Case Study of A Highly-Reliable Dimmable Road Lighting System with Intelligent Remote Control

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Dimmable road lighting system, industrial application, electronic ballasts, emerging technology

Abstract

This paper presents the phase-one results of a case study of a dimmable road lighting system with intelligent remote control. This is the first large-scale installation of such system for about 8000 street lamps in China and the phase-one of the project involves 1350 lamps. Patent-pending central control dimming systems, that can turn existing “non-dimmable” electromagnetic lighting systems into dimmable ones without major rewiring or replacement of equipment, have been installed in Heshan City, China since September 2004. This central dimming system provides a self-recovery feature and ensures high lighting system availability, as it will automatically withdraw itself from the lighting network if it cannot work normally. By retaining existing electromagnetic ballasts in all lamp posts, the use of this central dimming system does not require any expensive electronic ballasts. More importantly, electronic ballasts may help save some energy for a few years of their short lifetime but will become electronic waste and pollutants for many hundreds of years. The proposed system in this paper provides an environmentally-friendly and energy-saving solution for dimmable road lighting systems. Most of the advantages of electromagnetic ballasts such as long lifetime, recyclability of iron chokes, high reliability and immunity against extreme weather conditions and lightning are kept. During the 9-month operation, none of the streets with such dimming system installed suffers light blackout. It has also been independently confirmed that there was no increase in crime and traffic accident rates. No compliant has been received from residents by the road lighting management company. In phase-one of this project, an overall energy saving of 27% has been recorded without adversely affecting quality of life.

1.0 Introduction

Among various lighting devices, discharge lamps such as high-intensity-discharge (HID) and fluorescent lamps are popular choices because of their high efficacy (lumen per watt). Traditional incandescent lamps have an efficacy of typically 8-11 Lumen/Watt and fluorescent lamps have typical efficacies of 60-100 lumen/Watt. In general, HID lamps have typical efficacy of 100-200 lumen/Watt and lifetime of 10,000-24,000 hours. These attractive features of HID lamps make them the natural choices for public road
lighting applications. Together with highly reliable electromagnetic ballasts (sometimes simply called magnetic ballasts), HID lamps are commonly used in existing public road lighting systems [1].

With recent rapid advancements in power electronics, new dimming concepts and technologies for electronic lighting systems have emerged. Most of these dimming methods have been adopted in modern electronic ballasts for both high-pressure and fluorescent lamps. Electronic ballasts for HID ballasts have also attracted much attention, but their wide spread applications have been severely hampered by the acoustic resonance problems in HID lamps when operated at high frequency. Despite the fact that some efforts have been devoted to the use of dimmable electronic ballasts for public road lighting systems [2], the high initial equipment replacement cost is a major hindrance to their application. More importantly, the use of individual dimmable electronic ballasts in each lamp-post of a large lighting network could be a maintenance and environmental nightmare for road lighting management organizations because electronic ballasts do not have fail-safe feature and they will become non-biodegradable/toxic electronic waste for many hundreds of years after only a few years of service. Simple problem such as blowing of a fuse in the electronic ballast means that the lamp will not be turned on. For major cities which have typically 100,000-300,000 street lamps, a problem of 0.1% (e.g. due to severe lightning) means problems for 100-300 street lamps.

In addition to a brief review on the state-of-the-art lighting technology, this paper describes some results of a large-scale implementation of a central dimming technology for about 1350 lamps as phase-one of the full installation for 8,000 street lamps in Heshan City, China. The system features of this new dimming control system for public road lighting applications are reported. Various cost and environmental benefits, such as energy saving and reduction of greenhouse gases, arising from this new dimming system are addressed.

2.0 Brief Review of Dimming Technology for Road Lighting Systems

For road lighting applications, road safety, lighting pollution and energy consumption are important issues to be considered. In many existing public lighting systems based on magnetic ballast driven HID lamps, energy saving can be achieved by turning off a fraction of the total number of lamps in a road lighting network. For example, one out of every two or three lamps can be turned off in lighting network. While this approach can save energy, the uneven light distribution is a concern for road lighting. Two major road safety studies in 1972 [3] and 1994 [4] have indicated that lighted roads are safer than unlighted roads. At the same time, there are rising concerns in Europe and China on the over use of high brightness in road lighting that may lead to road safety problem, energy wastage [1,5,6] and light pollution [7, 14]. Light pollution is believed to have adverse impacts on health and environment such as the sleep disorders and abnormal hormonal changes of human beings, plant and wildlife disturbance. Most authorities require lighting throughout the night while allowing a brightness reduction in road lighting in order to save energy and reduce light pollution [1].

