LED Lighting Loads Actively Participating in Power System Frequency Regulation

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***Abstract*—LED lighting loads are of flexible controllability to be a viable alternative for participating in power system frequency regulation. In this paper, a decentralized control strategy is proposed to facilitate the active participation of LED lighting loads. Each LED load responds to local frequency signal independently. The aggregation of response is conducted on the basis of appropriate categorization of LED loads, which contributes to the primary and secondary frequency regulation. Simulation results verify the effectiveness of the proposed control strategy.**

***Index Terms*--Demand response, Frequency regulation, LED lighting, Monte Carlo simulation, Power system.**

I. Introduction

Real time balance between the supply and demand sides is a fundamental requirement of power systems. Conventionally, certain amount of capacity reserve is procured from the supply side in response to disturbances, which incurs great economic and environmental costs [1]-[3]. Exploring the potential of demand response has attracted much more attention in recent years. Among various types of electrical loads, lighting demand is of significant share. According to the national energy administration of China, the total electric power consumption in 2014 was 4.6591 trillion kWh, 10% of which came from lighting demand. The share of lighting demand in the housing and the building sector was even higher, i.e. reaching 30% to 40% [4]. LED lighting technology is expected to replace the traditional lighting technologies of low efficiency [5]. As the penetration of LED lighting grows, the power system operation could be more flexible. If left without control, a substantial lighting load will aggravate rigid power demand in times of peak hours, probably requiring more generation resource or ramping capability.

LED lighting loads are of flexible controllability to be a viable alternative for participating in power system frequency regulation. The key is how to modulate and aggregate power demand of LED lighting loads in response to power system frequency signal. The pulse width modulation (PWM) dimming is a dominating method for LED lighting luminance control, which regulates the average value of current by modulating its duty cycles [6]-[8]. However, few studies concern LED lighting modeling in large population size. The potential of controllable loads for demand response, coordinated scheduling and optimal power flow has been explored [9]-[11]. References [12]-[14] introduce multiple factors to depict the diversity of load characteristics that can effectively present stochastic state of load particles as well as their impact on the swarm. Reference [12] proposes a charging control design for plug-in electric vehicles to participate in frequency regulation and desired dynamic characteristics and control effects are obtained.

A control strategy to coordinate power consumption of LED lighting loads for frequency regulation is proposed in this paper. The control signal is in proportional to the frequency deviation, which is a droop-like response. Consequently, power consumption of a LED load is inversely correlated with the frequency deviation. The Monte-Carlo algorithm is applied to study the aggregated response of the groups of LED loads. The two-area interconnected power system is adopted to verify the control effects.

II. Decentralized Control Design for LED Lighting Loads

Typically, LED lighting users will simply switch lighting devices to a luminance level that may be in excess of the technical requirement. The smart control for LED lighting loads should save daily energy on the premise of maintaining users' comfort. Moreover, it is better for LED loads to meet the power system's requirement within a tolerable range of illumination. Using the decentralized control strategy, each LED load will respond independently to the local frequency deviation without heavy communication cost.

A. *Categorization of LED Lighting Devices*

From the utilization perspective, LED lighting devices can be categorized into three groups, i.e., local lighting, indoor lighting and street lighting. LED bulb lamps are typically used for local lighting while celling light devices have been widely applied to indoor space illumination. According to the survey conducted in 2010 by China Solid State Lighting Alliance (CSA), LED lighting devices are installed pervasively. LED bulb lamps occupied the largest ratio, i.e., about 41%. Spot light and street light devices accounted for 19% and 12%, Celling lights and the others accounted for 28% respectively

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[15]-[17]. The statistics and its extrapolation are used to estimate the partition of the LED lighting load population.

B. Generic Model for LED Lighting Illumination

Provision of appropriate illumination for users is the major utility of LED lighting loads, which is affected by multiple factors including lighting categories, user's comfort, and environment. Typical illumination values for three LED lighting categories are listed in Table I, which are obtained through experiments and verified by theoretical computation. The national standard for LED lighting illumination specifies the required illumination values. The margin for LED loads to be modulated is the difference between their typical illumination and standard illumination values. By using market statistics, LED lighting load power values can be obtained.

