Department of Electrical and Computer Engineering

Energy Saving Controller for Fluorescent Lamps

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ABSTRACT

Although fluorescent lamp is a very efficient lighting device in daily life, still the high harmonic distortion and low power factor cause unnecessary energy consumption. In today's environment demanding energy efficiency, it is important to reduce this energy loss by integrating an energy saving controller in the electromagnetic ballast of fluorescent lamps. The research presented in this thesis investigates the design and implementation of a new energy saving controller for electromagnetic fluorescent lamp network. The newly developed controller attempts to reduce power losses in both the electromagnetic ballasts and fluorescent lamps by regulating the incoming supply voltage to an optimum level. In addition, the new controller is able to adjust the illuminance level of working environment lightings under either dark or bright condition. Moreover, the function of the new controller is extended with time scheduling control capability, where the switching of lighting systems can be controlled at predetermined times based on occupancy schedule. Both simulation and practical results show that the implemented controller reduces energy consumption by at least 37.5%, by reducing the incoming supply voltage by 15%. In addition, it is desirable to have variable illuminance level control to decrease the energy losses. The experimental results show that the illuminance output level of electromagnetic ballast fluorescent lamps can be decreased by 50% using the new controller while maintaining unity power factor. Integration of the new energy saving controller into electromagnetic ballast fluorescent lamps impressively outperforms the existing electronic dimmable ballast. This new controller brings great ideas for energy saving in the use of fluorescent lamps.

Keyword: energy saving, illuminance level control, voltage control, electromagnetic ballast fluorescent lamps

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NOMENCLATURE

Abbreviations

A	Ampere
AC	Alternating current
ASA	Australia Standard Authority
BAS	Building automation system
C	Capacitor
CCF	Current crest factor
CPU	Central processing unit
DC	Direct current
ESF	Energy saving factor
FLS	Electromagnetic ballast fluorescent lamp
FMS	Factory management system
HID Lamp	High intensity discharge lamps
HMI	Human machine interface
HVACR	Heating, ventilation, air-conditioning and refrigeration
IEC	International Electro-technical Commission
I/O module	Input / output module
L	Inductor
LCD	Liquid crystal display
LED	Light emitting diode
NEPIP	National light product information program
OPMS	Online programming unit monitoring system
P	Real power
PAF	Power adjustment factor
PID Controller	Proportional/integral/deferential controller
Pf	Power factor
PFL	Power of fluorescent lamp
PLC	Programmable logic controller
PV	Process variable
PWM	Pulse width modulation
R	Resistor
RAM	Random access memory

RMS	Root mean square
ROM	Read only memory
RTD	Resistance temperature detector
S	Apparent power
SME	Small and medium enterprise
SV	Set variable
TRIAC	Triode for alternating current
UPS	Uninterruptible power supply
V	Voltage
W	Watt
ºC	Degree Celsius
%RH	Relative humidity

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CHAPTER 1: INTRODUCTION

1.1 Motivation for study

In 2007, Australia and Canada enacted laws to phase out incandescent bulbs by 2012 as part of a plan to cut-down greenhouse gas emission by 800,000 tonnes a year [1, 2]. As a result, incandescent lamps are now being replaced by alternative lighting solutions and fluorescent lamps are most likely to be the primary replacement. Due to the increasing global demand for fluorescent lamps, major research attention is now paid to energy saving fluorescent lamp technique. Energy efficiency of fluorescent lamps can be improved by introducing an energy saving controller in the electromagnetic ballast fluorescent lamps. The use of energy saving controller in electromagnetic ballast can combine the benefits achievable from both the controller and electromagnetic ballast, which will surpass the known limitations of electromagnetic ballast.

Fluorescent lamps have always been the preferable lightings choice as compared to conventional light bulbs. However, there is still unnecessary energy consumption and losses in fluorescent lamps due to harmonics distortion and low power factor. Recent research in this area is limited to developing energy saving feature for electronic ballast fluorescent lamps. Although electronic ballast outperforms standard electromagnetic ballast in terms of weight and dimmable function, it possesses limitations including: 1) low power quality, 2) high starting inrush current and 3) environmental pollution from electronic wastes (non-biodegradable electronic wastes that are not recyclable) [3, 4]. Furthermore, the lifetime of electronic ballasts is limited by the lifetime of the electronic components, particularly the electrolytic capacitors.

Recent research studies have proven that the lifetime of the electrolytic capacitors is mainly dependent on the ambient temperature. Their lifetime is halved if the temperature increases by 10 ºC and is doubled if the temperature decreases by 10 ºC [5]. On the other hand, electromagnetic ballasts have lifetime in excess of 30 years [3, 6]. Since the reliability of electronic ballast is much lower than electromagnetic ballast fluorescent lamps, is it not ideal to implement electronic ballast fluorescent lamps in new lighting systems.

An alternative approach to the energy saving issue of fluorescent lamps has been considered in this study. The proposed solution investigates the integration of a central energy saving controller into the electromagnetic ballast fluorescent lamps network rather than further improvement of the electronic ballast that has limited benefits. The reason for this approach is that the use of energy controller in electromagnetic ballast can combine the benefits achievable from both the controller and electromagnetic ballast, which will surpass the known limitations of electronic ballast fluorescent lamps. The power losses in conventional electromagnetic ballast will be taken care of by the energy saving controller. The energy saving controller will reduce the incoming supply voltage to predetermined value after the lamps are switched on. This will reduce the current drawn by the electromagnetic ballast and the lamp, resulting in less energy consumption. In addition, there is no replacement cost for integrating the controller into the existing electromagnetic fluorescent lamps network as the energy saving controller is designed based on such system.

However, for existing installations where it is not cost effective to redesign a new lighting system, the following energy saving measures can be considered to reduce energy consumption:

1. **Minimise usage:** Lighting control system may consist of programmable time switch that has 24/7 programmable clock to control the switching of fluorescent lamps. Building automation system (BAS) or factory management system (FMS) may also be programmed to control the operating hours of fluorescent lamps.

2. **Illuminance level control:** Illuminance level control is a close loop control system, where installed lux intensity sensor will detect available daylight at a working environment and adjust the illuminance level according to the set target value.

3. **Minimise installed power:** Retrofitting or efficiently compensating the lighting due to lumen depreciation [7].

1.2 Objectives

The main objective of the research is to develop an energy saving controller for electromagnetic ballast fluorescent lamps in order to save energy and improve reasonable energy utilisation in the related sectors. Therefore, the conventional fluorescent lamp preheating technology with a superior energy saving controller will be investigated, designed and optimised. The objectives of this study were to:

1. Create a fluorescent lamp model to investigate the real performance of the energy saving controller for electromagnetic ballast fluorescent lamps.

2. Build appropriate component and system model to simulate the energy saving controller by using Matlab Simulink simulation software.

3. Investigate the voltage-current characteristics of electromagnetic ballast fluorescent lamps.

4. Based on the simulation model, design and implement an energy saving controller for electromagnetic ballast fluorescent lamps network.

5. Determine the electrical energy consumption data to support the implications of energy saving controller.

6. Evaluate the economic issues for investment on energy saving controller for electromagnetic ballast fluorescent lamps network.

1.3 Scope of work

This thesis presents all the work carried out in this research, from investigation and design of energy saving controller to the simulation and hardware implementation of the energy saving controller in electromagnetic ballast fluorescent lamps network. The introduction to the study is given in Chapter 1 and it addresses recent research constraints on florescent lamp technology and the objectives of study. Chapter 2 covers the literature review of different types of lamps. Various ballast technologies are discussed in this chapter. Chapter 3 explains the background information of all the individual system components used in energy saving controller. In chapter 4, the voltage - current characteristics, negative resistance characteristic of electromagnetic ballast fluorescent lamps and dynamic resistance have been studied and simulated to provide comparisons with the theoretical results. These models are later used as simulation models for evaluating the performance of the energy saving controller. Chapter 5 presents the design specifications of the energy saving controller. Experimental results, operating principle and features of the energy saving controller are also discussed. Chapter 6 discusses the balancing cost, operation, modelling of the flexibility, and the future performance of the energy saving controller. Chapter 7 presents a summary of the findings and proposes recommendations for future work.

CHAPTER 2: LIGHTING SYSTEM

2.1 Introduction

Knowing where and when energy is being consumed is the most important step to understand how energy can be saved. The largest energy demand in United States is in daily lightings, Figure 2.1 [8]. The energy consumption profile for large commercial building in many other countries is thought to be similar to those for the United States. From Figure 2.1 it is clear that heating, ventilation, air-conditioning and refrigeration (HVACR) system contributes 32% of total energy consumption and lighting system contributes 24% of the electrical energy consumed in large commercial building.

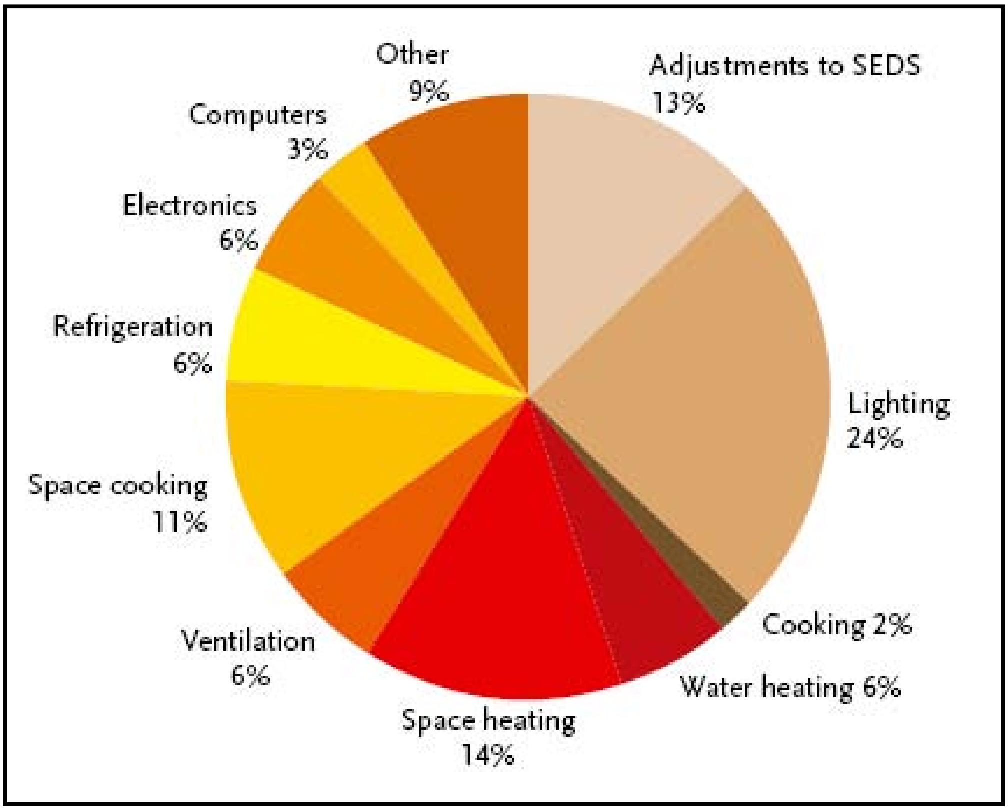


Figure 2.1: Energy consumption of a large commercial building in United States.

Fluorescent lamps have always been preferable lighting choice for residential and commercial building and thus take up a significant part in daily energy consumption. The energy saving of fluorescent lamps can be achieved through efficient energy conversion control algorithm. Such control methods reduce the energy consumption of electromagnetic ballast fluorescent lamp, and it also reduces the power losses of the electromagnetic ballast, which helps to save the energy consumption of lighting systems. This chapter provides a brief description on different type of lamps and discusses various ballast technologies.

2.2 Types of lamps

2.2.1 Incandescent lamps

Incandescent lamps are the oldest and most common lamps used in conventional lighting system due to its low cost. Incandescent lamps produce light using an incandescent filament which is sealed in a glass bulb containing an inert gas (nitrogen and argon or krypton) [9]. Figure 2.2 shows the structure of incandescent lamps.

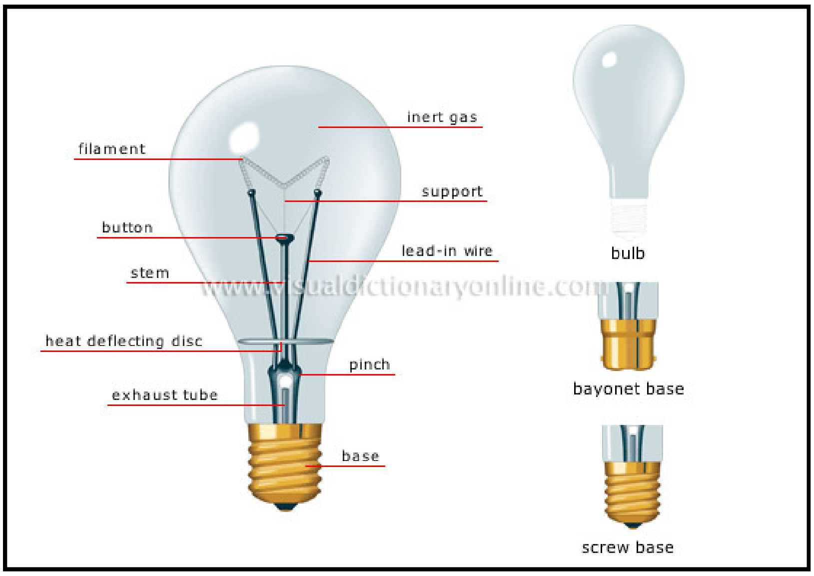


Figure 2.2: The incandescent lamp.

The operating characteristics of incandescent lamps are affected by its operating voltage. Initially, due to the low thermal capacity of incandescent lamp, a preheating period to heat up the lamp is required. After the preheating period, the input power of the incandescent lamps become stable. The illuminance level of the incandescent lamps is directly proportional to the square of voltage applied across the lamp [10, 11]. The main disadvantages of incandescent lamps are heat dissipation and short lifespan. According to [10], the incandescent lamps convert 92% energy into heat and only 8% energy is converted into useful light resulting in poor luminous efficiency. The dimming of incandescent lamps can be achieved by introducing a TRIAC dimmer switch in series with the incandescent lamps. The illuminance level of incandescent lamps can be controlled by varying its firing angle in the incoming supply voltage as shown in Figure 2.3.