The Dutch government has been actively pursuing a policy on energy conservation and environmental protection [7]. In the late 1990, the Dutch Ministry of Transport has tested a road lighting dimming system on a 14 km six-lane highway [1]. Under this test, 100% normal lighting level was used for high traffic density and 20% level was used for low traffic at night. The study found that the 20% lighting level was sufficient for light traffic at night and did not have any negative consequences. In 2002, a road safety research on M65 Motorway in England conducted by UMIST [5] concluded that the flicker effect of passing under a series of overhead light of high brightness at speed is uncomfortable and possibly dangerous. The report also concluded that driving is more comfortable under light traffic conditions when the lighting level is reduced. Therefore, dimming of road lighting has the potential of both energy saving and road safety.
2.1. Ballast Technology for Discharge Lamps

Traditional energy-efficient discharge lamps such as fluorescent and HID lamps use magnetic ballasts to limit the lamp current and thus control the lamp power. Magnetic ballasts are still dominant in the market because of their low costs and extremely high reliability and lifetime (>10 years). For outdoor applications such as road lighting, magnetic ballasts have an important advantage of its tolerance against extreme conditions such as wide temperature variation and lightning. For HID lamps, magnetic ballasts are the reliable choice because they operate at mains frequency that is well below the acoustic resonant regions of HID lamps.

Lots of recent research efforts have been focused on developing electronic ballasts for both fluorescent and HID lamps. Electronic ballasts for fluorescent lamps have been gaining the market share in recent years because they, unlike their magnetic counterparts, can eliminate the flickering effect by operating at high frequency (>20kHz) without encountering acoustic resonance problems in fluorescent lamps. It must however be pointed out that many electronic ballasts do not live up to the expectation of saving costs. The reason is that, very often, the price difference between an electronic ballast and magnetic ballast may not be fully recovered from the usage of the electronic ballast during its relative short lifetime.

Despite the launch of some high-frequency electronic ballasts for HID lamps in the market, reliability is a serious issue among them because of the inherent acoustic resonance problem in HID lamps at high frequency operation (>1kHz). It has been shown that HID lamp characteristics could change with operating time and this ageing effect [8] is seldom considered in the electronic ballast design. Recent research focuses on the use of extra-high-frequency (>400kHz) in electronic ballast in order to ensure lamp arc stability [9,10,11], but extra-high-frequency operation requires very careful electromagnetic interference (EMI) filter design. In order to avoid acoustic resonance, commercial electronic ballast for HID lamps adopts a “hybrid” approach in which a high-frequency power converter is used to provide a controllable current source and an inverter turns this current source into a low-frequency ac supply to feed the HID lamps [2,12].

2.2 Existing Dimming Technology for Road Lighting Systems

The general schematic of a centrally controlled dimmable road lighting system is shown in Fig.1. The control device is working on a single phase principle as all lamps installed in this project are for phase voltage of 220V a.c. Dimmable Road Lighting Systems have been tested in the last decade in Europe. Existing methods can be broadly classified into (1) electromagnetic and (2) electronic dimming approaches.

(1) **Electromagnetic** approach refers to the use of “autotransformer” to adjust the ac voltage that powers a chain of magnetic-ballast-driven HID lamps housed in the lamp posts. This method has the following features;

(i) There is no need to replace existing highly reliable magnetic ballasts which are environmentally-friendly as the iron chokes can be recycled even at the end of their long lifetime (typically > 10 years).

(ii) No major change in existing power supply infrastructure is required.

(iii) Stepper motor is used to adjust the autotransformer in order to vary the ac voltage supplied to the lighting system.

(iv) Tolerance against extreme weather conditions and lightning is good.

(v) Over-voltage of HID lamps due to poor regulation of ac mains can be avoided.

