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Practical Evaluation of an Effective Intelligent Central Dimming Strategy Applied to Public Lighting Network

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Abstract—**In this paper design and successful implementation of a central intelligent lighting control system to realize the power consumption in street lighting network is addressed. Considering the importance of realizing energy saving in electrical power distribution network, some HID lamps of the type vastly used in public lighting were tested under voltage dimming control. According to test results, appropriate lighting control system has been applied. The final hardware has been installed in the corresponding distribution substation and the three-day data logging results of its operation approves the realized energy saving. Also, the economic aspects of the project have been investigated and the final results show a good interest of doing other similar projects.**

Keywords-street lighting; lighting control; voltage dimming; energy saving

I. INTRODUCTION

Nowadays the outspread of power system network and extension of consumers and loads in addition to financial matters of constructing new generation units have made the control of electrical energy consumption more sophisticated than before. Hence, the large scale energy consumption of loads should be monitored and controlled to maintain the balance of power generation and consumption as well as to respect the subject of energy saving. On the other hand, it is worth mentioning that a considerable amount of electrical energy (about 25% worldwide [1]) is consumed by lighting systems in which the largest share is dedicated to public lighting network. Therefore it is clear that by applying an optimized control to this type of loads, considerable amounts of energy and money can be saved. This control algorithm which decreases the output light of the lighting device when full-load operation is not necessary is called dimming control. Implementing such method in street lighting network will lead to several benefits such as:

- Providing flexibility for the power system operator to diminish the power consumption during peak hours.
- Decreasing the electrical energy demand from generation units and consequently, reduction of fossil fuels consumption and helping the environment [2].
- Reducing labor and maintenance cost realized for replacement of lamps by prolonging their useful lifetime [3].

The dimming control applied to discharge lamps is mostly implemented in two ways of voltage control [2]–[13] and frequency control [6], [7]. According to the study accomplished in [9] it is concluded that the voltage type dimming is more beneficial in aspects of energy efficiency and light efficacy (lm/W) making this method more popular in practice. The evolution of this method and different types of dimmers will be discussed in continue.

II. DIMMER TYPES

A. Non-electronic Dimmers

The first of dimmers were just a simple variable resistor that by altering the line resistance in series with the lamp, the supply current to the lamp will be varied and thus the power consumption of the overall lighting system can be controlled. Due to the serious defect of poor energy efficiency, these dimmers were soon replaced by magnetic dimmers, making use of saturable reactors whose magnetic flux is controlled by a separate DC source. Fig. 1(a) shows the circuit diagram of this dimmer type. Adjusting the reactor in its linear or saturation region, the impedance in series with the lamps will change and consequently power supplied to the lamps will be dimmed. The need for an extra DC source aside from the ac line was the main drawback of this dimming device. Another type of magnetic type dimmers was the Constant Wattage Autotransformer (CWA) dimmer which is shown in Fig. 1(b). Applying this device, power consumption of lamps can only be adjusted in full or half load levels, although providing high reliability [3]. In order to modify CWA, single phase autotransformer was introduced as a dimmer [3], [8]. As shown in Fig. 2, by changing taps (either in continuous or discrete way) the output voltage and thus the active power consumed by loads will be altered. Applying this dimmer can reduce power consumption to 60% of full load value. Furthermore, high reliability and good accordance with magnetic ballasts of HID lamps widely used in street lighting network are other advantage of such dimming

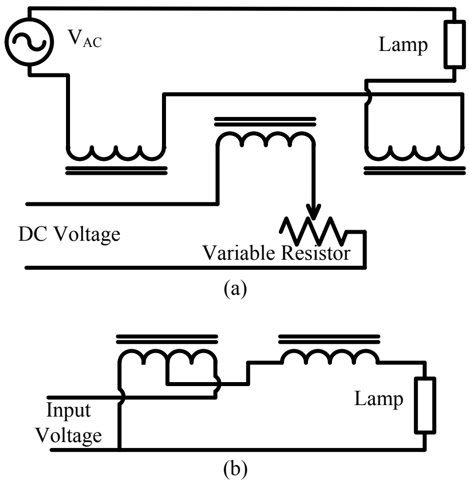


Fig. 1. (a) Saturable reactor dimmer (b) Constant Wattage Autotransformer (CWA) dimmer