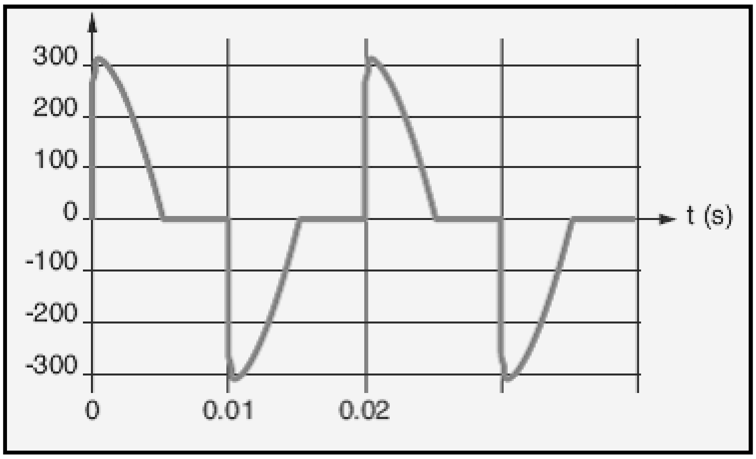


Figure 2.3: Output voltage waveform from the TRIAC dimmer.

From Figure 2.3 it is clear that the incoming supply voltage has been chopped by varying the firing angle of TRIAC. As a result, the illuminance level of incandescent lamps can be controlled. However, the chopped voltage is considered as non-linear voltage which will contribute to total harmonic distortion.

2.2.2 Halogen lamps

Halogens lamp is an improved version of incandescent lamps. It is invented by General Electric in 1958 with the intention to be the wing tip navigation light for Boeing 707 [12]. The coating of incandescent lamps will limit the light intensity output of the bulb. In order to resolve this drawback, small amounts of Halogen are inserted to combines with the evaporated tungsten. This helps the Halogen lamps to have good colour rendering index and it is 25-30% brighter than standard incandescent lamps. Conversely, this process only work when the temperature is over 200°C. Hence, the heat dissipation generated by Halogen lamps is much higher than incandescent lamps [13]. The lifespan of Halogen lamps is also doubled compared to conventional incandescent lamps. In addition, the efficiency of Halogen lamp is slightly higher than incandescent lamps. They are commonly used in commercial applications, particularly for highlighting merchandise. Figure 2.4 shows a typical Halogen lamp.

Figure 2.4: Halogen lamp.

2.2.3 Electromagnetic ballast fluorescent lamps

The low-pressure mercury vapour lamps or fluorescent lamps are the most cost effective and efficient lighting devices. Unlike incandescent lamps and Halogen lamps, electromagnetic ballast fluorescent lamps possess negative resistance dynamic characteristic and causes total harmonic distortion [6, 14, 15]. As a result, electromagnetic ballast fluorescent lamps cannot be connected directly to incoming supply voltage as it will draw an ever increasing amount of high inrush current through the fluorescent tube until it overheats and self-destruct due to uncontrolled current flow [16, 17]. The electromagnetic ballast provides a proper voltage to establish an arc between the two electrodes. Additionally, the ballast regulates the electric current flowing through the fluorescent lamp to stabilise the output light.

Figure 2.5 shows the circuit connection of electromagnetic ballast fluorescent lamps. When the fluorescent lamp is turn on (without starter), the voltage across the fluorescent lamp is not sufficient to continue the initial ionisation of the mercury. This happens because of a cold filament on both sides of the fluorescent lamps. Therefore, an electronic starter must be used to preheat the electrodes in order to facilitate electron emission. The electronic starter provides a high voltage to initiate the discharge of electron [10]. At the same time, the electromagnetic ballast will deliver a control amount of current through the electrodes in order to heat up the electrodes. The electrodes can attain proper temperature in a few seconds, after which the electronic starter is switched on automatically. Then, the electronic starter acted as a short circuit across the fluorescent lamps and leaves the gas in the fluorescent lamps. This will enable the current to travel, as the filaments are hot and arc is established and therefore the fluorescent lamp emits light [10, 18].

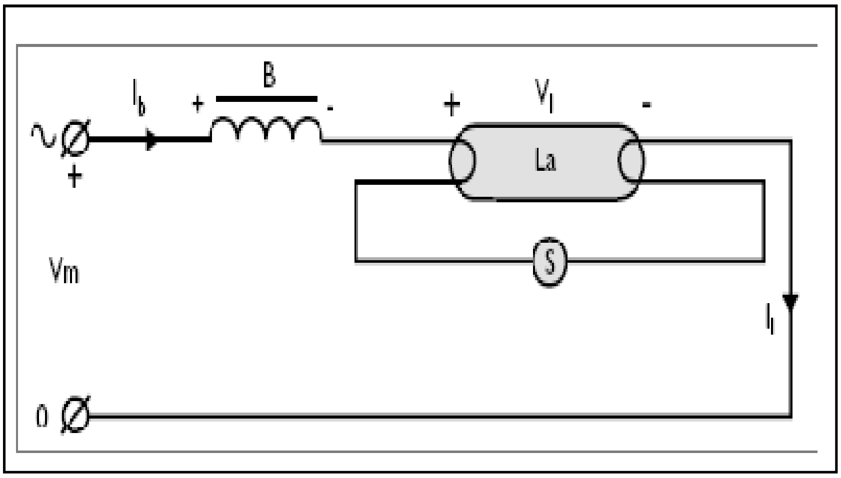


Figure 2.5: Circuit connection of electromagnetic ballast fluorescent lamp.

The incoming supply current $I_{in}(t)$ can be related with Figure 2.5 as in Equation 2.1.

$$I_{in}(t) = \frac{V_{in}(t) - V_L(t)}{Z(t)} \qquad \text{Equation 2.1}$$

Where $I_{in}(t)$ is the current across magnetic ballast and fluorescent lamps , $V_{in}(t)$ is the incoming supply voltage, $V_L(t)$ is the fluorescent lamp voltage and $Z(t)$ is the total impedance of magnetic ballast and fluorescent lamps

The power of fluorescent lamps $P_L(t)$ is equal to the voltage $V_L(t)$ times the current $I_L(t)$ of fluorescent lamp, as in Equation 2.2

$$P_L(t) = V_L(t) \times I_L(t) \qquad \text{Equation 2.2}$$

Equation 2.2 proves that the energy consumption of electromagnetic ballast fluorescent lamps are influenced by the current $I_L(t)$ and voltage $V_L(t)$ of fluorescent lamp. The fluorescent lamps current $I_L(t)$ varies as a function of incoming supply voltage $V_{in}(t)$. The reduction of incoming supply voltage $V_{in}(t)$ leads to a reduction on fluorescent lamp current $I_L(t)$. As a result, the energy consumption of electromagnetic ballast fluorescent lamp can be reduced (energy consumption of fluorescent lamp is proportional to the square of the voltage reduction).

From Equations 2.1 and 2.2 it can be concluded that energy saving of electromagnetic ballast fluorescent lamps is achievable by controlling the incoming supply voltage $V_{in}(t)$. Due to the inductive impedance of electromagnetic ballast, a single phase power capacitor is connected in series with the electromagnetic ballast fluorescent lamp to improve the power factor. From Figure 2.6, at operating frequency of 50 Hz, the voltage of fluorescent lamp presents two voltage spikes within each voltage cycle. This results from electron and ionised atoms having enough time to recombine at each current reversal.

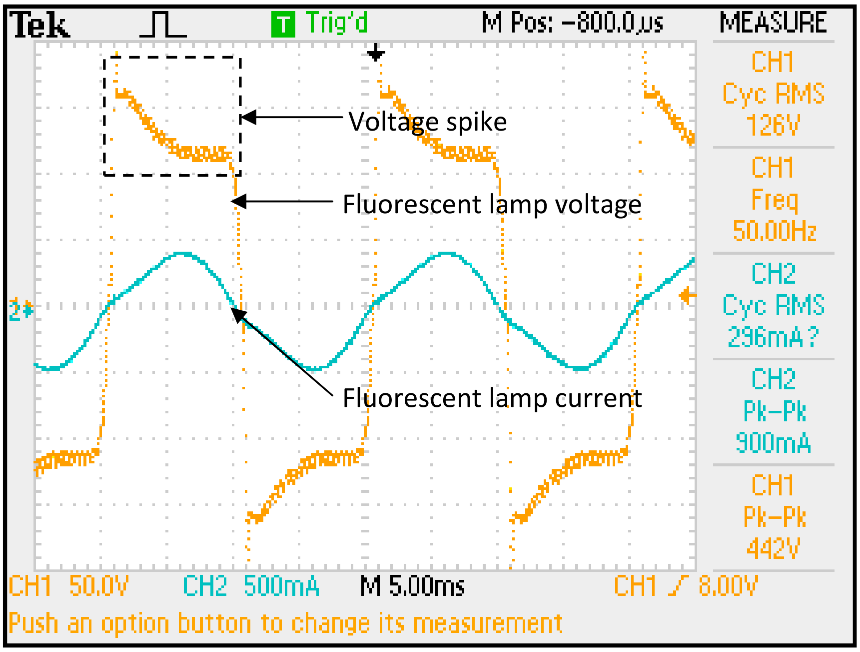


Figure 2.6: Voltage and current waveforms of electromagnetic ballast fluorescent lamps.

(Incoming supply voltage: 230 V, Frequency: 50 Hz, Fluorescent lamp type: GE T9 fluorescent tube, Fluorescent lamp power: 40 W)

[6, 14, 19, 20] found that electronic ballast fluorescent lamps produce high harmonic distortions compared to traditional electromagnetic ballast fluorescent lamps. In terms of total harmonic distortion, electromagnetic ballast fluorescent lamps only contribute to roughly 20% third harmonics in the phase current. When the amount of seventh or higher harmonic is too large, harmonic distortion can be reduced by introducing a filter coil in series with the power factor correction capacitor. However, adding the filter coils will result in higher third and fifth harmonics, because the total impedance for combination of capacitor and filter coil is lower than the impedance of power factor correction capacitor (without connect in series with the filter coil) [21].

The high harmonic distortions generated especially in large electromagnetic ballast fluorescent lamps networks will lead to serious interference to the stability of power system. Hence, a passive LC filter is installed in parallel with the electromagnetic ballast fluorescent lamps to absorb the harmonic distortion, thus improving the power quality in the power distribution network.

Vlavik [13] performed an analysis on flickering effect of electromagnetic fluorescent lamps in large lighting networks and reported that power factor correction capacitor will induce an oscillation in resonant circuit formed by ballast capacitor and inductance of electromagnetic ballast. Beside the power factor correction capacitor, lumped inductances such as transformer leakage inductance, blocking choke of surge protection also have significant influence on resonant frequency, thus causing lamp flickering. This flickering effect of electromagnetic ballast fluorescent lamps can be resolved by installing a central power factor compensation capacitor in series with the damping inductor.

2.2.4 Electronic ballast fluorescent lamps (compact fluorescent lamps)

Electronic ballast fluorescent lamps are one of the most common types of lamps used for general lighting. Unlike electromagnetic ballast fluorescent lamp, electronic ballast fluorescent lamp uses solid state electronic circuit to provide proper starting and current regulating to fluorescent lamps.

For electronic ballast fluorescent lamps, its discharge path is folded and so, its size is smaller compared to conventional electromagnetic ballast fluorescent lamps. On the other hand, for compact fluorescent lamp, its electronic ballast is integrated with the fluorescent tube. Therefore, the size of compact fluorescent lamps is smaller compared to electronic ballast fluorescent lamp. Furthermore, compact fluorescent lamp can be easily fitted into standard incandescent lamp's socket.

The operating temperature of the electronic ballast fluorescent lamp fitting is often high (typically more than 85 ºC). The high temperature has significant negative impact for the electronic components inside the electronic ballast. The lifespan of electronic ballast fluorescent lamps is generally affected by the lifespan of its electronic components especially electrolyte capacitor. High temperature in electronic ballast is the primary cause of electrolyte capacitor failure. High temperature may also cause either short-term catastrophic failure, or long term functional degradation of electrolyte capacitor. According to the technical specification of electrolytic capacitor, every 10ºC temperature increment results in halving the component lifespan. In contrast, the lifespan of electrolyte capacitor is doubled if the temperature decreases every 10 ℃ [5]. Table 2.1 shows the efficiency and average lifespan of common lighting sources.

Table 2.1: Lumen efficacy and average lifespan of common lighting source

Lighting source	**Lumen efficiency (Lumens / Watt)**	**Average lamp life (hour)**	**Colour rendering index**
Standard incandescent	5-20	750-1000	100
Electronic fluorescent	20-55	10,000	80
Electromagnetic fluorescent	60-100	15,000-24,000	50-90
HID-Metal halide	45-100	10,000-20,000	60-90
HID-high pressure sodium	45-100	Up to 24,000	9-70

Table 2.1 concludes that electromagnetic ballast fluorescent lamps are preferred to their counterparts due to its high efficiency, longer lifespan and cost effective. However, recent research in this area is limited to developing electronic ballast for compact fluorescent lamps [3]. Even though electronic ballast outperforms the standard electromagnetic ballast, in terms of weight and dimmable function, it possesses known limitations including high total harmonic distortion, high inrush current and environment pollution [3, 4, 6].

Figure 2.7 shows the inrush current of electronic ballast fluorescent lamps compared to electromagnetic ballast fluorescent lamps. This current is much higher than that of electromagnetic ballast fluorescent lamps. This phenomenon can be explained by the starting of electrolyte capacitor. When incoming voltage is applied to the electrolyte capacitor (which is fully discharge), the electrolyte capacitor behaves as short-circuit. So the inrush current will be very high. As the electrolyte capacitor is charging up, its voltage will increase and eventually equals to the system voltage. When this happens, the electrolyte capacitor behaves as an open circuit [11].

