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LED Growth Light with Flexible Photoperiods and Programmable Light Output Intensity

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Abstract. Water, food and energy are going to be a big challenge in the future. As a result of understanding this fact that the world cannot only depend on conventional agriculture, it is moving towards soil-free, sunlight-free, and pesticides-free self-sustainable indoor cultivation systems. Indoor cultivation works without changing anything about the genetics of seeds but just by optimizing the environment where plants are growing, so called a controlled environment. Researchers, engineers and programmers are helping to rebuild the global agriculture industry by providing a path of technological opportunities for people of modest means to become farmers. Thus, light emitting diode (LED) lighting systems were introduced to replace sunlight in indoor cultivation systems. When LEDs are applied in such high power application as multiple parallel strings it has a current deviation issue that leads to short life-time, uncontrolled light intensity, and additional energy consumption of LEDs. This paper presents an active current balance approach by using switch mode current converters to regulate and balance the current in each LED string with flexible photoperiod and light intensity levels. We also improved the current deviation deficiency from 32.7-28.5% to 6.5% in multi-parallel LED strings system.

Keywords: Indoor cultivation, Multi-LED strings, Current balancing, Programmable MCU, Light Intensity

1. Introduction

Other than natural sunlight based crops growing system, fully artificial light (FAL) based growing system is getting more attention globally not only because of climate change and increasing population. It is also a result of increasing awareness among public about pesticides free crops and diminishing nutrients level in fresh vegetables and fruits due to logistics and others [1], [2]. Therefore, plant factories or indoor cultivation systems are growing very fast in this decade.

In an indoor cultivation system, a light source is required to provide the necessary catalyst that allows plants to produce glucose and oxygen from carbon dioxide in the process of photosynthesis. This glucose or the "fuel" is used by plants to keep them survive and grow. The amount of this "fuel" produced in the photosynthesis process depends on the amount of light being absorbed by different pigments on leaf to promote growth. Major pigments including chlorophyll-a, chlorophyll-b and beta-carotene have different absorption peaks at different specific wavelengths of light spectrum.

Conventional light sources such as florescent and high intensity discharge (HID) lamps provide full light spectrum from which not all the light energies are being absorbed for photosynthesis process. LEDs, unlike florescent and HID lamps, can be manufactured to produce narrow light spectrum with specific peak and therefore can provide more effective absorption than the conventional light sources powered with the same amount of electricity. Other advantageous features such robustness, non-toxic, high efficiency, and longevity also make LEDs increasingly to be used for indoor farming.

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In order to promote plant growth, a large number of LEDs are connected to provide a sufficient level of photosynthetic photon flux density (PPFD). Series connection of LEDs can provide a simple solution, however it gives rise to the safety concern that a high-voltage stress is imposed on the LED driver. Changes in supply voltage of LEDs result into changes in LED's light output, and life time. For instance, a small drop in forward voltage causes a large increase in forward current at a given temperature. The increased current generates excessive heat at the PN junction of LEDs. If nothing limits the current, it may result in lower luminance or catastrophic failure. This phenomenon is known as thermal runaway.

Moreover, a single LED failure in such connection might cause the breakdown of the entire lighting system. Thus, several LED strings are used collectively and driven in parallel by a common bus voltage. However, due to the manufacturing spreads of I-V characteristics, negative temperature coefficient, and different forward voltages for LEDs with different wavelengths, current tends to distribute non-uniformly among the parallel-connected LED strings which leads to non-uniform light output or even a rapid deterioration of LEDs. As a result, a current balancing mechanism must be added into the LED driver to equalize the currents among the multiple LED strings.

In this paper, we propose an active current balance approach by using switch-mode current converters to regulate and balance the current in each LED string. By programming the ON-OFF time interval and pulse-width of each current converter, we can also select different photoperiods and provide light output of different peak wavelengths and intensities for different stages of plant growth.

2. Flexible Growth Light System

2.1 Current imbalance

Typical indoor cultivation systems consists of more number of LEDs connected in the form of strings, and each string has multiple LEDs in series to provide enough light intensity to the plant growth. While driving these multiple LED strings in parallel there is always an issue that string currents are not equal or unbalanced. The reason is that there is a disproportional relationship between the current and the voltage of LEDs because of its electrical characteristics variation due to manufacturing and wiring processes. Fig. 1 shows the relationship between forward voltage and forward current of two different LED strings. In which, the current (I_2) of string2 is greater than the current (I_1) of string1 for the same forward voltage value (V_{DC}). Thus, different forward voltage drop can cause dramatically different current flow through each string.