(vi) AC voltage variation (dimming range) is limited by the thermal limitation of autotransformer.

(vii) Autotransformer is relatively bulky and could be lossy in low-dimming level.

(viii) Continuous slow-transition from one power level to another is not easy.
Electronic approach refers to the use of dimmable electronic ballasts in the lamp posts and the use of a central dimming control system to control all the lamps in the network. This method has the following features:

(i) Dimmable electronic ballasts allow a wider dimming range than autotransformer.
(ii) Wired or wireless central dimming control compatible with the electronic ballasts is needed for uniform dimming control.
(iii) Over-voltage of HID lamps due to poor regulation of ac mains can be avoided.
(iv) High replacement cost because all magnetic ballasts are to be replaced by electronic ballasts.
(v) Electronic ballasts are more expensive and less reliable than magnetic ones, leading to a higher installation cost and possibly reduced reliability.
(vi) Tolerance against extreme weather conditions and lightning is relatively poor.
(vii) After a relatively short lifetime of 1-5 years, disposal costs of electronic waste may be involved. Electronic waste is a serious environmental problem for many hundreds of years due to the use of many non-biodegradable materials and components.

Fig. 1  Schematic of a centrally controlled dimmable Road Lighting System

2.3 Previous case studies on dimmable Road Lighting Systems

In late 1990, the Dutch Ministry of transport tested the DYNO 20-100-200 dimmable Road Lighting System, operating at 20%, 100% and 200% of normal lighting level on a 14 km stretch of a six lane highway. The aim was to match the lighting conditions with the traffic and weather conditions in order to reduce greenhouse gases emission by reducing the amount of energy used by the lighting system [6,7]. The lighting settings were designed for the conditions listed in Table 1.

<table>
<thead>
<tr>
<th>Light level settings</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>200%</td>
<td>Exceptional conditions such as fog or a combination of rain, high traffic density and accidents.</td>
</tr>
<tr>
<td>100%</td>
<td>High traffic density</td>
</tr>
<tr>
<td>20%</td>
<td>Low traffic density late at night</td>
</tr>
</tbody>
</table>

Table 1  Lighting level settings in the Dutch study.

Main conclusions obtained from this study are:

- Generous lighting when traffic density is not high results in high average speeds, which to some extent cancels the safety benefits of lighting.
- 200% light level is not justified because the cost is high and safety benefits are marginal or unmeasurable.
- 20% light level has no negative safety effects and is sufficient for low traffic density at night provided the weather is fine.
• Green objectives can be met with a reasonable payback time.

In 2002, the Optometry and Neuroscience Department of the University of Manchester Institute of Science & Technology (UMIST) investigated the effect of dimming of Road Lighting System on drivers’ comfort. The UMIST team studied the relationship of eye’s response to the glare from bright overhead lights in a seven miles (11 km) long installation on the M65 motorway in Lancashire in the UK. The Lighting level settings were determined by the traffic flow as listed in Table 2 [5].

<table>
<thead>
<tr>
<th>Vehicles per hour</th>
<th>Lighting level</th>
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<tbody>
<tr>
<td>&gt;3,000</td>
<td>100%</td>
</tr>
<tr>
<td>3,000 – 1,500</td>
<td>75%</td>
</tr>
<tr>
<td>&lt; 1,500</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 2  Lighting setting used in the UMIST study

The 2002 UMIST study contains the following conclusions:
• The flicker effect of passing under a series of overhead light of high brightness at speed is uncomfortable and possibly dangerous.
• Dimmed lighting reduces light pollution.
• 24% of energy can be saved in the test.
• Reduction of CO\(_2\) gas emission can be achieved.
• Significant improvements in driver comfort can be obtained where dimmable lighting is installed.
• It is likely that general road safety is improved by reducing ocular stress, enabling motorists to be remain alert and reduce road accidents.