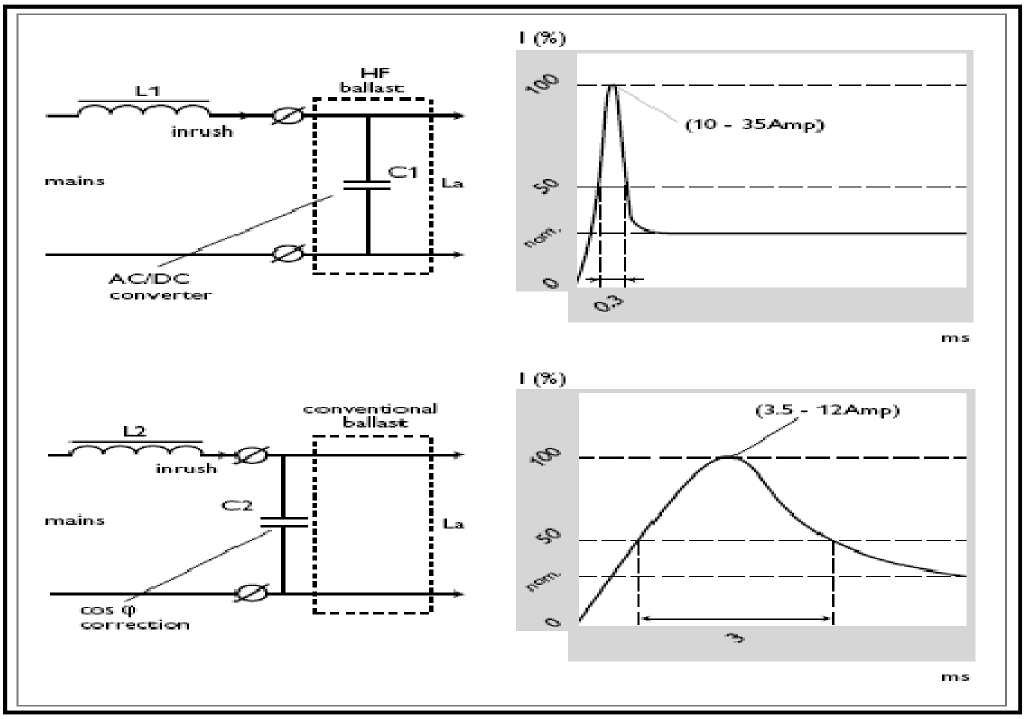


Figure 2.7: The inrush current of electronic ballast compared with electromagnetic ballast [19]. The Electronic ballast is on top, electromagnetic is on bottom.

In addition, the inrush current reaches its peak value when the electromagnetic fluorescent lamp is first switched on. This is caused by initial build-up of the magnetic field in electromagnetic ballast and the non-linear characteristic of fluorescent tube. The amplitude of the inrush current not only depends on the load characteristics, but also on the instant in the incoming supply voltage waveform. On the other word, the inrush current will reaches its greatest value, if the electromagnetic fluorescent lamp is connected to the incoming supply voltage around the zero crossing of the voltage waveform.

2.2.5 High intensity discharge lamps

The family of high intensity discharge (HID) lamps consists of metal halide lamps, mercury vapour lamps and sodium lamps. The HID lamps are different from incandescent lamps, Halogen lamps and fluorescent lamps. They are able to provide better illuminance level. It is commonly used in high-bay lighting such as commercial application, industrial application as well as street lighting.

HID lamps, which belong to the electric discharge lamps family, have negative resistance characteristics. As a result, series electromagnetic ballast is required to provide proper starting, control the operating voltage, limit the starting current and maintain the arc discharge [10]. The advantage of HID lamps is that they are able to produce large amount of lumen, which is suitable for high illuminance applications. However, the installation cost of HID lamps is very high and the preheating period of HID lamps is relatively long as compared to other discharge lamps; it takes up to a few minutes for HID lamps to reach their full power output (maximum efficiency). Figure 2.8 shows various types of HID lamps.

Figure 2.8: Various types of HID lamps.

2.3 Ballast

Ballast provides a positive resistance or reactance that limits the flow of current to an appropriate level. Furthermore, it provides a controlled amount of electrical energy to heat up the lamp electrodes [22]. The following sections give a brief description to the common ballast technology available for fluorescent lamps.

2.3.1 Resistor ballast

There are two types of resistor ballasts available for use with fluorescent lamps, namely fixed resistor ballast and self-variable resistor ballast. Fixed resistor ballast can be applied in low power loads such as neon lamp. It dominates the flow of current in the circuit even in the face of negative resistance introduced by the lamps because of high resistance characteristics of the ballast. In addition, the resistance of self-variable ballast increases as the current increases, this leads to increase in voltage drop. If the current decreases, the resistance of the ballast drops, and the voltage drop decreases [22]. Therefore, the ballast resistor tends to maintain a constant current flowing through it despite the variations in incoming supply voltage or changes in the rest of an electric circuit.

2.3.2 Electromagnetic ballast

Fluorescent lamps require the intensity of the arc to be limited and this function is fulfilled by connecting electromagnetic ballast in series with the fluorescent tube. This arrangement is the most common in domestic application with a limited number of fluorescent lamps. Figure 2.9 shows the circuit connection of electromagnetic ballast fluorescent lamp.

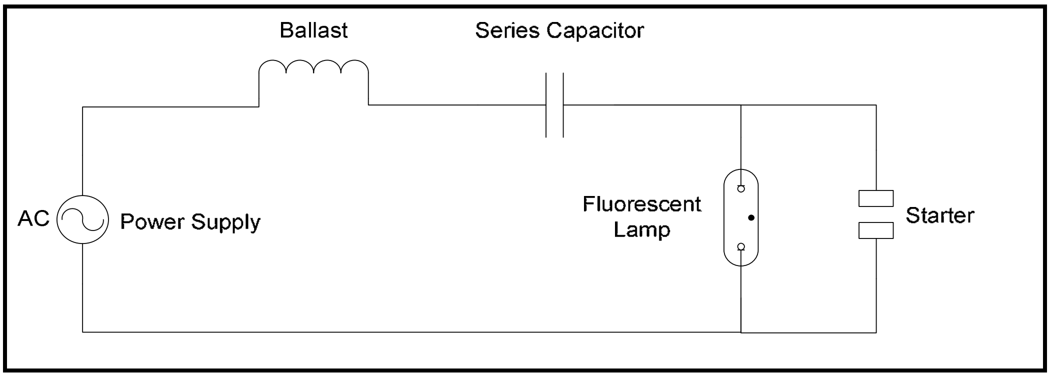


Figure 2.9: Circuit connection of electromagnetic ballast fluorescent lamp.

The primary component of electromagnetic ballast is a core of stacked steel laminations surrounded by wound coils of insulated copper wire. This core and coil design functions as both voltage transformer and a current limiter. The heat produced by the ballast’s operation can eventually break down the insulation around the coils and cause failure. The core and coil are potted in insulating material such as asphalt to conduct the heat away from the coils. This assembly is usually housed in a steel case [22]. Figure 2.10 shows the conventional electromagnetic ballast.

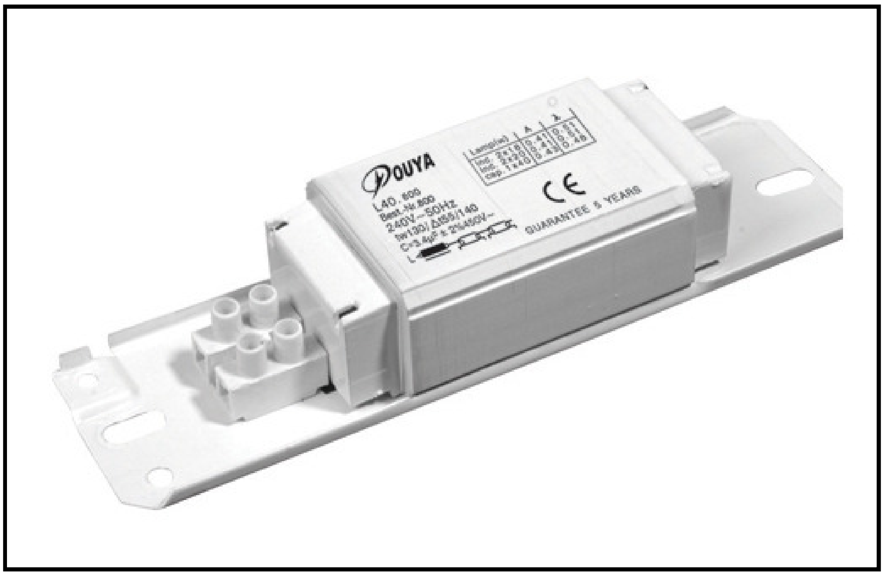


Figure 2.10: Conventional electromagnetic ballast.

The power factor of electromagnetic ballast is very low (on average of 0.4 to 0.5 depends on the characteristic of ballast), since the current drawn by the fluorescent lamp and ballast assembly are essentially inductive. Hence, it is crucial to provide compensation to improve the power factor, especially in large electromagnetic ballast fluorescent lamps networks. The power factor correction capacitor allows electromagnetic ballast to utilise energy more efficiently.

There are a few technical problems associated with electromagnetic ballast fluorescent lamps. Firstly, the non-linearity of the discharge itself will cause current distortion. Secondly, the fluorescent lamps possess flickering effect, which is highly undesirable, [1, 15, 23] studied the flickering effect and investigated the influence of voltage flicker on flux variation of fluorescent lamps. They concluded that electromagnetic ballast fluorescent lamps have the worst flickering bearing ability while high frequency compact fluorescent lamps are least sensitive to voltage flicker.

2.3.3 Electronic ballast

Electronic ballast is the replacement of electromagnetic ballast to supply electricity for fluorescent lamps. The principle of the electronic ballast consists of supplying the lamp arc via an electronic device that generates a regulated AC voltage. The switching frequency of electronic ballast varies from 20 kHz to 60 kHz, substantially eliminating the stroboscopic effect of flicker (100 or 120 Hz of the line frequency) associated with fluorescent lighting. On the other hand, electronic ballast has high inrush current than electromagnetic ballast and it may lead to Nuisance tripping of earth leakage circuit breaker [11]. Figure 2.11 shows an example of electronic ballast.

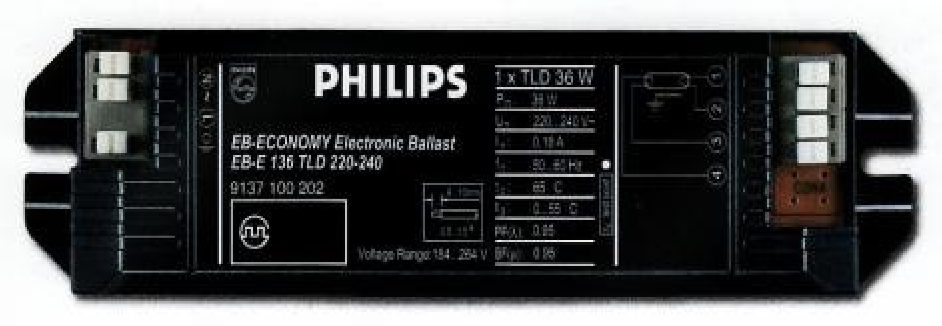


Figure 2.11: The electronic ballast.

During the preheating period of a discharged lamp, electronic ballast supplies the fluorescent lamps with increasing voltage with high switching frequency. In steady state, it regulates the incoming supply voltage applied to the lamp independent to any fluctuations in the incoming supply voltage [15, 23]. In addition, some electronic ballast provides dimming function, which controls the switching frequency and varies the current from the arc and hence the illuminance level of electronic ballast fluorescent lamps can be adjusted. The lifespan of electronic ballast is typically one to five years which depends on the quality and environment factor. On the contrary, traditional electromagnetic ballast has lifespan in excess of 30 years [3, 24]. At the end of their service, the copper winding of electromagnetic ballast can be recycled.

2.4 Chapter summary

In this chapter, the principles of various types of lamp technologies are briefly discussed. Incandescent lamps are the oldest and most commonly used lamp in conventional lighting systems. However due to heat dissipation losses, only 8% energy is converted into light resulting in poor luminous efficiency.

On the contrary, Halogen lamp is an improved version of incandescent lamps as the lifespan and efficiency of Halogen lamps are doubled compare to incandescent lamps. In addition, Halogen lamps have good colour rendering index and it is 25-30% brighter than normal incandescent lamps.

Compared to incandescent lamps and Halogen lamps, fluorescent lamps are the most cost effective and efficient lighting device. Fluorescent lamps are belonging to discharge lamps category, which possess negative resistance dynamic characteristic and causes harmonic distortion. As a result, fluorescent lamps cannot be connected directly to incoming supply voltage as it would draw high inrush current to flow through the fluorescent tube until the lamp self-destructs. In order to prevent this, ballast is required to connect in series with the fluorescent tube. The main function of the ballast is to provide proper starting voltage and current to establish an arc between the two electrodes. The operation principles of various ballasts such as resistor ballasts, electromagnetic ballasts and electronic ballasts are discussed in this chapter. Comparison between electromagnetic and electronic ballasts has been made. It can be concluded that conventional electromagnetic ballast has the advantages over electronic ballast as summarised in tables 2.2 and 2.3.

Table 2.2: Advantage and disadvantages of electromagnetic ballast

Types of ballast	Advantages	Disadvantages
Electromagnetic ballast	1. Low selling price. 2. Low maintenance cost. 3. Easy installation. 4. High robust and reliability. 5. Suitable to operate in extreme weather condition such as high humidity and wide temperature variation environment. 6. Copper winding of the ballast can be recycled.	1. Non dimmable illuminance control. 2. No energy saving feature. 3. Low power factor. (due to inductive load) 4. High inrush current. (due to the starting effect of electromagnetic ballast) 5. Flickering effect 6. High total harmonic distortion. (due to nonlinear components such as ballast and fluorescent tube)

Table 2.3: Advantage and disadvantages of electronic ballast

Types of ballast	Advantages	Disadvantages
Electronic ballast	1. Specific electronic ballast provides dimmable illuminance control, however it is expensive. 2. Provide energy saving feature. 3. No flickering effect. 4. High power factor. 5. Small in size.	1. High selling price. (especially for dimmable electronic ballast) 2. High maintenance and replacement cost. 3. Short lifespan. (due to the aging of electronic components) 4. Very high inrush current. (due to the starting characteristics of capacitor) 5. Not environmental friendly as the electronic waste cannot be recycled. 6. High total harmonic distortion.(due to nonlinear components such as electronic components and fluorescent tube)

CHAPTER 3: ENERGY SAVING CONTROLLER

3.1 Introduction

Energy saving in existing electromagnetic ballast fluorescent lamps networks can be achieved by optimising the fluorescent lamps network using controller. This energy saving controller needs to be carefully designed in order to reduce energy consumption of electromagnetic ballast fluorescent lamp and provide dimmable illuminance feature. It is expected that the efficiency of the existing lighting system (which are over-designed) can be improved by installing this central controller. Sections 3.2 describe the principal operations of energy saving controller and Section 3.3 discusses the major components of the energy saving controller.