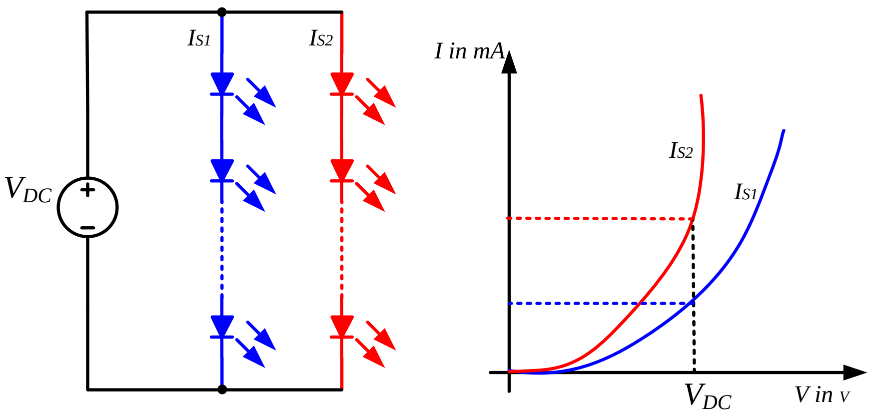


Fig. 1: Current Imbalance in multi-string LEDs

Generally, LEDs have a long life time upto 100,000 hours when compared to incandescent lamps with only 1000 hours, fluorescent lamps with 20,000 hours and HID lamps with 30,000 hours. But the unbalanced currents may cause high current with high junction temperature on LEDs. This can give over stress on LEDs and result early light degradation and may largely affect the longevity of LEDs. Also, the unbalanced currents can cause different luminous output and unintentional light intensity from LED strings that can impact the plant growth. If there is no individual control on LED strings then the light intensity variations may not provide an optimal growth environment to indoor cultivation system.

Therefore, it requires a current balancing mechanism to ensure that each LED string has the same current. There are some previous works proposed the current balancing mechanisms for multi-parallel LED strings [3]-[16] which are based on either i. passive components such as resistors [3], inductors [4], transformers [5], and capacitors [6] or ii. active components with linear and switching mode [7] techniques.

2.2 Programmable Current Balance Controller

In this paper, we have used a programmable microcontroller with a low cost DC/DC converter in order to control individual LED strings of the lighting system. The current control was achieved using pulse width modulation (PWM) where the current supplied to the LEDs is in terms of a rectangular wave with varied duty cycle. The current sharing was simply realized by assigning a reference driving signal to LED strings through gate controlled switches (ex. SW1, SW2 … etc.), while individual current regulation is accomplished by assigning a different duty cycle command for each string as shown in Fig. 2.

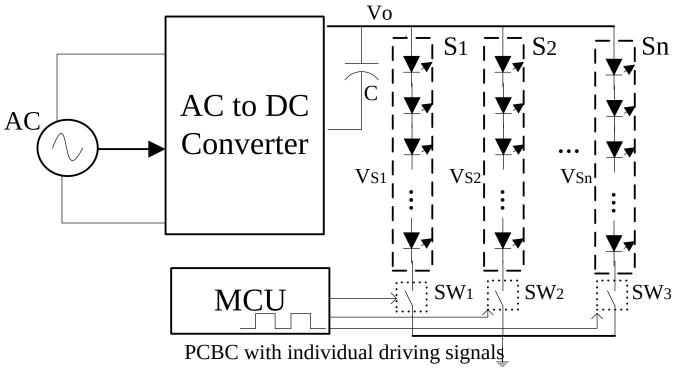


Fig. 2: Proposed Programmable Current Balance Controller (PCBC) with individual LED string drive signals