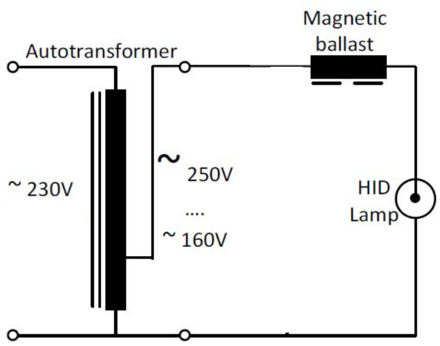


Fig. 2. Single phase autotransformer dimmer

method. The only drawbacks are the autotransformer large size and high initial cost which make it feasible just for large scale prototypes.

B. Electronic Dimmers

Generally speaking, these dimmers occupy less size and volume and are far more efficient compared to dimmers of previous type. On the contrary, they have a poor operation characteristic in terms of power quality. The first method of implementing voltage dimming by means of electronic dimmers, takes advantage of Silicon Controlled Rectifiers (SCRs) as shown in Fig. 3. Adjusting the firing angle of the thyristor eliminates a portion of input sine waveform being supplied to load (lamps) and consequently injecting high amounts of current harmonic into the grid line. Other types of electronic dimmers are somehow integrated into the drive circuits of LED lamps or electronic ballasts of CFLs [4]. Different methods of voltage dimming have been employed in these cases including duty cycle control and dc link voltage control [9].

III. Discharge Lamps Dimming Capability

Among all different lighting applications, street lighting has a much significant impact on power distribution. The power consumption portion of this section is about 3 percent in Iran. Therefore, implementing a cost-effective reliable dimming strategy to this part of loads will have a great impact on power distribution. As the first step, the dimming capability of street lighting lamps has to be ensured before taking further steps. Among all different gas discharge lamps, HID lamps have been numerously used for public lighting purposes. These lamp types show poor characteristics in voltage dimming tests since their arc discharge is so susceptible to extinguish when disturbance occurs in supply voltage. This fact has caused HID lamps to be less dimmable compared to other lamp types and a general reliable way of implementing dimming control to these lamps, specially a central controlling unit, has not yet been introduced. Although a central lighting control system for HPS lamps has been introduced in [2] which guarantees a 30% reduction in power consumption in exchange of 40% deduction of output light, a straightforward and reliable controlling scheme for mercury vapor lamps which are frequently used for street lighting purpose has not yet been proposed.

In order to implement voltage dimming control on street lighting network, the dimming capability of its lamps must be investigated first. Therefore, HID lamps of different types of HPS, MH and mercury vapor in power ratings of 125 to 400 watts have been tested by a single phase autotransformer with continuously changeable tap. Table I reports the test results only for 125 W mercury vapor lamp since it is the common lamp type used in public lighting. It is worth mentioning that the measured active power is the sum of power consumption of the lamp and its magnetic ballast as well as the power loss in the

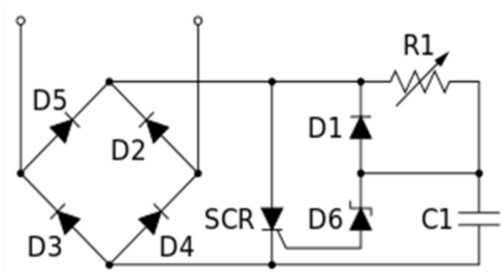


Fig. 3. Circuit diagram of basic electronic dimmer taking advantage of SCRs

TABLE I. VOLTAGE DIMMING TEST RESULTS OF 125 W MERCURY VAPOR LAMP

Supply Voltage (%)	100	90	80	70
Supply Voltage (V)	220	198	176	154
Lamp Current (A)	1.37	1.11	0.94	0.77
Active Power Consumption (W)	144	116	90	71
Power Factor	0.45	0.45	0.42	0.39
Lominous Flux (%)	100	73.4	45.9	21.1

