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Spectrum optimization of light-emitting diode insecticide lamp based on partial discharge evaluation[☆]

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ABSTRACT

The spectrum distribution of light-emitting diodes (LEDs) is a critical issue in adopting LEDs as an attractant in insect-catching apparatuses via phototaxis effects. Numerous research efforts have attempted to configure the LED spectrum in line with the insect-sensitive spectrum under designed test conditions. Although successful methods have achieved a stationary spectrum configuration, it is less effective when applied directly to an LED insecticide lamp due to the time-variant behaviors of insects in complex environments. Therefore, dynamic optimization for spectrum distribution of the LED insecticide lamp in practical fields remains essential to improve energy efficiency and the control quality of insects. In this paper, an online learning and dynamic control method has been proposed, where dead insects are evaluated by a partial discharge waveform and a cost function derived from the lamp's safety, efficiency, and effectiveness is optimized using a proposed jumping-predication algorithm. Then, a detailed procedure for developing a smart and effective LED insecticide lamp based on photovoltaic power supply is illustrated, and finally the LED insecticide lamp is validated. The suggested methodology and experimental results shed light on controlling insects and pests using an LED insecticide lamp in green agriculture.

1. Introduction

Physical control using artificial light [1] is a non-chemical insect and pest prevention approach applied in intensive agriculture. Traditionally, light sources including incandescent bulbs, T5 fluorescent lamps, and ultraviolet (UV) lights have functioned as attractants in insect-catching apparatuses. However, these attractants possess features of low electrical-optical efficiency and fixed spectral power distribution (SPD) and thus create major challenges in traditional light-based insecticide lamps, namely in terms of energy efficiency and control quality for insects. Recently, the light-emitting diode (LED) [2] has demonstrated advantages in higher electrical-optical efficiency and available peak wavelengths compared to traditional sources [3,4]. Hence, conventional insecticide lamps are being modified with LEDs to enhance performance, realizing energy-saving improvements of 85% and up to 1.2 times better trap effectiveness [5]. The development of a more effective LED-based insecticide lamp will further boost green agriculture.

The wavelengths of available LEDs ranging from 280 nm to 700 nm [6–8], which affect the responses of targeted insects, have been evaluated in numerous studies. For example, seven different wavelengths or colors of LEDs for attracting beetles have been compared, demonstrating that UV (375 nm) and blue (470 nm) LEDs have the highest attraction efficiency [9]. Although higher attraction capabilities for small wavelengths (e.g., violet LEDs; 405 nm) versus large wavelengths (e.g., red LEDs; 650 nm) have been demonstrated for certain insects such as moths [10], not all insects follow the rules outlined in neurological studies [11], including those exploring electrophysiological techniques [12]. Taking whiteflies as the example, a favorable wavelength is a green LED (526 nm) rather than a UV or blue LED [13]. Meanwhile, most of the fruitful results are derived from the carefully designed test conditions. In fact, insects live in complex environments, and their wavelength sensitivities are dependent upon both their morphological characteristics such as size [14] and meteorological factors such as temperature [1,13,15]; thus, the phototaxis effects of insects are time-variant. Therefore, the rates of trap capture by LED insecticide lamps in field applications are reasonably degraded if the laboratory-oriented LED selections are applied directly to the configurations of its attractant.

To address the field-dependent LED response behaviors of insects,

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multiple wavelength combinations [10] have been proposed, such as a 570-nm card trap equipped with 530-nm LEDs [11], which has shown potential promise for attracting pests or repelling natural enemies across various species. Additionally, time-variant behaviors including the types and numbers of insects are usually monitored in the field using sensor technology, as indicated through data mining methods [16] such as image-based pest management systems in tobacco fields [17]. Trap efficiency also may be increased by dynamically configuring the spectral power distribution (SPD) of multiple LEDs according to the measurement method used to examine insect behaviors [18]. However, the development of LED insecticide lamps poses several challenges including soaring costs and decreasing reliability due to the simply combination and complex image process. Studies have attempted to optimize the general LED system to cut costs [19] and boost performance [10,20,21], but little is known about LED insecticide lamps with dynamic PSD control.

Considering the excellent mortality rate when attracting insects by dielectric barrier discharges [22], partial discharges (PDs) are first utilized in this paper as an alternative field evaluation of killed insects. The extracted PD features are entered into the suggested stochastic control method to reach the optimal spectral distribution, which is constrained by the energy efficiency of the lamp. Then, a prototype is established in which power is supplied by solar photovoltaic power generation [23]. Last, the experimental results and conclusions based on the proposed LED insecticide lamp are given.

2. Optimal spectrum control method

The proposed LED insecticide lamp consists of three basic units as outlined in standard GB/T 24689.2-2009, China: the LED light source to trap insects, a high-voltage fence for killing insects, and a lamp control gear to manage energy. The spectrum distribution of the LED source, whose wavelength usually ranges from 320 nm to 680 nm, should determine the types and numbers of trapped insects, and the PD is induced by dead insects in the high-voltage fence (e.g., 2300 V). Therefore, the spectrum distribution of the LED insecticide lamp can be configured from evaluations of insect-induced PD, as shown in Fig. 1.