TABLE I. ILLUMINATION DATA FOR LED LIGHTING LOAD GROUPS

Categories	Typical illumination (Lx)	Standard illumination (Lx)	LED lighting load power (W)
Local Lighting	420	300~500	3
Indoor Lighting	179.2	200~300	24
Street Lighting	58.24	50~100	160

Power consumption of a LED unit is as

$$P = [V_o + (R_{LED} + R_S)I]d_{on}I \tag{1}$$

where V_O is the turn-on voltage of LED; I is the current through LED; d_{on} is the turn-on ratio of the duty cycle; R_{LED} is the thermal resistance of LED; R_S is sensing resistance.

The illumination provided by the LED load is proportionate to its power consumption as

$$E_{ij} = P_{ij} \times \eta_{ij} \times C_j \tag{2}$$

where P_{ij} and η_{ij} represent rated power and luminous efficiency of the j-th LED load in the i-th category; C_i is the power-illumination conversion coefficient of the i-th category, which is derived through dividing elements in the 2nd column by those in the 4th column of Table I; E_{ij} is the illumination provided by the j-th LED load in the i-th category.

C. Decentralized Control for LED Lighting Loads

Dimming control for LED lighting devices can be realized in a flexible way through PWM modulation. Power system frequency signal is easily to be sensed and responded by LED lighting loads on the basis of their existing dimming control modules with inexpensive sensors added. The control performance is ensured within a wide operating range. A droop-like control law is applied to frequency response for LED loads as

$$E_{rij} = K_{fi} \times \Delta f + E_{\min ij} \tag{3}$$

where Δf is the deviation of frequency from the normal value; K_{fi} is the droop coefficient of the i-th category; $E_{\min ij}$ and E_{rij} represent the minimum tolerable illuminance and responsive illuminance for the user of the j-th LED load in the i-th category, respectively.

Note that various categories of LED lighting devices are different in their technical specifications and adjustable illuminance ranges, which is reflected by adjusting the droop coefficient K_{fi}. The wider the adjustable illuminance range is, the larger the value of K_{fi} is.

III. FREQUENCY RESPONSE OF LED LIGHTING LOAD POPULATION

Frequency value is the indicator of real-time power balance between the generation and load sides. A normal range is set around the nominal frequency value to ensure the secure operation of the power system, e.g., 60±0.1 Hz. Whenever the frequency value deviates from the normal range, power system frequency regulation functions will be activated.

A. Frequency Regulation Mechanism for Interconnected Power System

For a power system with multiple interconnected areas, the coordinated frequency regulation mechanism between different areas is usually employed. With a plenty number of LED lighting loads integrated into the power system, response of the LED load population can contribute to the frequency regulation. A two-area interconnected power system is used to illustrate frequency regulation with the LED load population participating in. The schematic of frequency regulation blocks of the two-area interconnected power system is shown in Figure 1, where active participation of LED loads is added. Parameters and functions of the control blocks can be referenced to [18]. Response of LED loads is represented by ΔP_d which is the aggregation of various groups of LED loads as shown in Figure 1.

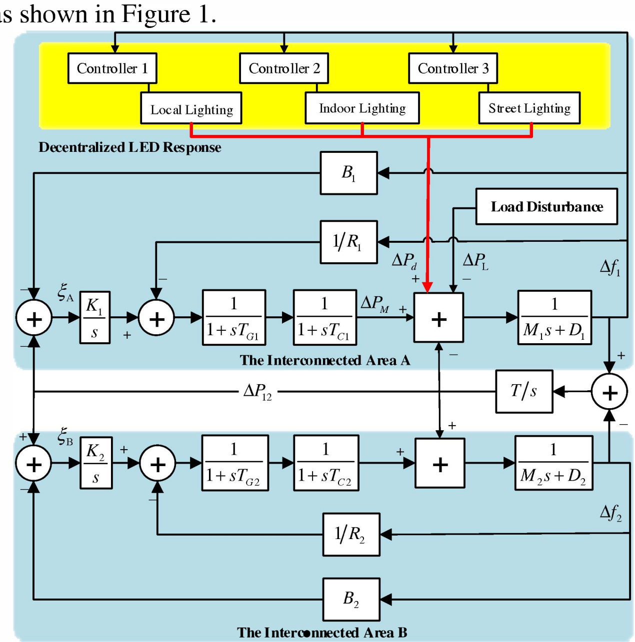

Figure 1. Two-area interconnected power system model with LED load response

When a disturbance ΔP_L occurs, each LED load will respond according to the decentralized control law. With the contribution from the LED load population, the value of power imbalance can be reduced between the generation and load sides,