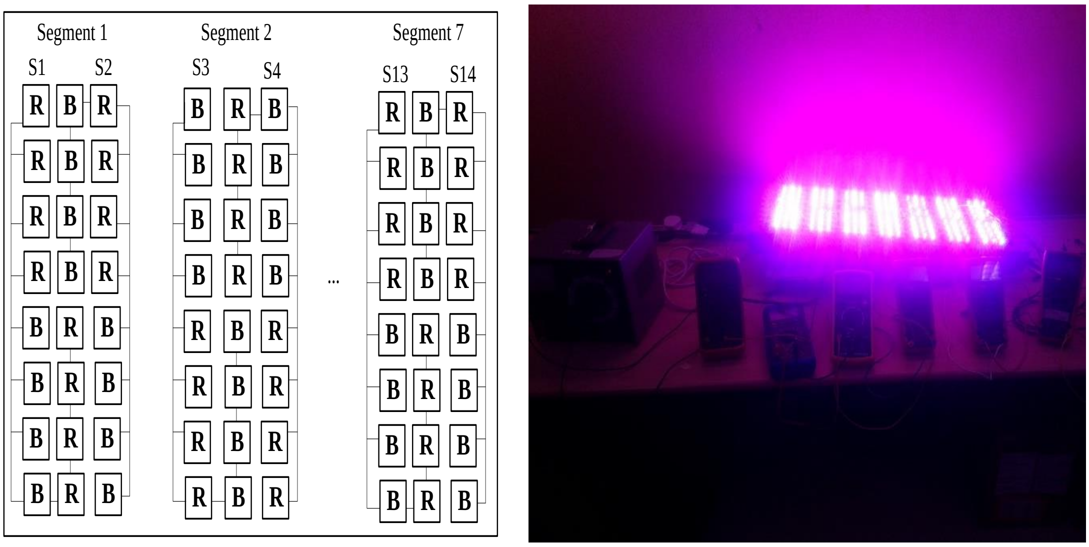
The proposed technique can dim-down or brighten-up or turn-on or turn-off every single LED string in the system. In multi-parallel LED strings of indoor cultivation applications, dimming one or more LED strings can help energy savings greatly. As an additional feature of the proposed work, it can be used to select a required wavelength for an each stage of the plant growth or a specific wavelength for different plants on the same growth bed. Also, it provides flexible, controllable and programmable light intensity to the optimal growth of plants. The basic idea of this paper lies in the process of controlling the amount of current supplied to every single LED string through MCU programs, and increase the longevity of LEDs through the current balance mechanism.

3. Experiments and Analysis

3.1 Test setup

The test case design consists of a LED lighting panel with the size of 60 cm x 30 cm that used 7 segments and each segment was with 2 strings. Each string contains 12 LEDs and there are 168 LEDs in 14 strings in order to generate the required light for the photosynthesis of the crop. To provide a uniform photosynthetic photon flux density (PPFD) generated by red and blue LEDs, the light panel used red and blue LEDs alternatively as shown in Fig. 3 (a). In total the panel used 84 red LED (660 nm) and 84 blue LEDs (450 nm) to ensure the light intensity ratio between the two types as shown in Fig. 3 (b). The average PPFD was measured with a photosynthetically active radiation (PAR) meter (Apogee MQ-200) at a distance 15 cm below the LED panel. In test case 1, AC/DC stage which generates a single common output bus that is shared by all the LED strings without current balancing. In test case 2, a low-cost high-efficiency programmable current balance controller (PCBC) was used to supply a separate output voltage pulses for each LED string in order to provide the current balance, desired light intensity, wavelength and photoperiod of LEDs.

However, our goal of the experiments is to identify the current imbalance of the conventional method where individual LED strings are not controllable regarding to their photoperiod, brightness and wavelength. We have addressed these drawbacks in our modified LED panel design in which we improved the current imbalance deviation from 32.7-28.5% to 6.5%. This plays a significant role in the lifetime of LED strings and the plant growth.



(a) (b)

Fig. 3: Test setup (a) LED Panel design, and (b) V and I measurements for individual LED strings

3.2 Experiment Results and Discussions

Case 1: Without Current Balancing

In test case 1, we measured the current and voltage for all 7 segments. The measurements are shown in Table 1. It shows that the voltage measurements across different segments are almost the same but the current flow varies in each segment. The minimum current measured was in Segment 2 such as 1.1A and the maximum current measured was in segment 7 such as 1.46A. It means the current deviation percent in this LED panel is 32.7%. This current imbalance can easily affect the life-time of the LEDs, and also plants growth to certain level.

