Research on Plant Lighting Driver Control Strategy Based on LED Spectral Characteristics

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Abstract. To realize the continuous adjustment of the light quality ratio of LED plant lighting power supply, a plant lighting driver control strategy based on the spectral characteristics is studied in this paper. First of all, the spectral mathematical model of monochromatic LED chip is established. Secondly, the mathematical model of the number of photons generated by LED the driving current is further studied and then, a new driver control strategy about the pant lighting is proposed based on the model of the number of LED photons. At last, a step-down circuit built by RT8471 chip is used as the LED driver power supply to verify the correctness of the new driver control strategy in this paper. Different color LED chips of Cree and Philips Lumileds companies are used as the circuit loads. It shows that the errors values between the results from the experiments and the theoretical model calculations of the number of LED photons are all less than 5%. So, the new plant lighting driver control strategy proposed in this paper is feasibility and has certain theoretical guiding significance and engineering value.

1. Introduction
Light is the primary driving force of plant growth [1]. However, in nature, sunlight changes with many uncertainties. As a new generation of light source, LED has many advantages including its spectral monochromaticity which made it become the most preferred light source in plant illumination [1].

For the driving circuit of LED plant lighting, the optical quality ratio is very important. Therefore, it is necessary to study a new control strategy for LED plant lighting [5]. Based on the optical principle of plant lighting and the luminous principle of LED, a simple and accurate mathematical model of LED relative spectrum is proposed in this paper. On the foundation of the LED spectrum model, the mathematical model of the relationship between the photon number and the current is further studied, and then, the new control mechanism of the LED plant illumination driving power source is proposed and verified by LED power supply experiments.

2. Principle of Plant Illumination Optics

2.1. Selection of Light Formula
From absorption characteristics of the main photosynthetic pigments in plants, we know that the absorption of light by plants is mainly concentrated in the red and blue regions. Red light has the ability to promote above-ground growth and drive photosynthesis, etc. Blue light can increase protein accumulation [2]. The use of red and blue light combination can greatly improve the photosynthetic efficiency of plants, and replace the continuous full-spectrum light source for plant cultivation. Therefore, the red and blue LED chips are chosen as the research target in this paper.
2.2. Conversion of Human Photometric Parameters and Plant Photometric Parameters
The intensity of light is often measured by the human eyes, which is commonly used in the photometric parameters of the lighting industry [3]. However, the visual function of the human eye is completely different from the sensitive curve of the plant. In plant illumination, how many photons are produced by the light source is more important [3]. Therefore, the number of photons is used as the evaluation standard in plant illumination.

Both the radiation and absorption of light are carried out through discrete units which are photons. \( P \) is used here to denote the number of photons radiated per second by the source, in units of μmol/s. The radiation wavelength for promoting photosynthesis is between 400 and 700 nm, so the radiant power \( P_f \) that promotes photosynthesis is the total energy value radiated by the wavelength region per unit time. Its expression is as in (1):

\[
P_f = \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} W(\lambda) d\lambda = \alpha \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S(\lambda) d\lambda
\]

(1)

Where \( W(\lambda) \) is the actual value of the spectral power distribution at a wavelength of \( \lambda \), \( S(\lambda) \) is a relative spectral power distribution function, \( \alpha \) is the conversion factor between the value of the relative spectral power distribution and the actual value of the spectral power distribution.

\( W(\lambda) \) can be obtained by the wave-particle duality of light as formula (2):

\[
W(\lambda) \cdot \Delta \lambda \cdot t = n \cdot N_i \cdot \frac{h \cdot c}{\lambda_i}
\]

(2)

Where \( \Delta \lambda \) is the wavelength interval of data acquisition, \( t \) is the time of data acquisition, \( h \) is the Planck constant, \( 6.6261 \times 10^{-34} \text{J} \cdot \text{s} \), \( c \) is the speed of light, \( 2.9979 \times 10^8 \text{m/s} \), \( nN_i \) is the number of photons included in the radiation of the light source at a wavelength of \( \lambda_i \), and the value of the Avogadro constant \( n \) is \( 6.022 \times 10^{17} \mu \text{mol}^{-1} \), and \( N_i \) is the number of photons included in the radiation of the light source where the wavelength is \( \lambda_i \) and expressed in units of μmol.