$$\Delta P_M + \Delta P_d - \Delta P_L = \Delta f\,(Ms + D) \tag{4}$$

where ΔP_M is the power output adjustment from the generation side; M and D are the inertia constant and damping coefficient of the interconnected power system, respectively; Δf is the deviation of frequency from the normal value.

To restore the frequency to its nominal value, area control error (ACE) signal is adopted considering frequency deviation and tie line power error. For area A,

$$\xi_A = \Delta P_{12} + B_1 \Delta f_1 \tag{5}$$

and for area B,

$$\xi_B = -\Delta P_{12} + B_2 \Delta f_2 \tag{6}$$

where ΔP_{12} is the tie line power error deviated from its scheduled value; B_1 and B_2 are frequency bias coefficients for area A and B, respectively.

B. Aggregation of LED Lighting Load Population

Through modulating the illuminance, LED lighting loads contribute to frequency control by adjusting their power consumption. The schematic of LED load population participating in frequency control is shown in Figure 2, where the illuminance of LED loads will be modulated in accordance with the system's states. In the normal state, values of illuminance distribute in a wide domain. When the system frequency deviates from its normal range, e.g., lower than 59.9 Hz, LED loads will respond by reducing their illuminance values while maintaining the minimum illuminance. After the system recovers from the emergency state, response of LED loads will be released with the illuminance returned to the values before control.

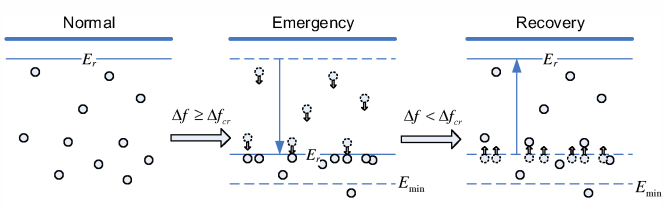

Figure 2. Schematic of LED lighting load population's response

The response of each LED lighting load is limited by its capability as

$$E_{cij} = \min(E_{rij}, E_{uij}, E_{nij}) \tag{7}$$

where for the j-th LED load in the i-th category, E_{nij} represents its rated illuminance; E_{uij} and E_{rij} represent user's self-adjusting illuminance before frequency control and responsive illuminance for frequency control, respectively; E_{cij} is the actual illuminance after control.

The aggregation of the LED lighting load population is

$$\Delta P_d = \sum_{i=1}^{n_c}\sum_{j=1}^{n_i}\frac{E_{uij} - E_{cij}}{E_{nij}} \times P_{nij} \tag{8}$$

where for the j-th LED load in the i-th category, P_{nij} represents its rated power; n_c and n_i represent number of categories of LED lighting devices and number of LED loads in the i-th category, respectively; ΔP_d represents the aggregated response from the LED lighting load population.

An architecture for LED lighting load population participating in frequency control is designed as shown in Figure 3. It is a hierarchical architecture consisting of layers of LED load groups, aggregators and power system dispatch center. Each LED load group responds to frequency signal measured locally according to the proposed decentralized control law. The respective load aggregator is in charge of aggregating the response from the decentralized LED loads while broadcasting the states and requirements of the power system. The dispatch center is responsible for integrating load response collected by the aggregators into the balancing capacity pool of the power system.