2.1. Dead insect evaluation based partial discharge waveform

The PD, a localized dielectric breakdown of an electrical insulation system under high-voltage stress, is a well-known effect in electrical engineering [22]. The trapped insect partially bridges the distance between electrodes of the high-voltage fence, leading to PD. In a specific period T_s, there is a total number of m PDs, induced by p total type of insects with ith insect type C_i of the number of N_i, constituting a time series $Pd(t)$. The number and type of killed insects can be mined from $Pd(t)$:

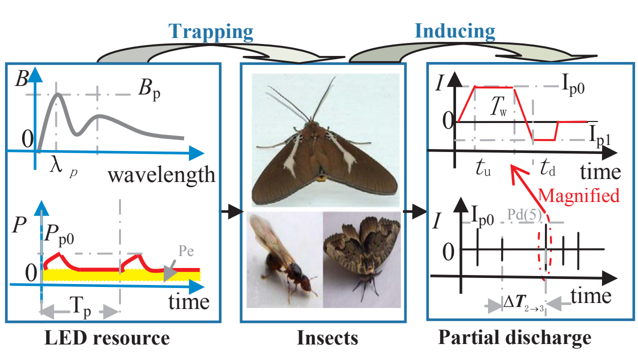

Fig. 1. Illustrations of catching insects by LEDs with the spectrum distribution B (upper-left) and power supply P (bottom-left), and the induced partial discharge waveform I (bottom-right) and its details (upper-right).

$$\{C_i,N_i\}_{i=1}^{p} = f_{MF}(Pd(t)) = f_{MF}(\{\Theta_j\}_{j=1}^{m};\{\Delta T_{j-1\to j}\}_{j=1}^{m}) \tag{1}$$

where $f_{MF}(\bullet)$ denotes the mining function; $\Delta T_{j-1\to j}$ is the PD intervals occurring between the j-1th PD and the jth PD (see the right column of Fig. 1); and Θ_j is the jth PD model parameter defined as,

$$\Theta_j = \{t_{u,j},t_{d,j},I_{p0,j},I_{p1,j},T_{w,j},f_{o,j}\} \tag{2}$$

Where $t_{u,j}$ and $t_{d,j}$ are the up- and down-time, respectively; $I_{p0,j}$ and $I_{p1,j}$ denote the minimum and maximum peak value, respectively; $T_{w,j}$ is the discharging charge; and $f_{o,j}$ is the oscillating frequency.

Although effective data mining algorithms such as artificial neural networks are available to solve Eq. (1), training data is costly to obtain, which makes it difficult to conduct in-field insect evaluations. PD-based insect evaluations can be simplified as follows:

$$C_i = \sum_{t=0}^{T_{w,j}} Pd(t) \in Q_{d,i} \quad (i = 1,\dots p;j = 1,\dots,m)$$
$$N_i = \sum_{j=1}^{m} Step(I_{p0,j} > I_{p0,th})\cdot \quad Step(I_{p1,j} > I_{p1,th})\cdot Step(\Delta T_{j-1\to j} > \Delta T_{th}) \tag{3}$$

where $Q_{d,i}$, $I_{p0,th}$, $I_{p1,th}$, and ΔT_{th} are thresholds of discharge quantity, current peak, and period, respectively; and $Step(\bullet)$ denotes the one-step function.

2.2. Cost function involving efficiency, effectiveness, and safety

The evaluated insect $\{C_i,N_i\}$ in Eq. (3) is assumed to be proportional to the phototaxis response of the ith insect phototaxis response θ_i, where the spectral visual efficiency curve to the LED resource is $s_i(\lambda)$, calculated as

$$\theta_i = \int s_i(\lambda)Sd(\lambda)d\lambda = \sum_{i=1}^{N} a_i \int s_i(\lambda)\exp(\frac{-(\lambda-\lambda_{p,i})^2}{B_{p,i}^2})d\lambda \tag{4}$$

where $Sd(\lambda)$ is the spectral distribution of the LED source, modeled approximately by the N-order mixture Gaussian function, and $\lambda_{p,i}$, $B_{p,i}$, and a_i are the dominant wavelength, bandwidth, and weight of the ith component, respectively.

By configuring LEDs with different wavelengths $\lambda_{p,i}$ and adjusting their intensities or weights a_i, the larger the phototaxis response θ_i is, the more killed insects can be reached. Furthermore, the discrimination of natural enemies and pests can be obtained. Meanwhile, energy supply costs and photo-biological safety issues (IEC 60335-2-59: 2002) should be minimized. Thus, the objective of the proposed method is to maximize the cost function of the LED spectrum configuration, where $B_{p,i}$ should be held constant. The cost function is defined as,

$$\ell_{Sd}(\{\lambda_{p,i},a_i\}_{i=1}^{N}) = \max_{\{\lambda_{p,i},a_i\}_1^N}\left(\frac{\sum_{i=1}^{P}\alpha_i\cdot\theta_i-\sum_{i=1}^{Q}\beta_i\cdot\theta_i}{\int_{t=0}^{T_s}P(t)}\right) \tag{5}$$

where α_i and β_i denote the ith weight of the insect (type number of P) and the beneficial (type number of Q), respectively, and the time-power data of the LEDs source with N wavelengths combinations is,

$$P(t) = \sum_{i=1}^{N}\frac{a_i}{\eta_{eo}(\lambda_{p,i})}T_{cont}(t) \tag{6}$$

where $\eta_{eo}(\lambda_{p,i})$ denotes the electrical-optical efficiency of a LED with a wavelength of $\lambda_{p,i}$, and $T_{cont}(t)$ denotes the power supply control behaviors of the lamp controller at time t.

2.3. Jumping-predication control algorithm

The optimal solution for Eq. (5) is to determine the relative spectrum $B(\lambda)$ and its power supply $P(t)$ for the entered environmental conditions and to maximize the insect-capture numbers of the LED