3.2 Principle operation of energy saving controller

Fluorescent lamp systems are essential for building to ensure the comfort of the building's occupant. However, research found that most of the lighting systems are over designed to ensure a minimum illuminance of fluorescent lamps for working environments. According to Australia Standard Authority (ASA), the recommended illuminance for general working environment is 500 lux. The general working environments include office, classroom, lecture hall and laboratory [25]. Table 3.1 illustrates the recommended light level in different working environments.

With recent rapid development of dimmable electronic ballast, electronic ballast fluorescent lamps have been promoted as the replacement for electromagnetic ballast fluorescent lamps. Despite the fact that dimmable electronic ballasts have the advantage of energy saving feature and dimmable illuminance level control, the high investment cost, short lifespan and reliability of dimmable illuminance control are their major hindrances. Furthermore, dimmable electronic ballast does not support central illuminance level control. Therefore, in order to control the illuminance level in a large fluorescent lamp network, each fluorescent lamp must be installed with a set of dimmable electronic ballast. From engineering point of view, the installation of dimmable electronic ballast in each fluorescent lamp is not practical, attracts high installation cost and time consuming. On the contrary, the energy saving controller for electromagnetic ballast fluorescent lamps provides central energy saving control system to existing electromagnetic ballast fluorescent lamp, without major modification to the electrical wiring. In addition, the energy saving controller for electromagnetic ballast fluorescent lamp is able to provides energy saving and illuminance level control for large lighting system.

Table 3.1 Recommended illuminance level in different working environments (ASA Standard)

Activities	Illumination (lux)
Public areas with dark surroundings	20 – 50
Simple orientation for short visits	50 – 100
Working area where visual tasks are only occasionally performed	100 – 150
Warehouses, homes, theatres	150
Easy office work, classroom	250
Normal office work, library, showroom	500
Supermarket, mechanical workshop	750
Normal drawing work, operation theatres	1000
Detailed drawing work	1500 - 2000

One of the best ways to reduce energy consumption in daily lightings is by making adequate use of sunlight. This method can be integrated into the proposed energy saving controller in electromagnetic ballast fluorescent lamps by using a daylighting control instrument. The daylighting control instrument consists of lux intensity sensor that measures the illuminance level at a reference location and lux PID controller. The lux PID controller (proportional/integral/deferential controller) compares the actual illumination level with a preset level. After that, the energy saving controller will gradually reduce the illuminance level of fluorescent lamps until the reference level has been reached. The daylighting control method is deployed for power adjustment factor (PAF) lighting credits in the day-lit areas, such as areas adjacent to windows [7, 10]. The proposed energy saving controller is able to control and maintain the illuminance level of the working environment and reduce energy consumption. The illuminance level should not exceed the limit of ASA standard and it can be adjusted according to end user preference. In general, energy consumption of fluorescent lamps can be reduced by reducing the incoming supply voltage or by controlling the illuminance level of the working environment.

The proposed energy saving controller can be implemented by various types of voltage reduction topologies, such as autotransformer voltage control and power electronic voltage control topology. However researches proved that the lifetime of power electronic components is relatively short [3, 5, 13]. Therefore, power electronic voltage control topology will not be considered in the design. Instead, variable autotransformer will be used to control the incoming supply voltage of electromagnetic ballast fluorescent lamps.

The major components of energy saving controller consist of lux PID controller, lux intensity sensor, programmable logic controller PLC and one variable autotransformer to reduce the incoming supply voltage to predefined value after the energy saving control method is switched on. The functions of the energy saving controller include process control of the dimmable illuminance level, voltage reduction control, preheating feature, earth leakage protection, backup power system and time schedule function for the switching of electromagnetic ballast fluorescent lamps. All of these are done by controlling both the analogue and digital signals received by the controller.

In order to preserve the lifetime of electromagnetic ballast fluorescent lamps, the energy saving controller will first switch on the electromagnetic ballast fluorescent lamps at full voltage of 240 V for lamp preheating. After the preheating period of 10 minutes, the energy saving feature is switched on. Under energy saving control operation, lux intensity sensor controls the switching of electromagnetic ballast fluorescent lamps to dim the fluorescent lamps according to the surrounding light available. This can be done by controlling the incoming supply voltage of electromagnetic ballast fluorescent lamps. The reduction in incoming supply voltage leads to a reduction in incoming current drawn. As a result, the energy consumption of electromagnetic ballast fluorescent lamps can be reduced. Note, the preheating period of 10 minutes can be resetting by PLC program to any other value suitable for preheating period.

The process of the controller is mainly determined by the illuminance level setting. The illuminance set variable can be set at the front control panel of lux PID controller. The illuminance level is measured and compared with the set variable in the lux PID controller. The magnitude and sense of any difference between the set variable (SV) and process variable (PV) of the output is considered as an error signal to the lux PID controller which in turn actuates the correcting device i.e. motorise actuator in such a way as to reduce the percentage of error. As a result, the output voltage of variable autotransformer varies as a function of lux PID controller's output signal.

In order to ensure system stability, the energy saving controller provides a bypass control for electromagnetic ballast fluorescent lamps. The bypass control system will be activated automatically when the controller experiences abnormal conditions such as overheat, burnt variable autotransformer or system failure. Figure 3.1 shows the block diagram for the bypass control of energy saving controller.

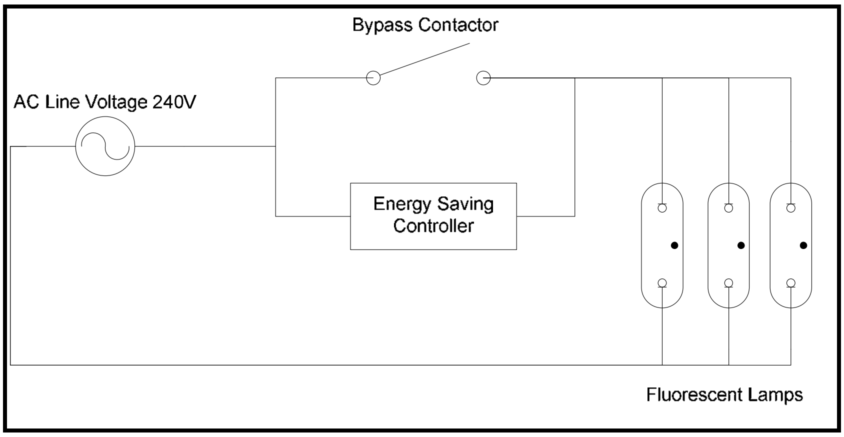


Figure 3.1: Block diagram of bypass control of energy saving controller.

A major concern regarding electromagnetic ballast fluorescent lamps system with energy saving controller is its lifespan. Various researches have proven that the life of electromagnetic ballast fluorescent lamp is affected by fluorescent lamp current crest factor (CCF). Current that has a high crest factor can cause material to be eroded from lamp electrodes and prematurely shortening the lamp life [26]. Since the energy saving controller reduces starting inrush current and nominal current of electromagnetic ballast fluorescent lamps, it will improve the lamps CCF and thus extend the lamps life.

Furthermore, according to National Light Product Information Program (NEPIP) by US Environment Protection Agency, the life span of electromagnetic ballast can be extended by reducing incoming supply voltage. The reduction of incoming supply voltage leads to the reduction on ballast temperature, which prolongs the ballast life [9, 10]. The proposed energy saving controller works on the basis of reducing the supply voltage to the fluorescent lamps, thus it can also extend the lamps life indirectly in this context.

Electromagnetic ballast fluorescent lamps installed with the proposed energy saving controller has the following advantages, some of which are not present in dimmable electronic ballast fluorescent lamps.

1. The energy saving controller can turn the conventional non-dimmable electromagnetic ballast fluorescent lamps into dimmable lightings with illuminance control.

2. Unlike dimmable electronic ballast fluorescent lamps, the proposed energy saving controller is able to provide centralised control in large electromagnetic ballast fluorescent lamps networks. Consequently the installation cost of a central energy saving controller for existing lighting networks is much cheaper than installing dimmable electronic ballast to each fluorescent lamps. Furthermore, no ballast replacement cost is required to

upgrade existing electromagnetic ballast fluorescent lamps networks with to the ones with energy saving controller.

3. With the help of energy saving controller, the lifespan of electromagnetic ballast can be extended. This has been confirmed by US environment agency.

4. Energy saving controller is suitable to operate in extreme weather condition such as high humidity, and high temperature environment

5. The advantages of electromagnetic ballast fluorescent lamps can be retained, resulting the high reliability, low maintenance and replacement cost.

3.3 Energy saving control system components

3.3.1 Programmable logic controller

In modern programmable logic controller (PLC) architecture, PLC performs all the traditional relay replacement function. Besides, it is also integrated with many other functions such as high speed counter, time delay relay control system, clock sequential control, proportional integration and derivative (PID) control, pulse width modulation (PWM) switching control and other mathematical functions. A modern PLC possesses high speed central processing unit (CPU) which is able to perform high speed data processing for inputs and outputs data.

A general PLC consists of five major components, namely programming device, DC power supply, central processing unit, memory and input/output control module. The DC power supply unit acts as a rectifier, which converts the incoming supply voltage to 24 V voltage. The power supply drives the CPU, I/O module, memory and some other peripheral devices. It also provides isolation and protection to solid-state components against over voltage.

The real time process variables of a PLC are obtained from its input and output signals. The input and output signals of a PLC can be either digital or analogue signals. The digital input signals are presented to PLC in binary values, where input “1” indicates on state and “0” indicates off state to PLC. Conversely, the analogue input signals are presented to PLC in the form of continuous DC voltage (0 to 10 V) or DC current (4 mA to 20 mA). Analogue signal from personal computer, temperature transmitter, pressure transmitter, lux intensity sensor, resistance temperature detector (RTD) are common analogue input signals. Similarly, the output signal of PLC is divided into two categories i.e. digital and analogue output signals. Generally, the digital output signal of PLC is in the form of 0 V or 24 V, it is used to control the switching of external control device such as relay and timer. Analogue outputs, in a form of continuous DC voltage (0 to 10 V), are used to for controls such as the rotation of motorise actuator and rotational speed of the variable speed drive. In modern PLC design, I/O system modules can be plugged into the existing PLC bus structure as shown in Figure 3.2

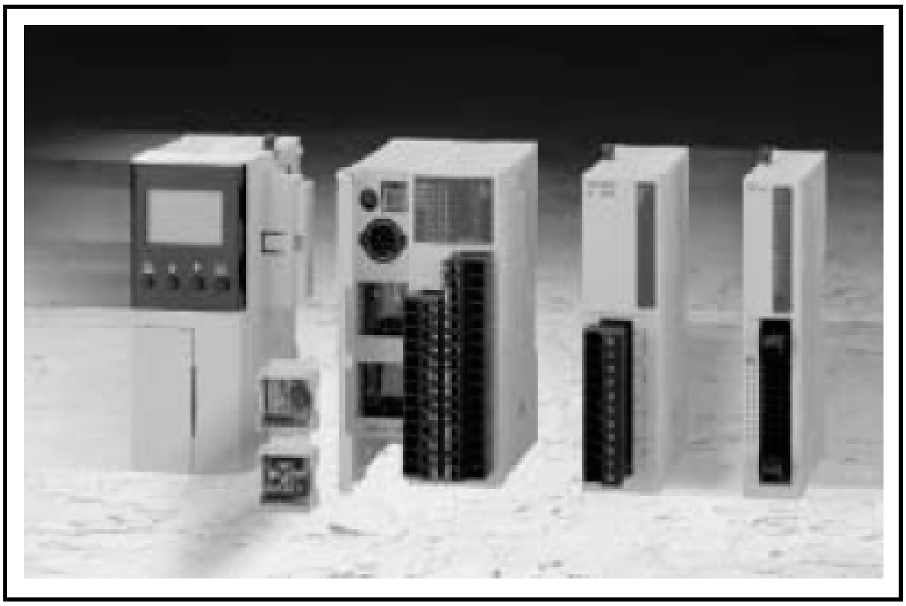


Figure 3.2: PLC with expansion module and extension

The I/O bus structure is a high speed multiplexer that carries data back and forth between the I/O modules and the central processing units as shown in Figure 3.3 [27].

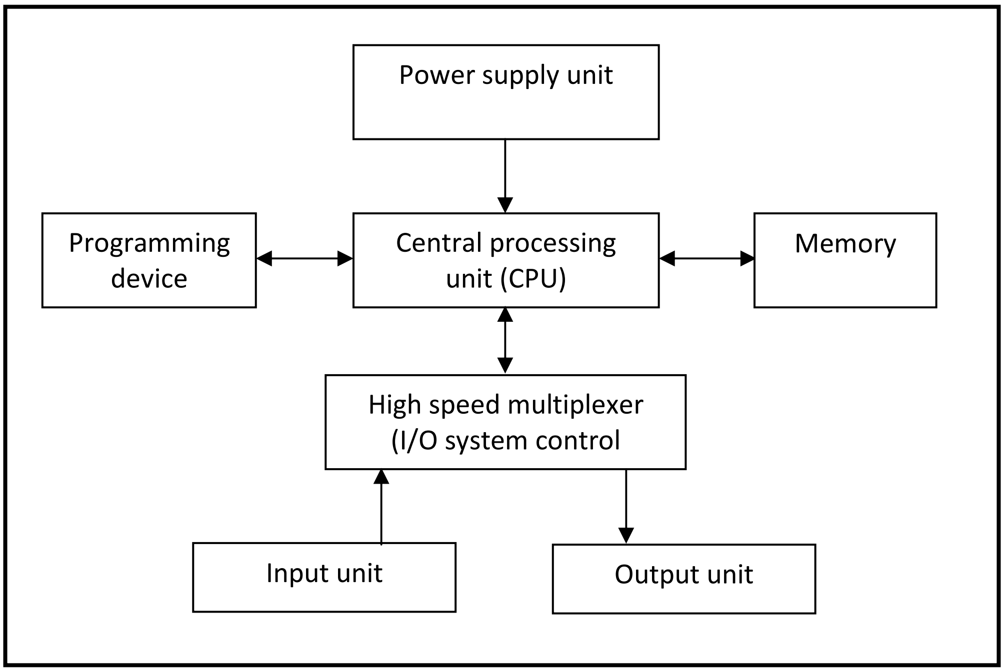


Figure 3.3: Block diagram of programmable logic controller.

The CPU performs the tasks such as scanning process, I/O multiplexer control, data handling, memory management and data handling process according to the control sequence of ladder diagram The data scanning process consists of a series of operations as shown in Figure 3.4. Initially, the CPU checks the changes and the allocated data from the input module. After that, the CPU executes the program from the memory according to the changes of input state. Program execution begins from first rung of the ladder diagram and continues to the end of the PLC program. As the program execution is done, CPU sends the updates state to the output module.