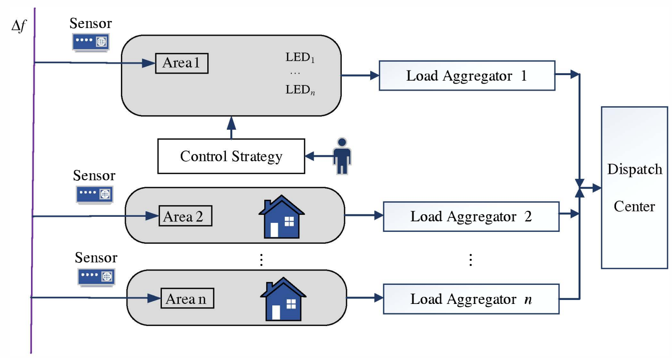

Figure 3. Architecture of LED lighting load population participating in frequency control

C. Monte Carlo Sampling

The Monte Carlo sampling method is used to simulate the diversity of working space, LED lighting devices, environmental factors and users' preference, which is capable to reflect randomness and variance among different LED lighting loads. Detailed parameters are listed in Table II.

TABLE II. PARAMETER PROBABILITY DISTRIBUTION OF LED LIGHTING LOADS

Types	Parameters	Probabilistic distribution
Working space	Efficiency of light utilization, Reflectivity	Uniform distribution
Characteristics of LED lighting devices	Rated power, Luminous efficiency	Uniform distribution
External environment	Environmental Illuminance	Gaussian distribution
User's preference	User's preferred Illuminance	Gaussian distribution

IV. SIMULATION RESULTS

A two-area interconnected power system was constructed and programmed under the MATLAB Simulink environment. The base capacity of each area is 1000 MVA and nominal frequency value is 50 Hz (the nominal frequency value of the power grid in China).

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A. Two-area interconnected system

Parameters of the test system is shown in Table III. Assume that a disturbance occurs in area A of ΔP_L=0.15 p.u., and no demand response is included. As shown in Figure 4, frequency experiences dynamics and the fluctuation is much larger in the local area than that in the neighbor area.

TABLE III. PARAMETERS OF TWO-AREA INTERCONNECTED SYSTEM

Grid	*G*	*D*	*T*	*1/R*	T_g(s)	T_c(s)	*B*
Area A	10	0.8	2	20	0.2	0.5	20.6
Area B	8	0.9	2	16	0.3	0.6	16.9

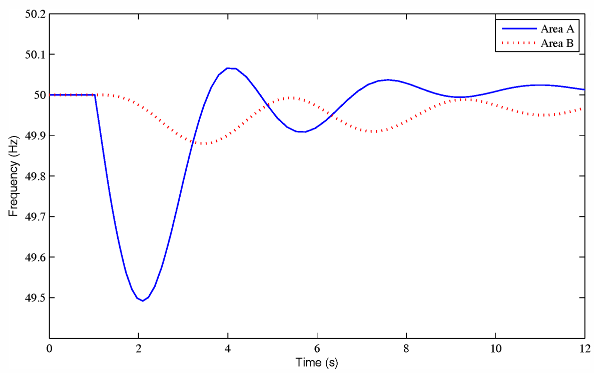

Figure 4. Frequency response of the test system

B. Participation of LED Loads

Assume that a disturbance occurs in area A with ΔP_L=0.1875 p.u. and about 3 millions of LED lighting loads participate in frequency regulation with the total power consumption of 120 MW. With the active participation of LED loads, a significant improvement is achieved in the performance of frequency dynamics, as shown in Figure 5. Frequency nadir raises from 49.36 to 49.56. The overshoot reduces from 0.68 to 0.57. The recovery time to the stable range (50±0.2 Hz) reduces from 9 s to 6s. The system swings after frequency rises up to 50 Hz without LED loads participation. However, LED loads participation can diminish frequency swing significantly.

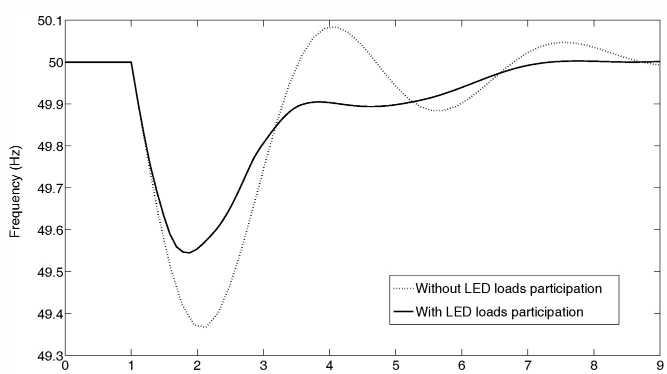

Figure 5. Response of LED loads

C. Priority of LED Load Groups in Response to Disturbances

Accounting for various adjustable illuminance ranges, the priority of LED load groups in response to disturbances is determined. Local lighting devices is of the top priority for its widest adjustable illuminance range. Followed are indoor lighting and then street lighting devices. The priority is reflected by adjusting the droop coefficient K_{fi} that is set to 1200, 400 and 90 for local lighting, indoor lighting and street lighting devices, respectively.