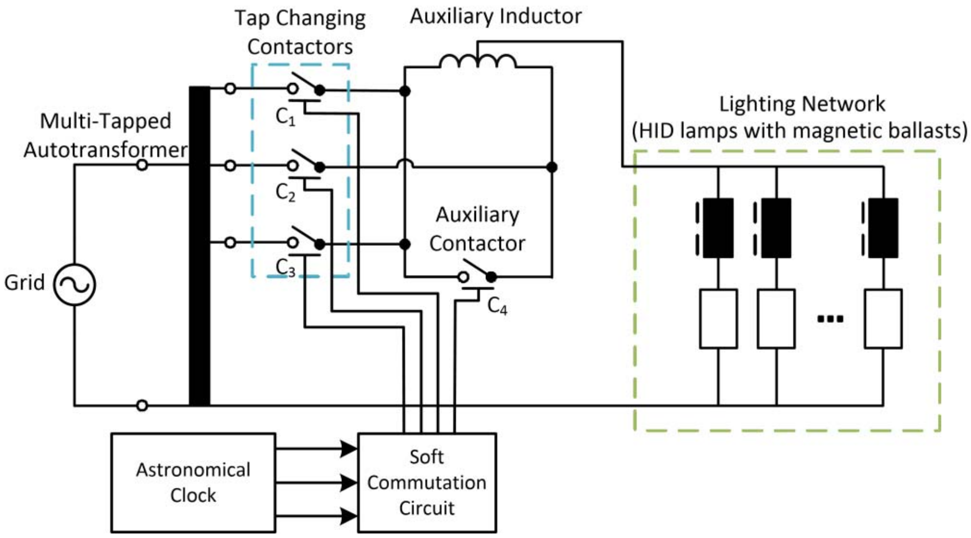


Fig. 4. Circuit diagram of the proposed central intelligent dimming control system for street lighting

autotransformer core. Also, the tested mercury vapor lamp was extinguished in voltages lower than 70% nominal.

IV. Proposed Lighting Control Strategy

The conducted test on mercury vapor lamp approves its capability for sufficient voltage dimming range. The next step is to find a suitable control method to implement in public lighting network. Besides providing energy consumption reduction, the designed lighting control system has to maintain several essential characteristics; as long as public lighting has a significant impact on social security, the proposed lighting control method must prevent lamps from extinguishing. On the other hand, it must be as straightforward as possible so that operating personnel will have the least difficulty interfacing with the control plant. Accordingly, the main stage of the lighting control system hardware uses a three-phase autotransformer with discontinuously changeable taps. The transformer along with all other equipment shown in the single line diagram of Fig. 4 will be mentioned in continue.

A. Three-phase Autotransformer

This 40 kVA autotransformer along with its three lowering taps performs the main act of voltage dimming control. Among them, three taps of 220, 210 and 190 V are connected to the corresponding three phase contactors. Using the autotransformer not only makes the dimming control straightforward, but also provides a soft start-up of the lighting network; the lighting feeders of street lighting network will turn on by a voltage lower than nominal value provided by autotransformer helping to decrease the starting current and peak reduction of demanded power in the early hours of evening. Fig. 5(a) shows the three phase autotransformer placed in the rear side of lighting control panel.

B. Astronomical Clock

Tap changing command comes from the astronomical clock which stores the timetable for each day of year and performs the act of energy saving automatically and intelligently. Since the single-output type of this device is frequently used in other street lighting panels, the three-output type (according to three taps of autotransformer) is used in this project to maintain simplicity and similarity to other lighting panels so that operating personnel will not face any difficulty dealing with the system. The exerted astronomical clock is programmed with two different saving schemes which are brought in Table II.