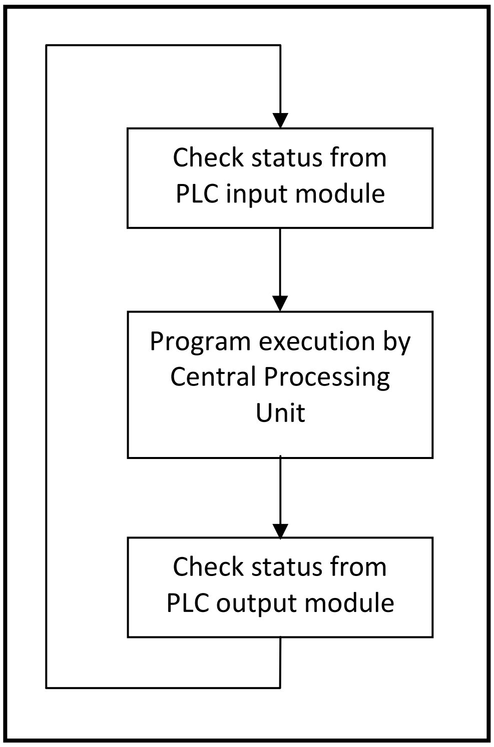


Figure 3.4: The input / output scanning process of CPU.

Memory is one of the functional units of PLC system. Process data from input modules and control data for output modules are temporarily stored in the memory. Memory can be classified into two categories, i.e. random access memory (RAM) and read only memory (ROM). RAM is considered as volatile memory, where its content is erasable and will be cleared when the power of PLC is switched off. Obviously, this type of memory is used for temporary data storage and it is not suitable to store PLC program. In order to prevent data loss from RAM in case of power failure, backup battery can be provided to the PLC.

The ladder program of a PLC can be transferred into non volatile memory by using programming unit. In the other word, the programming unit provides an interface between the PLC and programmer during program development stage. Programming unit can be applied to design control program and online programming unit monitoring system (OPMS). It allows continuous modifications of the program while PLC is controlling the process of the machine.

3.3.2 Lux intensity sensor

The lux intensity sensor consists of a photodiode sensor to measure the luminance level of the control zone. Photodiode is an electronic pn junction constructed such that its voltage – current characteristics will change when exposed to light. The voltage – current characteristics of a typical photodiode sensor is shown in Figure 3.6. The operation of photodiode can be divided into two phases, namely forward biased and reverse biased. In forward biased mode, the width of the depletion region, and therefore its barrier potential, is reduced. This phenomenon allows majority carriers to cross the junction, thus allowing current to flow through the photodiode.

For reverse biased operation, negative terminal of the DC voltage is connected to P-type crystal and positive terminal to N-type crystal. In reverse biased mode, the photodiode behaves as a photo conductor device and its resistance changes with the changes in received light intensity. The changes of resistance can be calculated as in Equation 3.1,

$$R = \frac{V_R}{I_R} \qquad \text{Equation 3.1}$$

Where V_R represents reverse biased voltage of photodiode, and I_R represents the reverse biased current of photodiode.

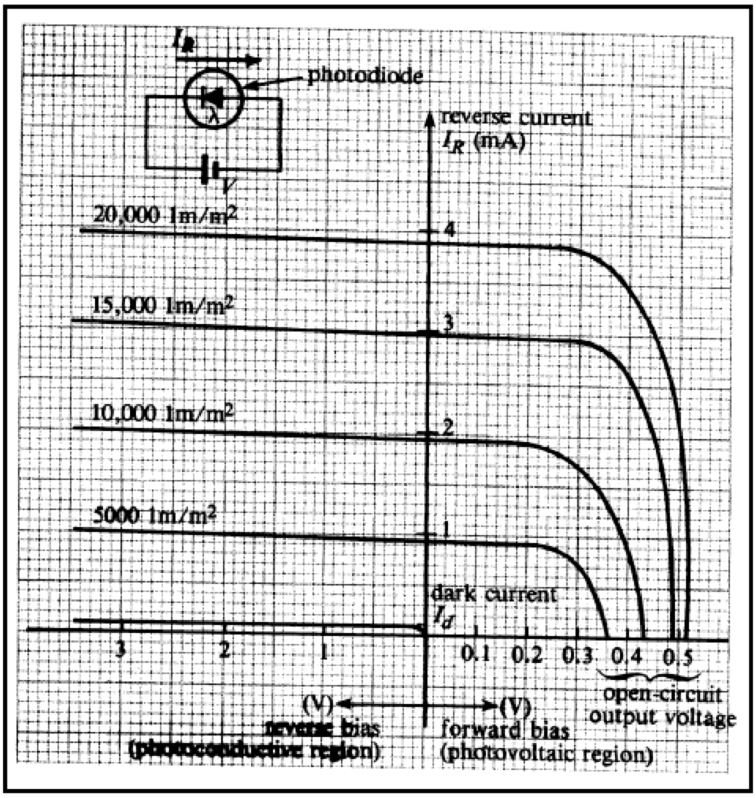


Figure 3.5: Voltage – current characteristics of photodiode.

From Figure 3.5, the resistance of photodiode at $5000/\text{m}/\text{m}^2$ is calculated by Equation 3.2,

$$R = \frac{V_R}{I_R} = \frac{2}{1\,mA} = 2\;k\Omega \qquad \text{Equation 3.2}$$

and its resistance at $20000/\text{m}/\text{m}^2$ is calculated by Equation 3.3,

$$R = \frac{V_R}{I_R} = \frac{2}{3.9\,mA} = 512\;\Omega \qquad \text{Equation 3.3}$$

Where V_R represents reverse biased voltage connects to the photodiode with a magnitude of 2 V, which is belongs to the limit of photodiode's maximum reverse voltage. The application of reverse biased voltage is very useful in improving the frequency response, linearity and efficiency of the photodiode. However care should be taken in order to maintain the reverse biased voltage within the limit and to ensure that the cathode is maintained at a positive potential with respect to the anode [28].

The change in reverse biased resistance of photodiode is inversely proportional to the changes in light density. As light intensity increases, reversed biased current increases and thus the resistance of photodiode decreases. The lux intensity sensor has a flat glass windows to provide a built in colour correction factor based on the approximation to the spectral response in the human eye. A light emitting diode (LED) is mounted next to the sensor to compensate for the measurement error of the photodiode [29]. Figure 3.6 shows the connection diagram of the lux intensity sensor.

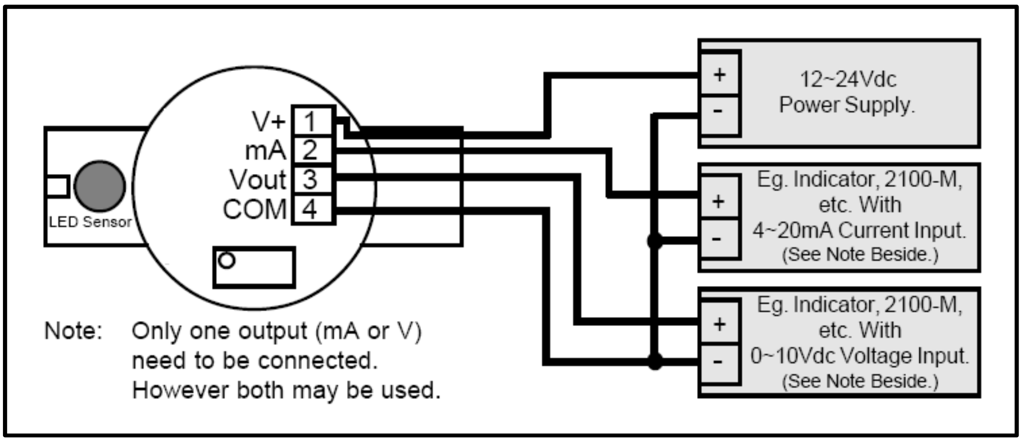


Figure 3.6: Connection diagram of lux intensity sensor.

A signal transformation circuit is incorporated inside the lux intensity sensor. It is used to convert photodiode's output resistance to a more useful 4 – 20 mA DC analogue output signal. Output signal of the lux intensity sensor is proportional to the measurement of light intensity. Figure 3.7 shows the block diagram of the lux intensity sensor.

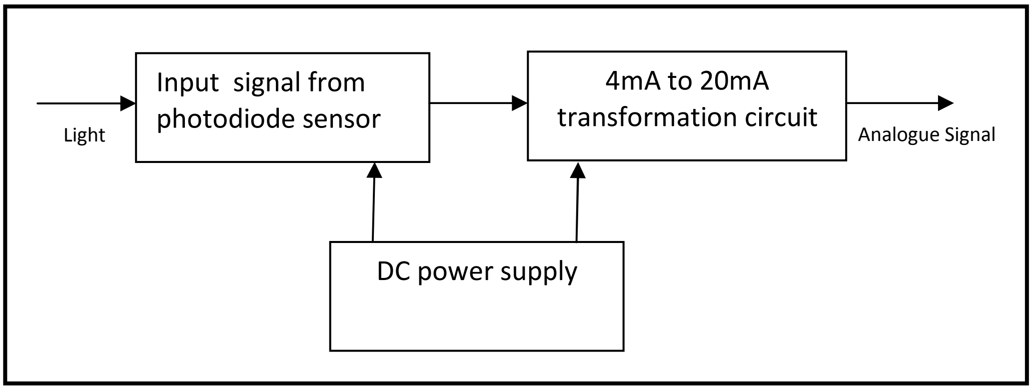


Figure 3.7: Block diagram of lux intensity sensor.

3.3.3 Autotransformer

Transformer is a device that converts ac voltage from one level to another through magnetic field. A conventional transformer consists of two windings, i.e. primary and secondary winding. The winding connecting to incoming supply voltage is primary winding and the other from which energy is drawn out is the secondary winding. Generally, the transformer can be divided into three categories namely power transformer, distribution transformer and autotransformer.

Power transformer has high utilisation factor. It is designed to operate at constant load which is equal to their capacity. The maximum efficiency of power transformer is designed to be at full load. Under this full load operation, the winding loss of the power transformer must be equal to the core loss and the losses are minimal. Another type of transformer is called distribution transformer. This transformer has an intermittent and variable load which is usually considerably less than the full-load rating. The distribution transformer is designed to have their maximum efficiency between 50% and 75% of full load.

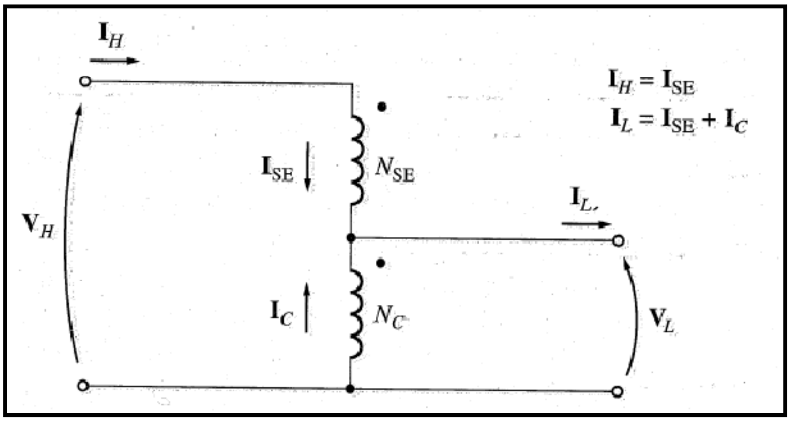


Figure 3.8: Equivalent circuit of variable autotransformer (step down).

Another special purpose transformer called variable autotransformer, which is used to control the incoming supply voltage for electromagnetic ballast fluorescent lamps. Figure 3.8 shows the equivalent circuit of a variable autotransformer. In general, the relationship between primary and secondary voltage is controlled by the turn ratio of the variable automatic transformer. Unlike conventional transformers, the input voltage of the variable auto transformer is the sum of the voltage across the common and series winding while the output voltage is simply the voltage across the common winding. Equation 3.4 and 3.5 give the input and output voltage of an autotransformer.

$$V_{in} = V_H = V_C + V_{SE}$$ Equation 3.4

$$V_{out} = V_L = V_C$$ Equation 3.5

where V_L represents the voltage at low voltage side, V_H represents the voltage at high voltage side, V_C represents the common winding voltage, V_{SE} represents the voltage on the series coil.

The auto transformer input and output current is defined in Equation 3.6 and 3.7 respectively.

$$I_{in} = I_H = I_{SE}$$ Equation 3.6

$$I_{out} = I_L = I_C + I_{SE}$$ Equation 3.7

where I_L represents the current at low voltage side, I_H represent the current at high voltage side, I_C represents the current on the common coil and I_{SE} represents the current on the series coil.

According to Equation 3.4 and Equation 3.5, the voltage and turn ratio characteristics of variable transformer can be derived as in Equation 3.8,

$$\frac{V_L}{V_H} = \frac{N_C}{N_C+N_{SE}} \rightarrow V_L = V_H \times \frac{N_C}{N_C+N_{SE}} \qquad \text{Equation 3.8}$$

where N_C and N_{SE} are the number of turns in common and series winding respectively.

Equation 3.8 furthers confirmed that the output of step down variable autotransformer is determined by the magnitude of incoming supply voltage, N_C and N_{SE}. Since the secondary winding is now merged into the primary winding, variable transformer has the advantages on saving in winding material and hence the cost is much cheaper as compared to conventional transformer. However the principal disadvantages of variable autotransformer are:

1. There is a direct connection between the primary and secondary winding. The electrical isolation between input and output voltage is lost.

2. The impedance of a variable autotransformer (at both input and output sides) is lower as compared to conventional two windings transformer. This can be

a serious problem in some applications where the series impedance is needed to limit current flow during power system fault (direct short circuit). [30]

These two disadvantages have been taken into consideration for the design of energy saving controller.

The variable autotransformer for energy saving controller is constructed by arranging one of the output terminals to be connected to a sliding contactor, which can be moved across the entire range of the common (output) winding. The sliding contactor will be moved according to the output signal of the lux PID controller, thus appropriate supply voltage to the electromagnetic ballast fluorescent lamps can be controlled. For safety consideration, the variable autotransformer is overwound so that the output voltage higher than incoming supply voltage may be obtained. On the other hand, the application of autotransformer as listed below:

1. Boosting or bucking a small amount of incoming supply voltage. (The smaller the different between the input and output voltage the greater saving in winding material.)

2. It can be applied on starting of AC induction motor, where the motor supply voltage is raised in two or more step from a small value to the full supply voltage.