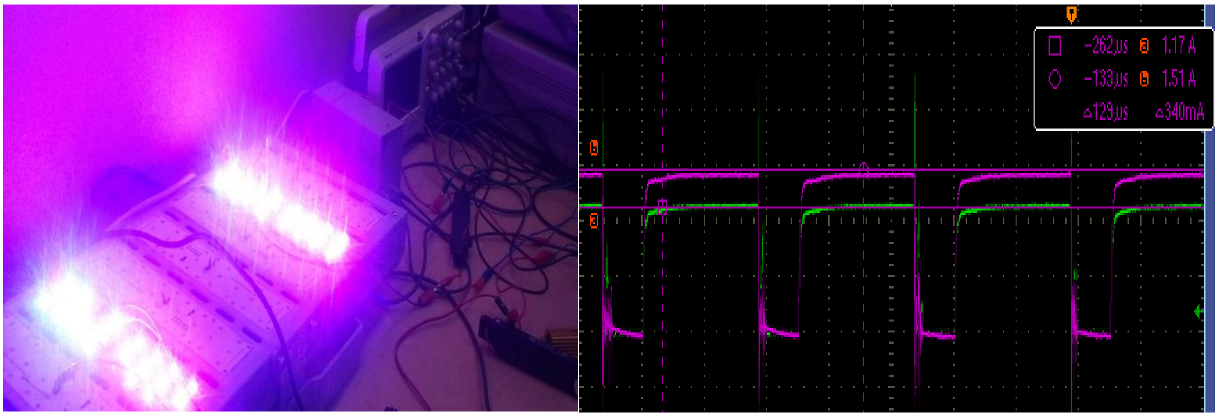
Table 1: Measurements of LED Panel

	Segment 1	**Segment 2**	**Segment 3**	**Segment 4**	**Segment 5**	**Segment 6**	**Segment 7**
No. of red LEDs	12	12	12	12	12	12	12
No. of Blue LEDs	12	12	12	12	12	12	12
Voltage in V	34.3	34.3	34.3	34.3	34.3	34.3	34.3
Current in A	1.42	1.10	1.37	1.45	1.16	1.45	1.46

Case 2: With Current Balancing

In test case 2, we conducted two different experiments. In the first experiment, we considered two extreme segments that showed the minimum and maximum current values. For instance, segment 2 and segment 7. We applied current pulses to drive these two strings under the same duty cycle (*D*) such as 0.752. The current in LED strings of segment 2 and segment 7 were measured as 1.51A (I_1) and 1.17A (I_2), respectively. It shows the average current on segment 2 was $DI_1=1.13A$, and the average current on segment 7 was $DI_2=0.879A$. These current values are different even though the segments were driven through MCU pulses. Here, the observed current deviation percentage is high such as 28.5.

In the second experiment, we adjusted the duty cycle values and applied different on-time duty cycles to segments 2 and 7 under the same condition as above. When $D_1=0.640$, we achieved the average current in segment 2 as $D_1I_{1=}\ 0.966A$, and when $D_2=0.776$, we achieved the average current in segment 7 as $D_2I_{2=}\ 0.907A$. In this case, the observed current deviation percentage is 6.5%, and these two current values are close to each other. It shows that we achieved a current balance on LED string for these duty cycle values. By following the same procedure, we can identify the combination of different duty cycle values that can provide a current balance in LED strings of all segments and the reference values can be supplied to LED strings automatically through a programmable current balance controller (PCBC). We used ATMEGA2560 with ATMEL processor for programming. The experimental results and current waveforms are shown in Fig. 4.



(a) (b)

Fig. 4: (a) Current measurements for LED strings from segments 2 and 7, and (b) I_1 and I_2 waveform

The key idea is to achieve the current balance in multi-parallel LED strings by adjusting duty cycle values. This also gives an additional features such as dimming, brightening, on and off control on LED strings that can be effectively achieved by PCBCs.

3.3 Indoor Cultivation Application

To apply the current balanced multi-parallel LED strings system to plant studies and cultivation, our system used 4 wavelength bands (450nm, 525nm, 630nm, 660nm). The ratio of each bands are mixed to optimize the growth of plants at different stages. Since chlorophylls are the most important pigments for growth with peaks detected at 429 to 455nm and 642 to 659nm [1], it gives the basis of the LED selection for plant lighting. The driving circuit has a desired control over the lighting environment. The PCBC program allows a linear adjustment of duty ratio from 0% to 100%. Since plant requires different spectral emission and luminous at different growth stages, the light content of individual LED strings are adjustable so that peak wavelength emission can be selected to match the absorption peak of light pigments in different growth cycles. In order to regulate different spectral ratios, the PWM signal can be adjusted to control the amount of photosynthetic photon flux density (PPFD) to be received. The observed root and produce results are good as shown in Fig. 5. Thus, a controlled growth environment for indoor horticultural applications have been developed and can be used to study the optimal light conditions for different plant species.