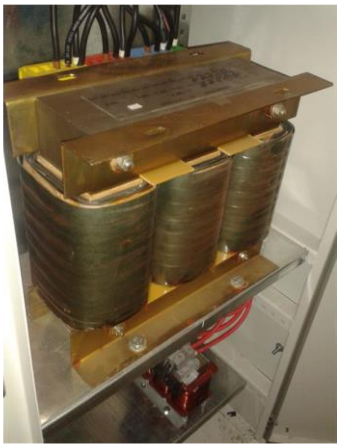
C. Auxiliary Inductance and Contactor

The discharge arc in HID lamps present a high instability to changes in supply voltage. Since the changing of taps is in not continuous, loss of lighting due to lamps being extinguished will be possible. In order to overcome such a critical problem, a three phase center-tapped inductance, 0.5 mH per phase, along with a three phase auxiliary contactor is used and its mounted view is displayed in Fig. 5(b). This inductance improves damping of the system during changing of taps to prevent lamp arc from quenching.

D. Soft Commutation Circuit

By inserting the new inductance and the corresponding contactor, switching of contactors needs to be modified. Hence, a control circuit is designed and applied to the lighting control system which receives the output signals of astronomical clock as input and controls the switching of the contactors correspondingly.

The tap changing act in the proposed lighting control algorithm is done in four steps. Step one is when one of the tap contactors, C_1 for instance, along with auxiliary contactor (C_4) are in on state and so the lighting network is supplied with the nominal voltage. It is worth to mention that there is no voltage drop on the auxiliary inductance as the flux flow in its two halves are opposite leading to voltages induced in two coil parts eliminating each other. When the time comes to tap changing point (from tap 1 to 2 according to the program) and the appropriate signal is sent by astronomical clock, C_4 is set off leading to current flow only through the first half of the auxiliary



(a)

(b)

Fig. 5. (a) Three phase autotransformer (b) Three phase auxiliary center-tapped inductor

TABLE II. TWO DIFFERENT CONTROL ALGORITHMS OF ASTRONOMICAL CLOCK

Program #1		Program #2	
Time Period	**Operating Tap**	**Time Period**	**Operating Tap**
Sunset to 15 minutes after	2	Sunset to 15 minutes after	2
15 minutes passed sunset to 21:00	1	15 minutes passed sunset to 22:00	1
21:00 to 23:00	2	22:00 to 1:00	2
23:00 to 5:00	3	1:00 to 5:00	3
5:00 to sunrise	2	5:00 to sunrise	1

coil. Next, C_2 is set on causing a slight short circuit of taps 1 and 2 through the auxiliary coil but having no harmful effect on the plant or the grid line since the inductance value is designed to handle this short circuit current. During this state, the voltage supplied to the output lighting feeders is the average of taps 1 and 2 voltage. Then C_1 is made off and after that C_4 is triggered to be on again to maintain the normal operation of the system with a lower voltage (tap 2) through the contactors of C_2 and C_4. The time duration of each step described above can be changed but is set to be 0.5 s.

Fig. 6. Frontal view of the intelligent lighting control panel

V. DATA LOGGING RESULTS

The intelligent lighting control system was established based on the described equipment and settled in the Maadar substation in Mashhad, Iran. In order to utilize the energy saving control scheme, four street lighting feeders (F_1, F_2, F_3 and F_4) were connected to the constructed lighting panel whose frontal view is displayed in Fig. 6. By means of the power quality analyzer device FLUKE 435, the operation of the proposed control system was monitored and necessary data were acquisitioned. It is worth mentioning that F_3 and F_4 were both connected to one phase due to lower load than other feeders. Fig. 7(a) illustrates the supply voltage of four feeders sampled during 3 days of data logging. As can be simply obtained, the control system works with the program 1 of the astronomical clock and lighting feeders have been started up by a voltage lower than nominal value to decrease the current rush of startup. Fig. 7(b), representing the data logging of feeder currents, shows this point clearly. Also the correct operation of the auxiliary inductance can be obtained from Fig. 7(b) that there is no loss of lighting during tap changing. Fig. 7(c) and (d) show the active power consumption and power factor of lighting feeders during data logging period respectively.