3. The over and under voltage of electrical problems are beyond the control of variable autotransformer. With the control of voltage stabilisation system, variable autotransformer is able to provide stable output AC voltage from fluctuating.

3.3.4 PID automatic process control system

The proportional-integral-derivative (PID) automatic process control system is one of the most important and widely used in automatic control systems. The performance of PID process control system is influenced by process variables (PV) and set variables (SV). PV can be in the form of temperature (ºC), relative humidity (%RH) or light intensity (lux). The control of PV is achieved by the control equipment such as motorise actuator or solid state relay. The overall control process can be viewed as an engineering science of measuring one or more of process variables and control them to achieve the desired SV in spite of disturbance [27, 31]. Figure 3.9 shows the block diagram of a PID automatic process control system.

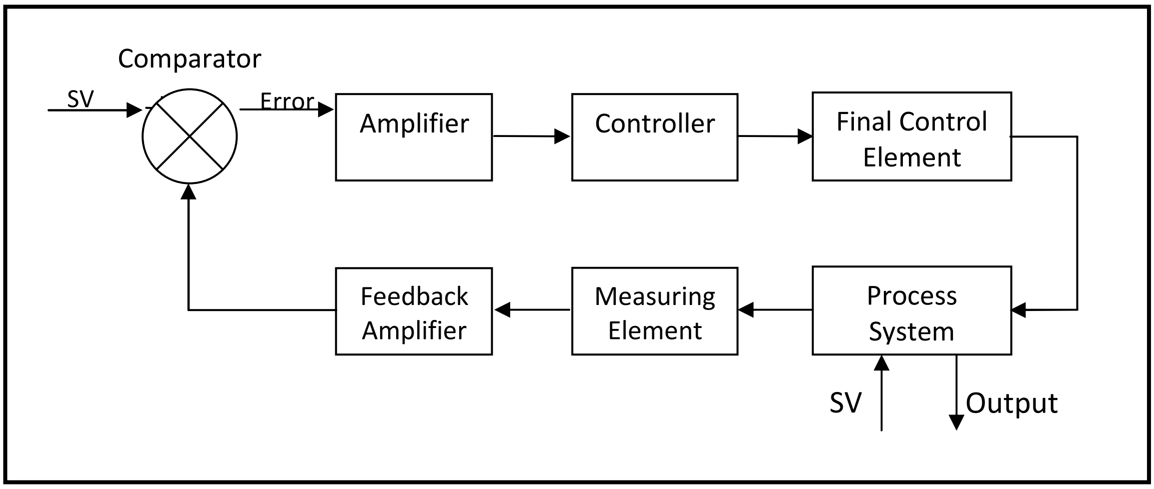


Figure 3.9: Block diagram of PID automatic process control system.

According to Figure 3.9, the actual output from the control process is measured and compared with a set variable in the comparison device. The difference between SV and PV of the output is considered as an error signal to the controller which in turn actuates the correcting device in such a way that the error is reduced. The correction process takes place no matter how the error arises. The key elements of the automatic process system are as follows.

1. Measurement device: The measurement device, which convert sensor's output signal to numerical form, which is used for comparing the output to the desired value.

2. Comparator: The comparator compares the actual value of the variable coming though a feedback circuit with desired value and produces an error signal, e.

3. Automatic controller: The automatic controller which normally incorporates with power amplification to control the output signal of automatic control system.

The PID controller uses in energy saving controller is a universal microprocessor-based instrument that is configurable as PID controller, or two ways (on-off) controller. The front panel of the PID controller is shown in Appendix A3, Figure A.2. The PID controller consists of an internal microprocessor that is employed for the computation of all algorithms and the handling of interface communication. The PID controller has an adaptive tuning feature which can be used for P, I, PD, PI and PID control algorithms. The parameters for these control algorithms can be updated automatically [27]. The PID controller also includes an event alarm system which is set by an absolute value. For example, to trigger the alarm action when the measured value exceeds 1000 lux, 1000 lux should be set as the upper limit for the alarm. Similarly, to trigger the alarm action at 500 lux and lower, 500 lux should be set as the lower limit. The alarm system only works for the PV with no relation to the target set value (SV). Table A.4 (Appendix A3) presents the functions part of the PID controller. The output control signal of PID controller can be in the form of voltage signal (0 – 10 V) or current signal (4 – 20 mA). The repeatability of the PID controller is 0.5% and its accuracy is ±1%. Refer to Table A.3 (Appendix A3) f or the technical specification of the PID controller.

For the development of energy saving controller, the PID controller and a non-spring return motorised actuator are coupled with the variable autotransformer to control the output voltage of the autotransformer. The motorised actuator control system is a feedback system which maintains an output position or motion in close correspondence to an analogue signal between 0 – 10 V. As a result, the output voltage of variable autotransformer varies as a function of actuator's motion. The non spring return direct coupled actuator is shown in Appendix A4, Figure A.3 The non-spring return motorise actuator is extensively used in various application such as chilled water control system, heating ventilation and air conditioning system, and motorised fire damper system [32]. Table A.5 (Appendix A4) shows the technical specification of the motorise actuator.

3.3.5 Magnetic contactor

Magnetic contactor is an electrically controlled device used for controlling the switching of power circuit. The function of magnetic contactor is similar to relay except with higher ampere rating [33]. It is possible to use magnetic contactor in various applications such as to control the switching of fluorescent lamps, starting of induction motor and power distribution network.

Magnetic contactor for switching of induction motors and three phases loads usually have three main poles and are selected in terms of the load current or based on the power rating of induction motor. The loading capacity of magnetic contactor varies from 10 A to 1600 A, and rated voltage capacity rises from 240 V to 660 V. The magnetic contactor is composed of three different elements, namely coil, electromagnet and switching parts.

1. Coil: A coil is installed and located in between moving core and fix core. The coil is used to produce a magnetic flux to the moving core and fix core.

2. Electromagnet: Electromagnet is used to attract the moving coil by controlling the attraction force. When AC voltage is applied to the coil, the AC current passes through the electromagnet and produces magnetic field which attracts the moving core of the contactor. The force produced by the electromagnet holds the moving contact and fixed contactor together, thus conducts current through the magnetic contactor. When AC voltage is disconnected from the coil, the coil is de-energised, and both moving core

and contact return to its original position. In such situation, the magnetic contactor is considered as "off-stage". Apart from local control (connect AC voltage to coil directly), the magnetic contactor can be switched on remotely by a remote selector switch or control device [33]. The structure and operation of magnetic contactor are illustrated in Figure 3.10 and Figure 3.11.

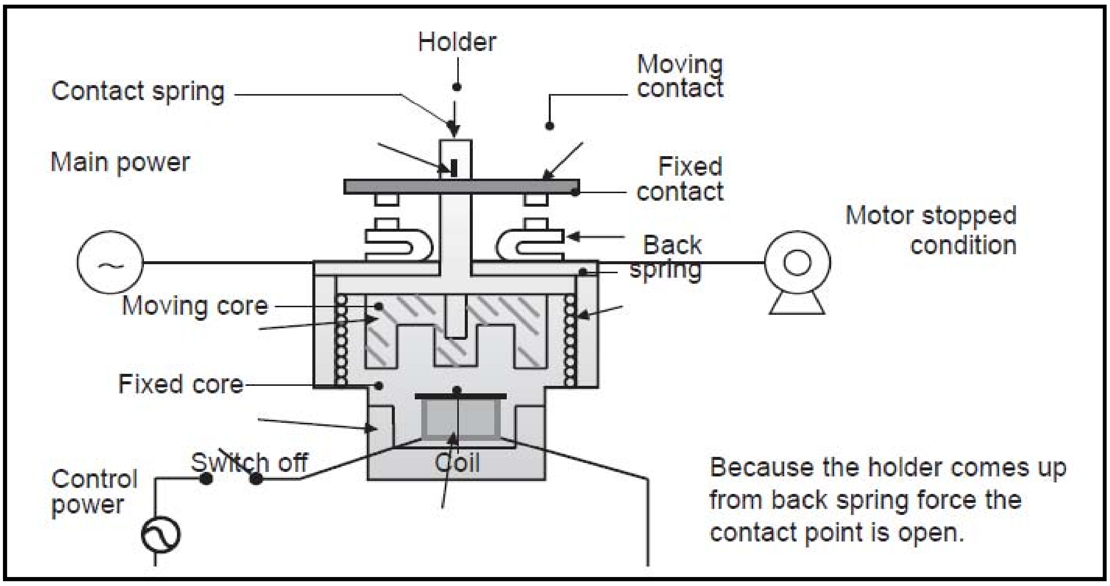


Figure 3.10: Operation diagram of magnetic contactor (off-stage).

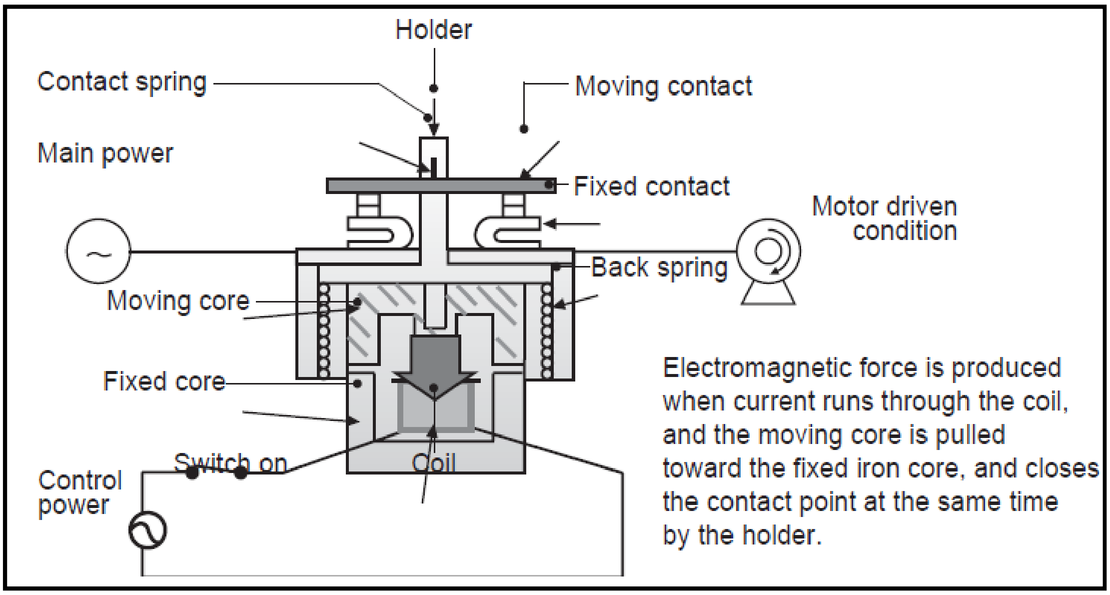


Figure 3.11: Operation diagram of magnetic contactor (on-stage).

3. Switching part: The switching part of magnetic contactor consists of a set of moving contact, fixed contact and grid. It has a structure to send arc to the grid and make the arc discharge by using electromagnetic force for breaking circuit quickly derived by running current [33].

For the design of energy saving controller, the selection of magnetic contactor type is done based on contactor applications categories from IEC standard 947-4-1 in Table 3.1 [11]. From Table 3.2, it is clear that the selection of magnetic contactor for energy saving controller falls under the AC-5a category. The selection criteria and consideration are further discussed in Section 5.2.2.

Table 3.2: Contactor application categories by IEC 947-4-1

Supply voltage	**Category**	**Application**
AC	AC-1	Load, resistance furnace with non-inducing or minute inducing characteristics
AC	AC-2	Drive and stop of wound-rotor type motor
AC	AC-3	Stop during the driving, starting three phase induction motor
AC	AC-4	Staring of squirrel cage type motor
AC	AC-5A	Switching of discharge lamp such as electromagnetic ballast fluorescent lamp
AC	AC-5B	Switching of incandescent lamp
AC	AC-6A	Transformer switching application
AC	AC-6B	Condenser bank switching
AC	AC-7A	Switching of home appliance and low power devices.
AC	AC-7B	Household operational motor load
AC	AC-8A	Manual reset type overload closed for freezing compressor
AC	AC-8B	Automatic reset type overload for freezing compressor

3.4 Chapter summary

In this chapter, the operation principles of energy saving controller for electromagnetic ballast fluorescent lamps are discussed. The dimmable electronic ballast fluorescent lamp has been compared with the proposed energy saving controller. It can be concluded that the energy saving controller for electromagnetic ballast fluorescent lamps has the following advantages, some of which are not present in dimmable electronic ballast fluorescent lamps.

1. The energy controller provides energy saving feature to electromagnetic ballast fluorescent lamps. It also turns the conventional non-dimmable electromagnetic ballast fluorescent lamps into dimmable lightings with illuminance control.

2. Unlike individual dimmable electronic ballast fluorescent lamps, the energy saving controller is able to provide centralised control for huge electromagnetic ballast fluorescent lamps networks. In addition, no ballast replacement cost is required to upgrade existing electromagnetic ballast fluorescent lamp network to the ones with energy saving controller. Furthermore, existing advantages of electromagnetic ballast fluorescent lamps can be retained, resulting the high reliability, low maintenance and replacement cost.

3. Due to the reduction of incoming supply voltage, the heat dissipation of electromagnetic ballast is reduced. As a result, the lifespan of electromagnetic ballast can be extended.

4. The energy saving controller is suitable to operate in extreme weather condition such as in high humidity and high temperature environment

During the installation of energy saving controller, care should be taken to ensure that non-lighting loads are not connected to the energy saving controller. The voltage variation may leads to the damage of non-lighting loads.

CHAPTER 4: SYSTEM MODELLING & SIMULATION

4.1 Introduction

As part of designing and developing an energy saving controller, different models for fluorescent lamps have been studied and derived from existing models [34, 35]. The voltage - current characteristics, negative resistance characteristic of fluorescent lamps and dynamic resistance have been studied and simulated to provide comparisons with the theoretical results. These models are later used as simulation models for evaluating the performance of the energy saving controller.

4.2 Modelling of fluorescent lamp

In contrast to incandescent lamps, fluorescent lamps possess negative resistance characteristic that causes harmonic distortion. Consequently, fluorescent lamps cannot be connected directly to an alternative current line voltage supply. It will draw an ever increasing amount of high inrush current through the fluorescent lamps until it is over-heated and self-destructed due to uncontrolled current flow. In order to prevent this, fluorescent lamps must be connected in series with a ballast to regulate the current flow.

