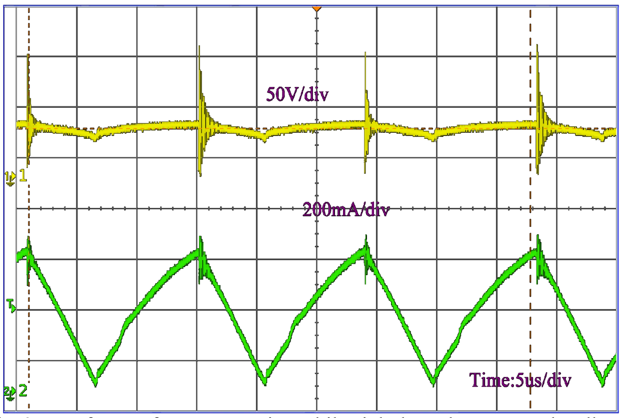

Fig.6 Waveforms of one LED string while eight branches operated well

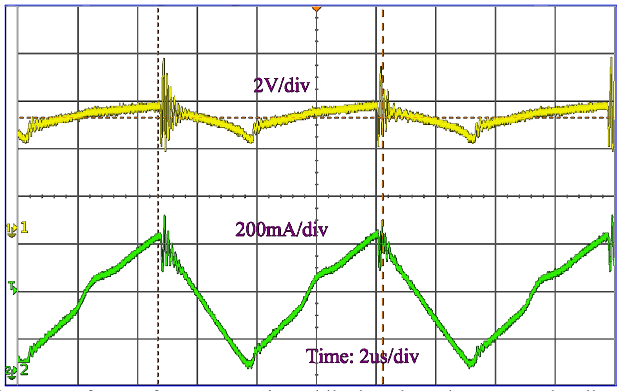

Fig.7 Waveforms of one LED string while three branches operated well

Tab.2 Input and output parameters with different open strings

Number of remainder branch	Input power (W)	Power factor	THD (%)	Switch frequeny (kHz)	Total Current (A)
8	123.7	0.987	7.4	36.33	2.648
7	106.0	0.981	8.2	38.1	2.342
6	95.3	0.978	9.2	42.4	2.017
5	76.4	0.967	10.8	46.1	1.660
4	59.4	0.948	13.3	53.2	1.350
3	42.8	0.910	17.8	65.6	1.003

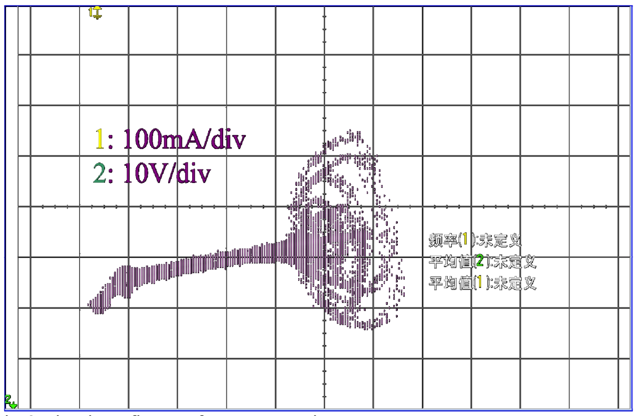

Fig.8 Lissajous figure of one LED string

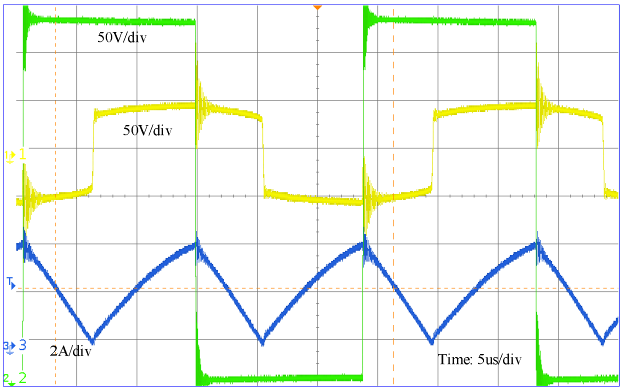

Fig.9 Waveforms of the voltage of the half bridge's mid-point and input voltage of the rectifier and the total current while all paralleled branches operate well

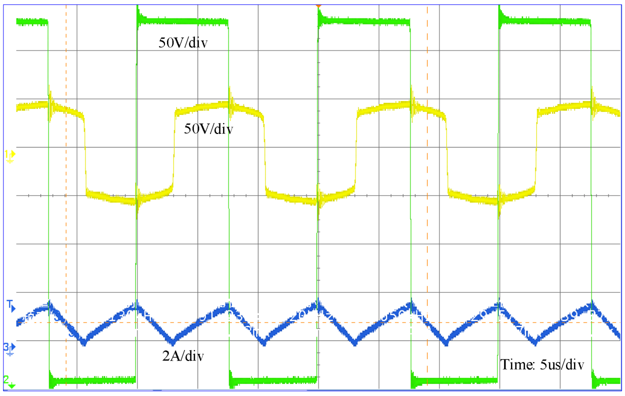

Fig.10 Waveforms of the voltage of the half bridge's mid-point and input voltage of the rectifier and the total current while only three paralleled branches operate well

Tab. 2 shows the input and the output parameters under different numbers of branches that are in the open-circuit state. If the load is smaller, the power factor is lower and the THD increases. The average LED current for each branch remains almost constant.

IV. CONCLUSION

A novel LED driver with digital control for high power level lighting based on auto-identifying open-circuit strings in LEDs array is proposed. The total drive current of the LED array is adjustable according to the identified number of the strings in the open-circuit state. With this control method, the current of each LED string is nearly constant no matter which branch is in the open-circuit state. The design method is presented in the paper. The experimental results verify the effect of the constant current driver with different number of open strings.

In the next step, we will reduce the resonant half-bridge bus voltage and increase the voltage transfer ratio by using other APFC circuits.

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