VI. ECONOMIC REVIEW

Optimal lighting control and energy saving are valued when economic efficacy is maintained at a reasonable degree. In order to study the cost effectiveness of the proposed control system, a simple but practical and revealing cost-benefit calculation is done and results will be reported in this section. This calculation

TABLE III. CALCULATED PAYMENTS OF THE PROJECT

Parameter	Description	Value (IRR)
P	Initial investment cost	-40,000,000
F_1	Economic saving of the 1st year	15,150,000
F_2	Economic saving of the 2nd year	18,180,000
F_3	Economic saving of the 3rd year	21,816,000
F_4	Economic saving of the 4th year	26,179,200

TABLE IV. CALCULATED PROJECT BALANCES OF THE PROJECT

Project Balance	Value (IRR)
PB_0	-40,000,000
PB_1	-32,850,000
PB_2	-21,240,000
PB_3	-3,672,000
PB_4	21,772,800

is done for 100 mercury vapor lamps of 125 watts. The calculated energy saved yearly with these assumed lamps based on the applied saving scheme is 101000 kWh. In order to calculate the economic equivalent of this saved amount of energy, the solution of "undistributed energy" is employed; meaning that every 1 kWh of saved energy is worth 1500 IRR. Accordingly, the main necessary data to fulfill the analysis are obtained and brought in Table III. Assuming the values of the table, the economic analysis is done based on the project balance criterion (PB) defined by the equation below:

$$PB_t = PB_{t-1}(1+i) + F_t \quad (1)$$

Where i is the yearly interest rate and equal to 20%, t is the year indicator in the whole period of study and F_t and PB_t are the final value and the project balance at the end of the t-th year respectively. Using (1) and taking into account that $PB_0 = P$, the project balance of the four-year study period is calculated and brought in Table IV. According to parameter values of the table, the absolute investment return of this project will take 4 years. The reason for this return period being somehow long is the lighting feeders being too old, preventing the system from gaining expected energy saving amounts. Applying this project led to only 20% of energy saving. However, the expected value was to be at least 30% which would lead the return period to be shorter and approve the cost effectiveness of the proposed control scheme.

VII. CONCLUSION

In order to realize the important desire of energy saving and power loss reduction in electric power distribution network, different methods of lighting dimming cotrol were discussed and the most beneficial one was chosen and described in this paper. After examining the voltage dimming capability of the gaseous lamps used in street lighting networks, necessary hardware and equipment to fulfill the mentioned purposes were assembled and the final panel was settled in the corresponding substation in Mashhad, Iran. Data logging results of several street lighting feeders operating with the proposed control system during three days were somehow satisfactory. The only problematic issue was the oldness of lighting feeders HID lamps which lead to an energy saving of 20% being less than expected.

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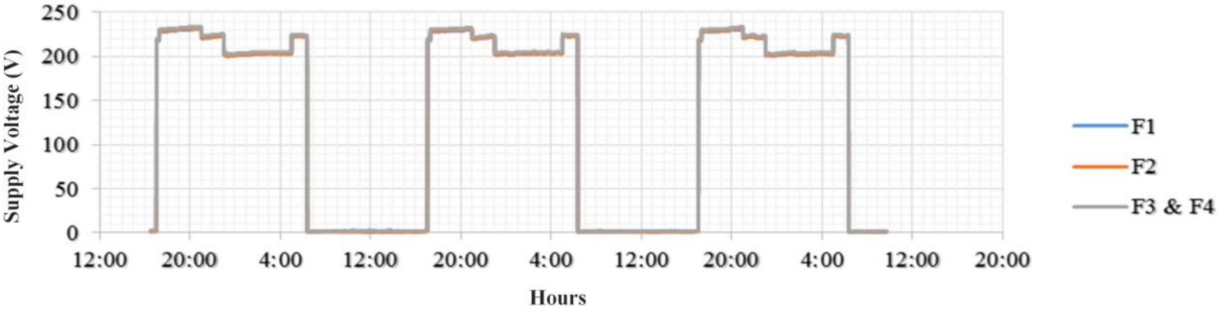