3.0 New Central Dimmable Road Lighting System

The positive conclusions drawn from the two independent case studies mentioned in the previous section show that dimmable Road Lighting System is an attractive solution to achieve (i) road safety, (ii) reduction in energy consumption, (and hence the reduction in greenhouse gas emission) and (iii) reduction in light pollution. In this section, we describe a new dimmable Road Lighting System. The proposed dimming system has the same infrastructure as described in Fig.1. The central dimming system controls a network of ballast-lamp units in the lamp posts. This new dimmable system retains most of the advantageous features of previous methods. However, it can achieve a very high energy efficiency (>95%) with dimming loss not more than about 3% of full power of the lighting system. In particular, it has a non-intrusive (fail-safe) or self-recovery feature. Non-intrusiveness refers to the fact that even if the dimming system fails to operate normally, the lighting system will still function at full power without dimming ability. No major infrastructural change is required.

3.1 Functional Block Diagram of the Dimmable Road Lighting System

Fig.2 shows the overall block diagram of the Dimmable Road Lighting Management System. The patent-pending power electronics based central dimming control is used to provide a variable ac voltage for controlling the brightness of electromagnetic ballast-HID lamp sets in existing lamp-posts. The system interface can be connected to a central location via a wired or wireless communication system so that the required control signal can be received and executed. Fig.3 shows a photograph of one installation that consists of three dimming modules and a local controller (intelligent control unit) that is connected to a central control center via a telephone network. The schematic of the remote control scheme is shown in Fig.4. A data base of the lighting control boxes linked to the central control centre is available and the timed dimming profiles can be programmed via a control software which also handles system monitoring and reporting functions.
3.2. Functions of the New Electronic Dimming Systems

The functions of the new central electronic dimming system are summarized as follows:

- It can provide dimming functions (by ac voltage control) for all types of discharge lamps.
- It can turn existing “non-dimmable” electromagnetic ballast driven street lamps into dimmable ones.
- Typical dimming range is from 100% to 60% of lamp power.
- It is a centralized dimming system for a network of ballast-lamp units.
- Major re-wiring of existing infrastructure is not required.
It has a non-intrusive (fail-safe) feature to ensure high system reliability.
- It offers over-voltage protection, resulting in longer lifetime of lamps.
- It can be extended to include wired or wireless communication for control, fault identification and remote metering purposes.
- It can achieve real energy saving with a high energy efficiency (>95%).

4.0 Practical Results of the Phase-One of an Large-scale Installation in Heshan City, China for approximately 1350 street lamps.

Installation of the proposed central dimming control system has gone through the trial period successfully and large-scale installation in Heshan City in Guangdong Province, China began in September 2004. About thirty-eight 3-phase dimming systems rated at 220V-240V and 60A per phase are being deployed in several phases for controlling about 8000 HID lamps with rated lamp power ranging from 75W to 400W. This report describes the results of Phase-one of this project that includes about 1350 lamps.

4.1 Dimming profile and energy saving

Existing road lighting systems have no dimming function. While energy can be saved by turning off some of the lamps (e.g. one every three lamps) in the network, uneven light distribution could be a safety hazard. In order to meet the requirements for safety, energy saving and avoidance of light pollution, the ideal scenario is to achieve even light distribution through the use of an energy-efficient dimmable road lighting system.

Fig. 5 A dimming profile with about 24% energy saving

Fig.5 shows one example of a dimming profile for road lighting system. It is assumed that the road lighting system is used from 6pm to 6am each day. For the first 20 minutes, no dimming is programmed because the HID lamps need time to warm up to their steady-state temperature and operating states. This warm-up process is essential to the good health of the lamps. From 6:20 pm to midnight, a reduction of 20% power can be programmed. It is important that a slow power transition over about 15 minutes is employed to change the lamp power from one setting to another. By doing so, (i) road users cannot even detect such small reduction in luminous flux over time and so there will be no discomfort or distraction to the users; (ii) the lamp arc stability is ensured. Since the traffic density from midnight to 5am is low, a 30% reduction of power can be acceptable for road safety, driver comfort and reduction of light pollution. If such dimming profile is adopted, an overall energy saving of about 24% can be achieved. The choice of dimming profile depends on the locations of the street lamps. A power reduction higher than 20% may be preferable in urban areas where the neon lights of the advertising signs play a significant part in light pollution.
4.2 Practical Measurements and Overall Energy Saving
Before the installation of the central dimming system, the total power consumption of the 8,000 street lamps is 1,428 kW (average) and the total energy consumption each night is 15,711kWh (average). For the 1350 lamps in Phase-one of the project, the results are summarized as follows:

A. Average Energy Saving per Night
Before the installation of the central dimming system in Phase-one of the project:
- total energy consumption of 1350 street lamps each night: 2667 kWh (100%)

After the installation of the central dimming system in Phase-one of the project:
- total energy consumption of 1350 street lamps each night: 1946 kWh (73%)

Average energy saving each night: 720 kWh (27%)

B. Measured Dimming Profiles
Data loggers have been installed in various locations in order to check if the dimming systems follow the specified dimming profiles. Fig.6 shows the power measurement of one road lighting system for one night without activating the central dimming system. The full power of this road lighting network is about 27.5 kW. Fig.7 shows the 4-day power measurement of the same lighting system after the central dimming system has been activated. It can be seen that this dimming profile follows closely the example shown in Fig.5. An average energy saving of 24.2% has been measured in this 27.5kW lighting system based on the profile of Fig.5.
4.3 Avoidance of Overvoltage Conditions
The mains voltage in some regions of China may vary quite significantly (usually to the high side). Such high mains voltage leads to extra power consumption in lamps and also shortening of the lifetime of lamps. This phenomenon was observed in the some installation sites. Fig.8 shows the variation of the mains voltage and the output voltage of a dimming system in Heshan City over one night. While the nominal voltage is 220V, it can be observed that the mains voltage could stay well above the nominal value over the night and go up as high as 246V. This overvoltage situation is a main reason for shortening the lifetime of the lamps which would then dissipate more power than its rated power. The use of the central dimming system can avoid such overvoltage situation.

![Mains Voltage & Output Voltage of the Central Dimming System](image)

Fig.8 Measured mains voltage and output voltage of a central dimming system over one night.

4.4 Summary of Overall Performance
Several social aspects such as complaints from residents, crime and traffic accident rates have been monitored by various relevant organizations (without knowing the implementation of the central dimming system. It has been independently confirmed that no complaints from residents have been received. In addition, no unusual changes in crime and traffic accident rates have been recorded for the 9-month period from September 2004 to May 2005. Therefore, it can be confirmed that quality of life has not been affected since the installation of this central dimming system. The results of this case study are summarized in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>100 % - 60 % of Full System Power</th>
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<tbody>
<tr>
<td>Dimming range (System input power)</td>
<td>1.7 % - 3 % of Full System Power</td>
</tr>
<tr>
<td>Total power loss in central dimming system</td>
<td>Up to 40 % of Full System Power</td>
</tr>
<tr>
<td>Power saving capability</td>
<td>No increase</td>
</tr>
<tr>
<td>Crime rate</td>
<td>No increase</td>
</tr>
<tr>
<td>Traffic accident rate</td>
<td>No increase</td>
</tr>
<tr>
<td>Resident complaints</td>
<td>None</td>
</tr>
<tr>
<td>Blackout of road lighting systems with installation of central dimming system</td>
<td>None</td>
</tr>
<tr>
<td>Overall energy saving</td>
<td>27%</td>
</tr>
</tbody>
</table>

Table 3 Phase-one results of a new Dimmable Road Lighting System
5.0 Conclusions

This paper presents the results of a case study of a large-scale installation of an intelligent road lighting system for 1350 street lamps (Phase-one of the project). This is the first large-scale installation of such system for controlling about 8,000 street lamps in China. After over 9 months of installation, it has been confirmed that 27% of energy can be saved without adversely affecting quality of life. The moderate reduction in luminous flux does not lead to any increase in traffic accident and crime rates. No complaint against road light dimming has been received. This new technology has been proved to be an energy-saving and environmentally-friendly solution to dimmable road lighting systems. As all electromagnetic ballasts can be retained, no major replacement cost with electronic ballasts is involved when the central dimming system is adopted. Since the magnetic chokes of the ballasts can be recycled, the pollution problem caused by disposal of a large amount of electronic ballasts can be eliminated. This case study shows that this central electronic dimming system has been reliable as no blackouts of street lamps have occurred since its installation in September 2004.

References