(a) (b) (c)

Fig. 5: Indoor cultivation (a) system (a) root and (b) produce results under PCBC light environment

4. Conclusions

Indoor cultivation adapts LED based artificial lighting system mainly because of LED's long durability, reliability and energy saving features. When more number of LEDs are used in multiple and parallel operated strings its features are uncertain. In this paper, the program based controllable LED strings were studied and examined to ensure several features such as long lifetime, flexible light intensities with automatic preselected photoperiods, and different wavelengths selection through the forward current control of LEDs. The percentage increase in cost of this solution is 1.82% with several additional features. However, there is always tradeoff between LED driver's efficiency and its cost. The proposed PCBC technique can dramatically reduce the current imbalance and ensure the reliability of lighting system in industrial plant factories. Investigating the current balance with respect to plant physiological and morphologic responses under different plant species and different light intensity levels can be a further research direction. With the platform, the relationship between light spectrums, intensity, time duration can be studied thoroughly.

5. Acknowledgements

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6. References

[1] Vermeulen SJ, Aggarwal PK, Ainslie A, Angelone C, Campbell BM et al. Options for support to agriculture and food security under climate change. Environ SciPolicy 15: 136-144, 2012.

[2] Godfray HCJ, Crute IR, Haddad L, Lawrence D, Muir JF et al. (2010) The future of the global food system. Phil Trans R Soc B 365: 2769-2777, 2010.

[3] M. Khatib, "Ballast resistor calculation -Current matching in parallel LEDs," Application Report SLVA325, Texas Instruments, Dallas, TX, 2009.

[4] J. M. Zhang, J, F. Wang, and X. K.Wu, "A capacitor-isolated LED driver with inherent current balance capability," IEEE Trans. Ind. Electron., vol. 59, no. 4, pp. 1708-1706, Apr. 2012.

[5] Y. Hu and M. M. Jovanovic, "A New Current-Balancing Method for Paralleled LED Strings," in Proc. 26th Applied Power Electron. Conf. and Expo., Mar. 2011, pp. 705-712.

[6] K. I. Hwu and S. C. Chou, "A simple current-balancing converter for LED lighting," in Proc. 24th Applied Power Electron. Conf. and Expo. (APEC), Feb. 2009, pp. 587-590.

[7] K. I. Hwu, W. C. Tu, and Ming-jie Hong, "A LED current balancing driver with magnetizing inductance energy recycling considered," in Proc. 27th Applied Power Electron. Conf. and Expo., Feb. 2012, pp. 975-979.

[8] J. F. Wang, J. M. Zhang, X. C. Huang, and L. H. Xu, "A family of capacitive current balancing methods for multi-output LED drivers," in Proc. 26th Applied Power Electron. Conf. and Expo., Mar. 2011, pp. 2040~2046.

[9] S. M. Baddela and D. S. Zinger, "Parallel connected LEDs operated at high frequency to improve current sharing," in Proc. IEEE Ind. Appl. Conf., 2004, pp. 1677-1681.

[10] X. K. Wu, J. M. Zhang and M. Q. Zhao, "A simple two-channel LED driver with automatic precise current sharing," IEEE Trans. Ind. Electron., vol. 58, no. 10, pp. 4783-4788, Oct. 2011.

[11] U. Hu and M. M. Jovanovic, "LED driver with self-adaptive drive voltage," IEEE Trans. Power Electron., vol. 23, no. 6, pp. 3116-3125, Nov. 2008.

[12] C. S. Wong, K. H. Loo, Y. M. Lai, Martin H. L. Chow, and K. H. Tse, "Accurate Capacitive Current Balancing in Multistring LED lighting systems based on Switched-Capacitor-Controlled LCC Resonant Network", IEEE Trans. Power Electron., Issue 99, pp. 1-13, 2016.

[13] Si Nan Li, W. X. Zhong, W. Chen, and S. Y. R. Hui, "Novel self-configurable current-Mirror Techniques for reducing current imbalance in parallel light-emitting diode (LED) strings," IEEE Trans. Power Electron., vol. 27, no. 4, pp. 2153-2162, Apr. 2012.

[14] K. H. Loo, Y. M. Lai, and C. K. Tse, "Design and analysis of LCC Resonant Network for Quasi-Losslesss Current Balanicng in Multistring AC-LED Array", IEEE Trans. Power Electron., vol. 28, no. 2, pp. 1047-1059, 2013.

[15] H. J. Chiu, and S. J. Cheng, "LED backlight driving system for large-scale LCD panels," IEEE Trans. Ind. Electron. , vol. 54, no. 5, pp. 2751-2760, Oct. 2007

[16] S. Choi, and T. Kim, "Symmetric current-balancing circuit for LED backlight with dimming," IEEE Trans. Ind. Electron., vol. 59, no. 4, pp. 1698-1707, Apr. 2012.