According to [35, 36], the dynamic impedance for fluorescent lamps is non-linear and ohmic at high operating frequency. Hence, the dynamic model for electromagnetic ballast fluorescent lamps is investigated and can be described by a simple Equation 4.1.

$$R_{LAMP}(t) = \frac{V_{LAMP}(t)}{I_{LAMP}(t)} \qquad \text{Equation 4.1}$$

Where $V_{LAMP}(t)$ is the fluorescent lamp voltage, $R_{LAMP}(t)$ is the dynamic resistance of fluorescent lamp and $I_{LAMP}(t)$ is the fluorescent lamp current. Equation 4.1 is capable of describing both the dynamic voltage and current characteristics of fluorescent lamp.

Perdigao and Saraiva [37] has used Levenberg-Mardquard algorithm to provide a useful expression for the dynamic resistance in Equation 4.1. According to the Levenberg-Mardquard algorithm, the dynamic resistance is related only to the fluorescent lamp power by monotonically decreasing double exponentials as in Equation 4.2.

$$R_{LAMP}(t) = ae^{bP_{LAMP}} + ce^{dP_{LAMP}} \qquad \text{Equation 4.2}$$

Where P_{LAMP} is the low pass filtered lamp power. The constants a, b, c and d are lamp dependent and can be determined from simulations and experiments.

Table 4.1: The fluorescent voltage, current and resistance characteristics of fluorescent lamp at different supply frequencies

V_{LAMP} (V)	I_{LAMP} (A)	P_{LAMP} (W)	R_{LAMP} (Ω)	Frequency (KHz)
99.53	0.28	28.74	344.66	51.65
103.18	0.25	26.57	400.54	57.33
104.64	0.23	24.28	450.84	61.12
110.98	0.19	21.90	562.21	68.87
113.20	0.18	20.61	621.68	72.04
114.15	0.16	19.29	675.48	75.58
120.26	0.14	17.12	844.53	80.77
126.67	0.11	14.36	1117.04	85.47
143.89	0.04	6	3450.72	90.90

Where V_{LAMP} represents fluorescent lamp voltage, I_{LAMP} represents fluorescent lamp current, P_{LAMP} represent average fluorescent lamp power measured from the experiment and R_{LAMP} represents the dynamic resistance of fluorescent lamp.

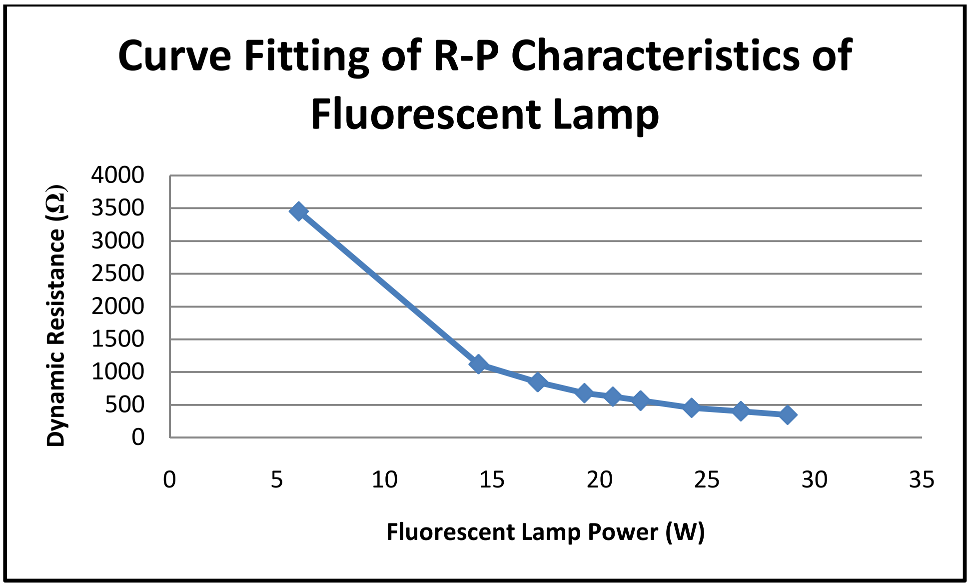


Figure 4.1: Curve fitting of the equivalent characteristics of fluorescent lamps versus fluorescent lamp power.

In order to determine the constants a, b, c and d, experimental measurements on GE F36W/54 fluorescent lamp has been done by Perdigao and Saraiva [37] and its data tabulated in Table 4.1. The dynamic resistance of fluorescent lamp presented is based on Equation 4.2 which represents a curve fitting to the experimental data of equivalent resistance versus average power, using only monotonically decreasing functions based on exponentials [37]. Figure 4.1 shows the equivalent characteristics of the dynamic resistance with fluorescent lamp power

From Table 4.1, the resistance of fluorescent lamp increases while its power decreases. This model implies a monotonically decreasing lamp equivalent resistance with a maximum value at zero power level. This further proves the existence of negative resistance of fluorescent lamps. From the monotonically decreasing lamp equivalent characteristics, the, b, c and d constants in Equation 4.2 can be determined by Matlab (at zero power level), the complete expression for the dynamic resistance is given by Equation 4.3.

$$R_{lamp}(t) = 8147e^{-0.2113P_{lamp(t)}} + 1433e^{-0.05353P_{lamp}(t)} \qquad \text{Equation 4.3}$$

The final simulation model for electromagnetic ballast fluorescent lamps with all required parameters determined is shown in Figure 4.2 and Figure 4.3. The fluorescent lamp voltage $V_{LAMP}(t)$ is generated by an external controlled voltage source, which is controlled by the multiplication of fluorescent lamp current $I_{LAMP}(t)$ and dynamic resistance of fluorescent lamp $R_{LAMP}(t)$. The instantaneous fluorescent lamp power $P_{LAMP}(t)$ is obtained from $V_{LAMP}(t)$ and $I_{LAMP}(t)$ measurements.

This resulting instantaneous power is then low-pass filtered to obtain P_{LAMP} as required in Equation 4.2. The time constant of the low-pass filter used is dependent on the ionisation constant of the plasma ionisation, and it affects the voltage spike of fluorescent lamp voltage $V_{LAMP}(t)$ [34, 35, 37].

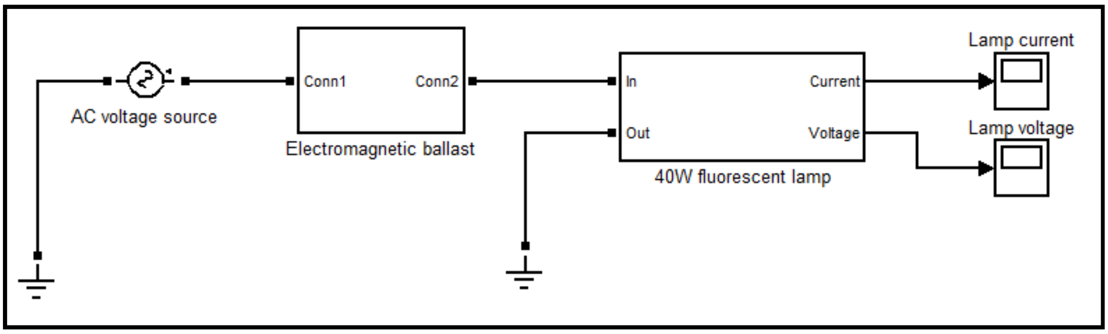


Figure 4.2: Matlab Simulink connection of electromagnetic ballast fluorescent lamp.

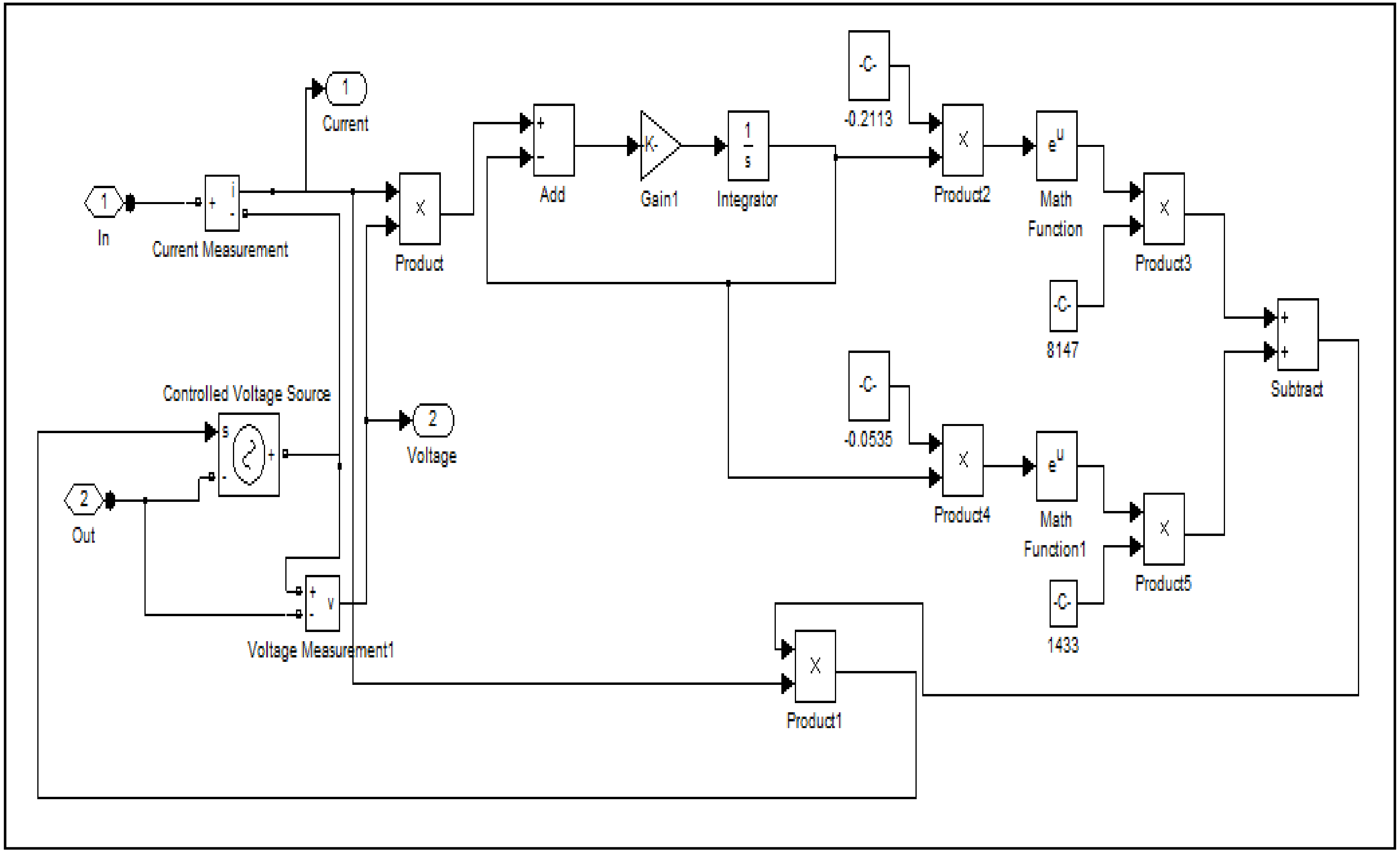


Figure 4.3: Fluorescent lamp model in Matlab Simulink.

4.3 Simulation results

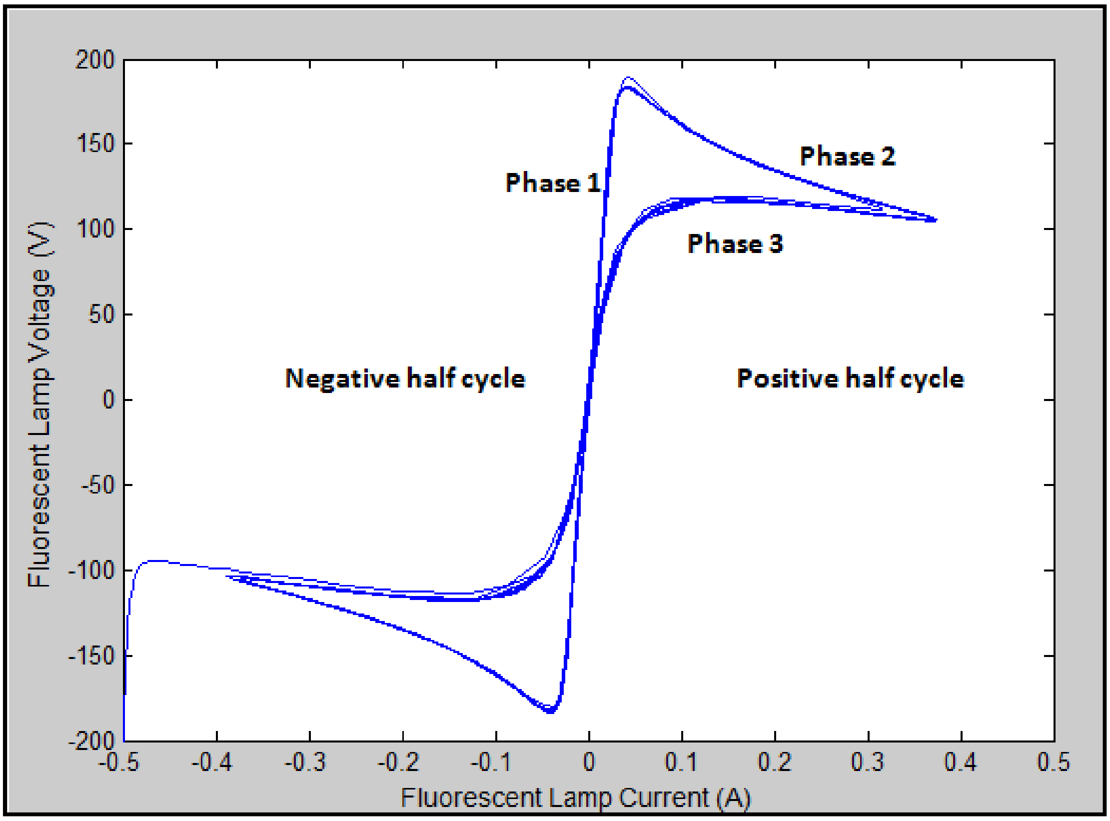


Figure 4.4: V-I Characteristics of electromagnetic ballast fluorescent lamp at 230 V incoming supply voltage, 50 Hz

The voltage - current characteristics of electromagnetic ballast fluorescent lamps obtained from the simulation is shown in Figure 4.4. The entire half cycle of the discharge can be separated into three phases.