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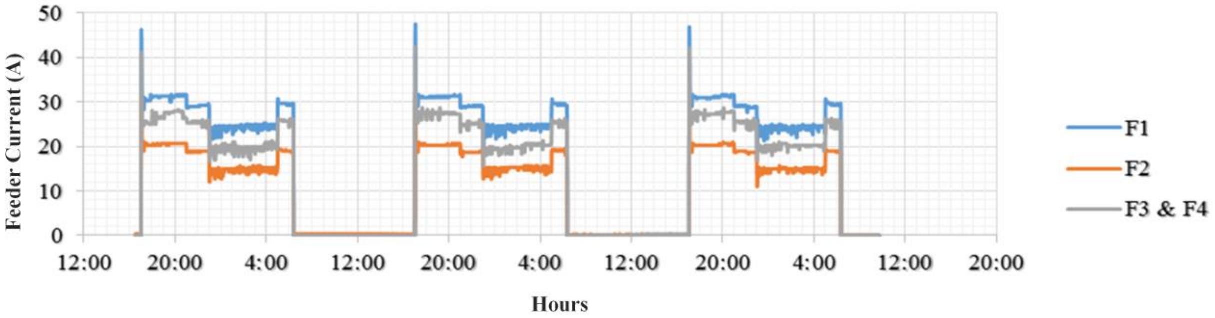

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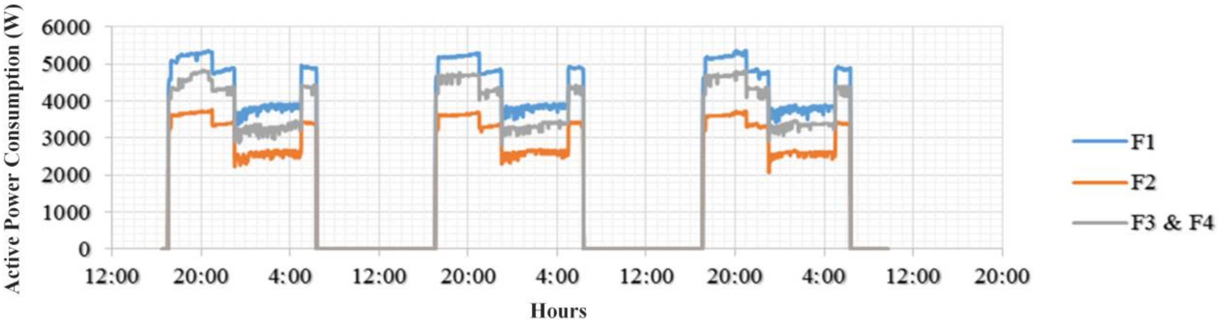

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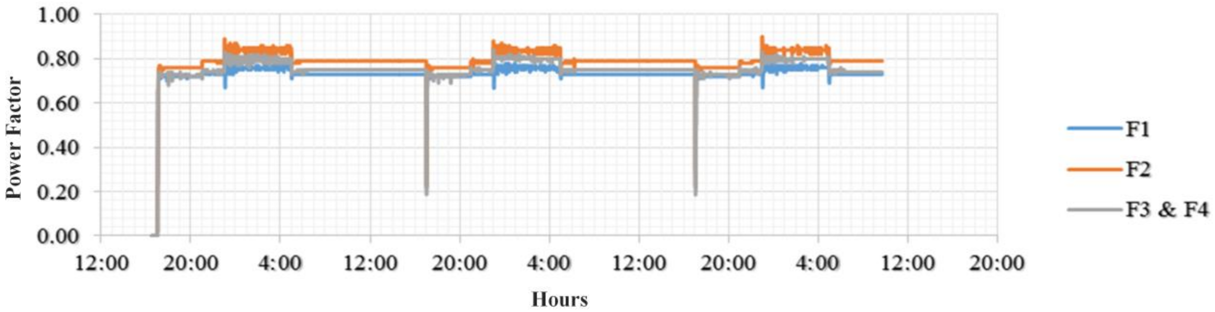

(d)

Fig. 7. Recorded parameter values during three-day data logging of four street lighting feeders (a) supply voltage (b) current (c) active power (d) power factor