Define \( P_i \) as the number of photons contained in the radiation per second when the wavelength is \( \lambda_i \). The number of photons radiated per second by the source that promotes photosynthesis is expressed as formula (3):

\[
P_i = \frac{N_i}{t} = \frac{W(\lambda_i) \cdot \Delta \lambda \cdot \lambda_i}{n \cdot h \cdot c} = \frac{10^{-9} \cdot \alpha \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S(\lambda) d\lambda}{n \cdot h \cdot c}
\]

(3)

The luminous flux \( \Phi \) is defined as:

\[
\Phi = K_m \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} W(\lambda) \cdot V(\lambda) d\lambda = K_m \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \alpha \cdot S(\lambda) \cdot V(\lambda) d\lambda
\]

(4)

Where \( K_m \) is the maximum value of the spectral optical performance of the radiation, which is 683lm/W under bright visual conditions. Substituting (4) into (3), the equation of \( P \) is formula (5):

\[
P = \frac{10^{-9} \cdot \Phi \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} S(\lambda) d\lambda}{K_m \cdot n \cdot h \cdot c \cdot \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} \alpha \cdot S(\lambda) \cdot V(\lambda) d\lambda}
\]

(5)

3. Model Research

3.1. Modeling on LED Spectrum Mathematical Model
According to the physical mechanism of semiconductor LED illumination, when electron-hole pairs are combined, excess energy is emitted as photons and luminescence. Gaussian distribution function and Lorentz distribution function are commonly used to describe the spectral curve of a monochromatic LED [4]. Since the radiation spectrum of a monochromatic LED is an asymmetric single-peak curve, there is a large error value in describing the spectral curve of the monochromatic
LED. There are many improved Gaussian and Lorentz models are proposed. Also new models obtained by combined Gaussian and Lorentz models [4]. But all these lack of physical meaning. LED emission spectrum \( r(E) \) corresponding to the radiative recombination in the semiconductor junction is shown in equation (6).

\[
r(E) = \frac{1}{\tau_r} \rho(E) f_c (1 - f_v)
\]

Where \( \tau_r \) is the electron-hole radiation composite lifetime, \( \rho(E) \) is the combined density of electron and hole states, and \( f_c (1 - f_v) \) describes when the LED chip achieves thermal equilibrium. The probability of possession of energy states in the conduction band and the valence band is obtained by Fermi-Dirac statistics which is shown in equation (7).

\[
f_c (1 - f_v) = \left[ 1 + \exp \left( \frac{E - E_F}{kT} \right) \right]^{-1}
\]

Where \( E_F \) is the Fermi level, \( k \) is the wave number of the particle, and \( T \) is the temperature of the carrier whose unit is K.

In fact, the radiation mechanism of LED semiconductor junctions is very complicated. Fluctuations in the composition or thickness of the quantum well of the semiconductor material cause the carriers to form a localized state. Therefore, some scholars describe the state density \( \rho(E) \) of a carrier as a Sigmoid function as shown in equation (8):

\[
\rho(E) = A_1 \left[ 1 + \exp \left( - \frac{E - E_1}{\sigma_1} \right) \right]^{-1}
\]

Where the parameter values of \( A_1, E_1 \) and \( \sigma_1 \) depending on the semiconductor material.

Therefore, when photon energy is used as a research variable, the radiation spectrum model of a monochromatic LED can be expressed by equation (9).

\[
r(E) = A_2 \left[ 1 + \exp \left( - \frac{E - E_1}{\sigma_1} \right) \right] \cdot \left[ 1 + \exp \left( \frac{E - E_F}{kT} \right) \right]^{-1}
\]

Where \( A_2 \) is a coefficient.

However, studying the power distribution of LED spectra with energy \( E \) as a research variable is not convenient for measurement and application. The relationship between energy \( E \) and wavelength \( \lambda \) is shown in equation (10).

\[
E = h c \lambda^{-1}
\]

Substituting the formula (10) into the formula (9), and using the curve characteristic simplification of the exponential function, this paper puts forward the LED relative spectrum mathematical model with the wavelength being variable. At the same time, when \( \lambda - \lambda_c >> \omega_1 \), \( \exp ( (\lambda - \lambda_c)/\omega_1 ) >> 1 \), the mathematical model of LED relative spectrum is simplified as:

\[
S(\lambda) = A \cdot \exp \left( - \frac{\lambda - \lambda_1}{\omega_1} \right) \cdot \left[ 1 + \exp \left( - \frac{\lambda - \lambda_2}{\omega_2} \right) \right]^{-1}
\]

\( A, \lambda_1, \lambda_2, \omega_1, \omega_2 \) are the parameters that related to the material of the semiconductor.

The correctness of the proposed model (11) above is verified by four types LED chips from two famous LED manufacturer, CREE and Philips Lumiled. They are Cree's Xlamp XPE 450-455nm Blu-ray LED chip and Xlamp XPE 655-665nm red LED chip, Philips Lumiled LUXEON Rebel 450-455nm Royal blue LED chip and LUXEON Rebel 620-630nm red LED. Because of the limited space, there are only two kinds of LED chips results given here. Based on the
Levenberg-Marquardt (LM) algorithm and the Origin software, the parameters of $A, \lambda_{c1}, \lambda_{c2}, \omega_1$ and $\omega_2$ are obtained. The $S(\lambda)$ curves of the two chips are shown in Fig. 1 and Fig. 2, and the specific expression of $S(\lambda)$ is shown in the equation (12).