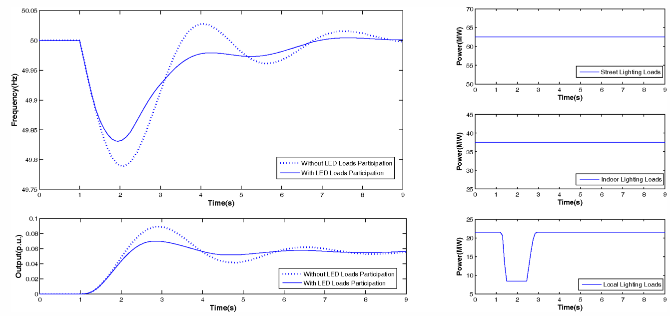

Figure 6. Response to the 50MW-disturbance

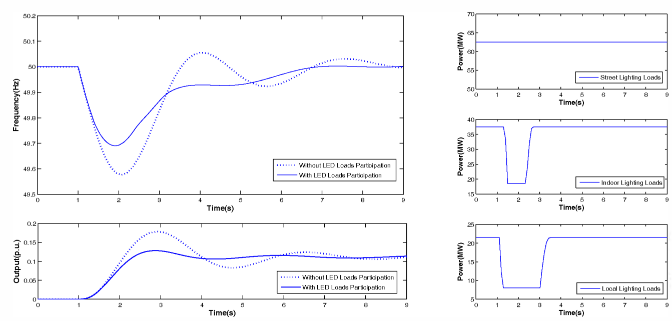

Figure 7. Response to the 100 MW-disturbance

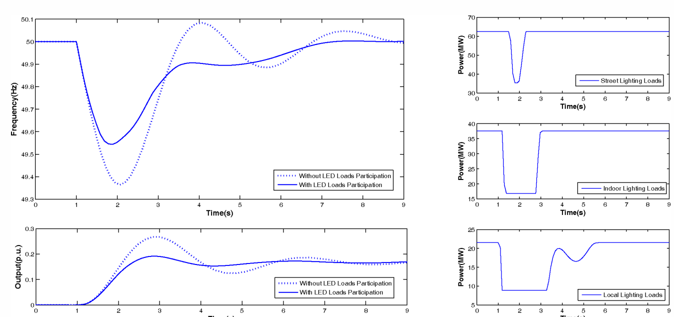

Figure 8. Response to the 150 MW-disturbance

Three scenarios are simulated. When the magnitude of disturbances is lower than 50 MW, only local lighting loads respond as shown in Figure 6. With 8 MW reduction in power consumption, the local lighting loads contribute 16% of total reserve capacity activated in frequency control. When the disturbance increases from 50 MW to 100 MW, indoor lighting loads start to respond as shown in Figure 7. An extra of 17 MW power reduction is provided by the indoor lighting loads and the contribution of LED loads (the sum of local lighting and indoor lighting loads) is 21%. Only when the

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disturbance reaches 150 MW, street lighting loads participate in frequency regulation as shown in Figure 8. In this situation, street lighting loads complement 25 MW of response and the total contribution of LED loads is 31%.

With LED loads participating in, system frequency dynamics is remarkably improved. The contribution of LED loads reduces requirements for the amount and response rate of reserve capacity from the generation side. It even helps improving the dynamic performance of generators during the process of frequency control.

V. Conclusion

A control strategy is proposed to facilitate the active participation of LED lighting loads in power system frequency regulation. Individual LED load responds to local frequency signal independently. The Monte Carlo sampling is applied to the aggregation of load response on the basis of categorization of LED lighting devices. Simulation results on a test power system verify the effectiveness of the proposed control strategy.

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