$$
\begin{align*}
S_{CB}(\lambda) &= \frac{1.92}{1 + e^{-\frac{\lambda - 448}{4.5}}} e^{-\frac{\lambda - 448}{9.3}} \\
S_{LR}(\lambda) &= \frac{1.92}{1 + e^{-\frac{\lambda - 652}{5.45}}} e^{-\frac{\lambda - 652}{3.95}}
\end{align*}
$$

(12)

Where $S_{CB}(\lambda)$ is relative spectral power distribution function of Cree's royal blue LED chip, and $S_{LR}(\lambda)$ is the one of Philips Lumiled Red LED chip. The correlation coefficients between the model curve and the measured values of the relative spectral curves of the $S_{CB}(\lambda)$ and $S_{LR}(\lambda)$ reached 99.896% and 99.941%, respectively. The correlation coefficients of another two chips are also 99.942%, 99.943%.

3.2. Mathematical Model of Photon Number

In PWM dimming, the relationship between the average luminous flux $\Phi$ of the LED and the peak luminous flux $\Phi_P$ and the duty cycle $D$ is shown as in equation (13):

$$
\Phi = \Phi_p \cdot D
$$

(13)

There is a linear relationship between the average luminous flux $\Phi$ and the peak current $I_p$, as in equation (14):

$$
\Phi = k \cdot D \cdot I_p + b \cdot D = k \cdot I + b \cdot D
$$

(14)

Where $I$ is the average current of the LED.

Based on the model (12), equation (14) and the proposed spectrum equation (5), the $P$ models of the photon number and the average current $I$ of the four chips is obtained in equation (15). That is the principle of the new LED driver control strategy. It can be seen that for the LED driving circuit, the number of photons $P$ emitted can be adjusted by controlling the average current $I$, and the ratio of red and blue light can be changed to meet the needs of plant illumination.
\begin{align}
\begin{align*}
P_{\text{CB}} &= 5.313 \cdot I + 0.224 \cdot D \\
P_{\text{CR}} &= 2.897 \cdot I + 0.082 \cdot D \\
P_{\text{LB}} &= 4.941 \cdot I + 0.19 \cdot D \\
P_{\text{LR}} &= 1.65 \cdot I + 0.243 \cdot D
\end{align*}
\end{align}
(15)

$P_{\text{CB}}$ and $P_{\text{CR}}$ are respectively the expressions of photons of CREE blue and red light per second, $P_{\text{LB}}$ and $P_{\text{LR}}$ are those of LUXEON's blue light and red light per second.

4. Experimental Verification
In this paper, by using RT8471 driver chip, a LED driver circuit is built to verify the proposed control model. Experiments were carried out to measure the number of photons emitted by four LED chips at duty cycle of 0.3, 0.5, and 0.65, and then compared with the theoretical values calculated by the model. Due to limited space, only two LED chips experimental data are shown in Tab. 1.

It can be seen from Tab. 1 that the average current $I$ of the two LED chips are in the range of 180 mA to 390 mA, and the error values between the measured value of the photon number $P$ and the model theoretical value are all within 5%. The results of another two chips not given here are the same as above.

| Chip type             | Duty cycle | Average current (mA) | $P$ theoretical value (μmol/s) | $P$ measured value (μmol/s) | Error  |
|-----------------------|------------|----------------------|-------------------------------|----------------------------|--------|
| CREE Xlamp XPE 450-455nm royal blue | 0.3        | 180                  | 1.023                         | 1.037                      | 1.4%   |
|                       | 0.5        | 300                  | 1.706                         | 1.687                      | 1.1%   |
|                       | 0.65       | 390                  | 2.218                         | 2.138                      | 3.6%   |
| LUXEON Rebel 620-630nm red | 0.3        | 180                  | 0.37                          | 0.357                      | 3.5%   |
|                       | 0.5        | 300                  | 0.616                         | 0.598                      | 2.9%   |
|                       | 0.65       | 390                  | 0.801                         | 0.807                      | 0.7%   |

5. Conclusions
In this paper, a new LED plant lighting driver control strategy is introduced on the foundation of modeling the LED photon number $P$ which is used as the evaluation standard of plant lighting, the experimental circuit is built to verified the theoretical research, and the following conclusions are obtained:

- An improved mathematical model of relative spectral power distribution function $S(\lambda)$ of monochromatic LED is proposed, and the correlation coefficients of four type LED chips between the experimental curves and the theoretical calculation curves are all above 99%.
- A new LED plant lighting driver control strategy is realized, and the experimental study of the four type LED chips shows that the error value of $P$ between the measured and the theoretical model are all within 5% in the range of 180mA-390mA average current.

6. Acknowledgments
Thanks are due to Professor Yuzhen Xu for guidance with the research and to Ruyu Lin for valuable discussion. This research is funded by the Scientific Research Foundation of Jinjiang campus of Fuzhou University (2019-JJFSDKY-24).

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