(1) The discharge plasma starts with a relatively high resistance at the beginning of the half-cycle.

(2) In second phase, the fluorescent lamp presents negative resistance characteristics where more ionisation causes the fluorescent lamp voltage $V_{LAMP}(t)$ to decrease and its current $I_{LAMP}(t)$ to increase.

(3) Finally, the voltage and current of fluorescent lamps return to the off-state with a much lower resistance than it started off with as the incoming supply voltage returns to zero [38].

Figure 4.5 shows the simulation model of energy saving controller. The simulation model consists of the proposed energy saving controller, which is a PID controller, a controlled voltage source, electromagnetic ballast and the derived fluorescent lamps model. The functions of the energy saving controller include controlling the lamps illuminance level and regulating the incoming voltage supply.

Figure 4.6 shows the simulation results of incoming supply voltage and current waveform. Simulation results show that the incoming supply voltage is purely sinusoidal waveform. However, the current waveform is a distorted sinusoidal waveform. These phenomena can be explained by the non-linear characteristics of electromagnetic ballast and fluorescent tube. The non-linear components of fluorescent lamp consist of fluorescent tube and the electromagnetic ballast. [35, 37] presented a dynamic model for electrical characteristic of fluorescent lamps. According to these models, there are regular voltage spikes in fluorescent lamps when operating at low frequency (50 Hz). This is illustrated in Figure 4.7 where the regular voltage spikes occur at every zero-crossing of current. These voltage spikes are caused by recombination of electrons and ionised atoms. At low operating frequency operation, electrons and ionised atoms have sufficient time to recombine at each current reversal.

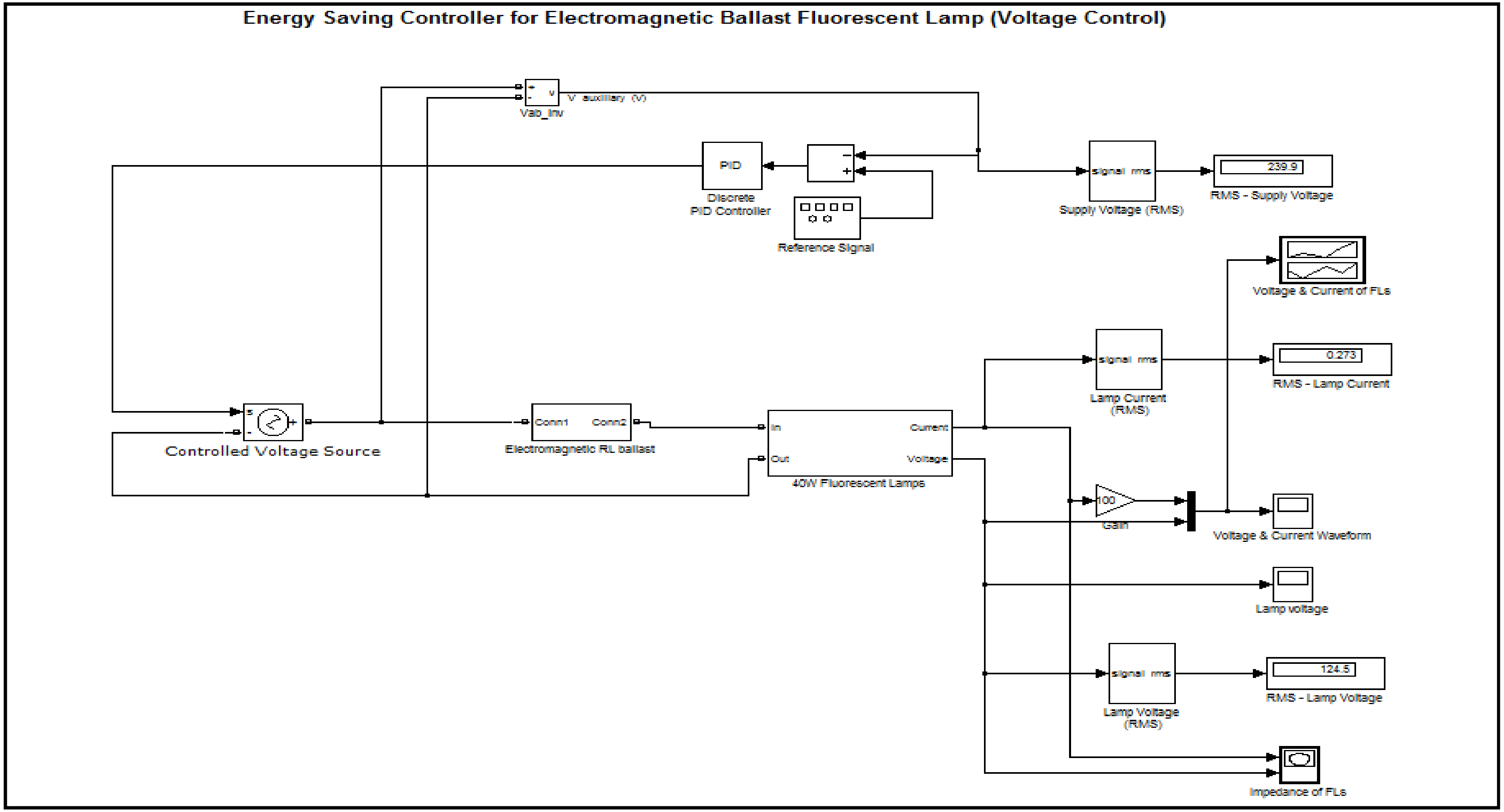


Figure 4.5: Matlab Simulink connection for electromagnetic ballast fluorescent lamp.

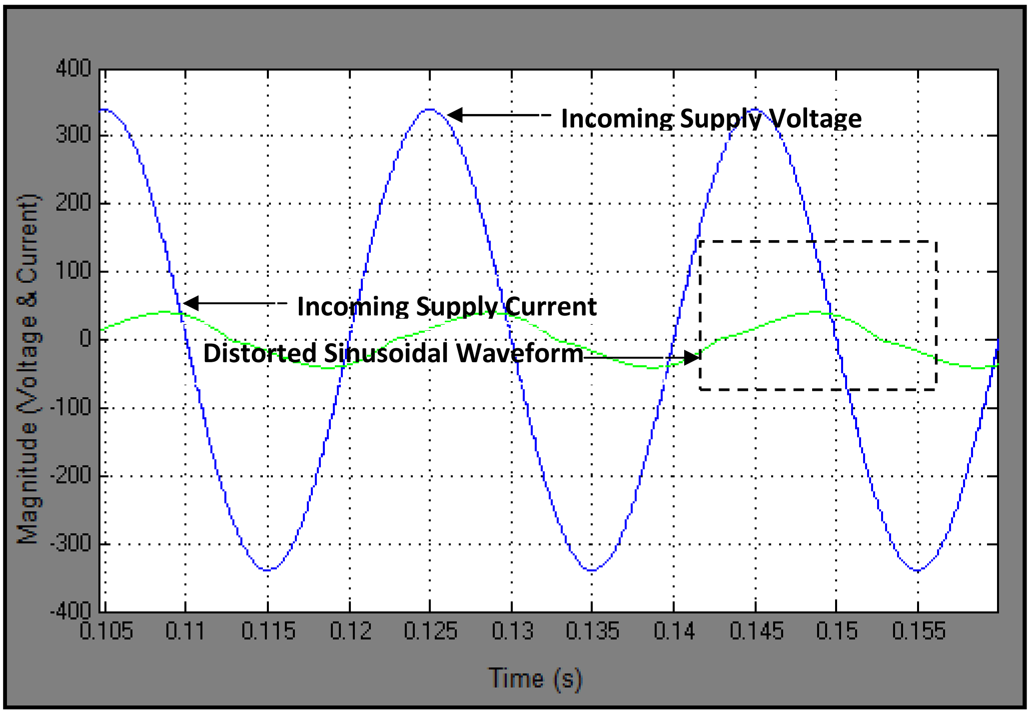


Figure 4.6: Incoming supply voltage and current waveforms of electromagnetic ballast fluorescent lamps (Incoming supply voltage: 230 V, Supply voltage frequency: 50 Hz).

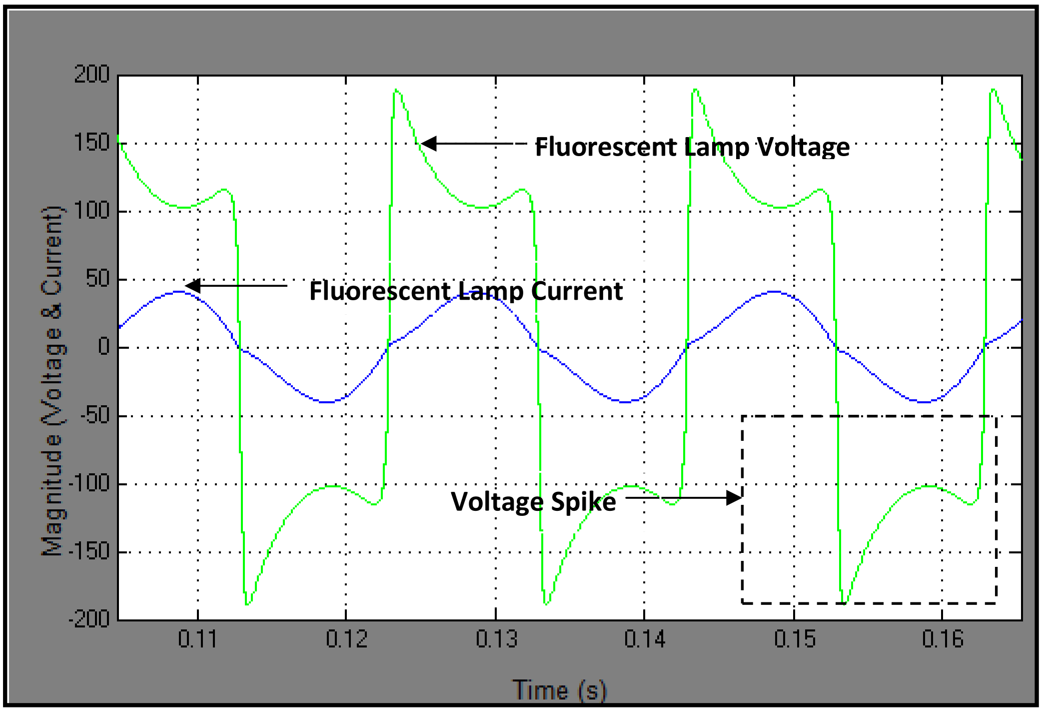


Figure 4.7: Fluorescent lamp voltage and current waveforms of electromagnetic ballast fluorescent lamps (Incoming supply: 230 V, Supply voltage frequency: 50 Hz).

As show in Figure 4.8, due to the high switching frequency (above 20 kHz), of electronic ballast fluorescent lamps, the current reversal cycle is too short for the electrons and ionised atoms to recombine, thus voltage spikes is not an issue [3, 6, 35, 37]. This shows that the electrical behaviour of fluorescent lamps change according to operating frequency.

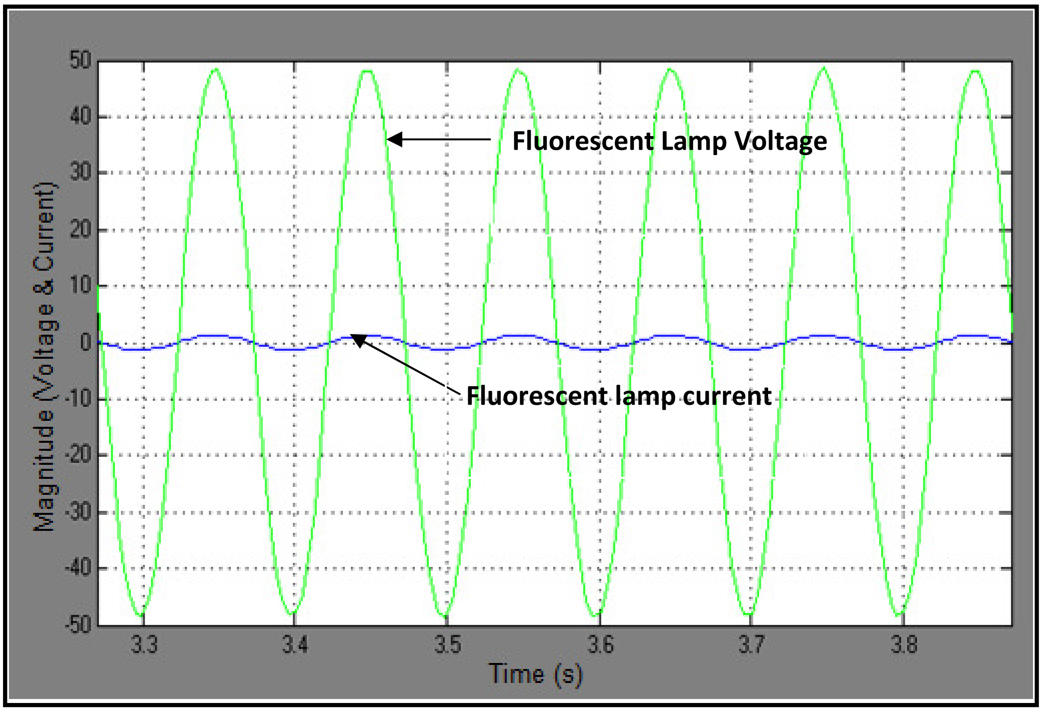


Figure 4.8: Fluorescent lamp voltage and current waveforms of electronic ballast fluorescent lamps (Incoming supply voltage: 230 V, supply voltage frequency: 50 Hz, switching frequency of electronic ballast: 20 kHz)

Illuminance level is controlled by a discrete PID controller using Ziegler-Nicholas algorithm. The PID controller performs automatic tuning process on the proportional (K_p), integration (K_i) and derivative constants (K_d). The K_i and K_d gains are first set to zero, and the gain K_p is increased until the controller reaches critical gain = K_c, at which the output of the loop starts to oscillate. The critical gain K_c and oscillation period P_c (from Ziegler-Nicholas estimation) are then used to set the gains. The tuning process stops when the output measurement stabilises at the desired illuminance level.

Another important issue is the effect of electromagnetic ballast fluorescent lamp on incoming supply voltage. In general, theoretical incoming supply voltage for optimum operation of fluorescent lamp is 180 V. As the energy saving controller reduces the incoming voltage from 230 V to 180 V in order to save energy, there may be voltage drop across electromagnetic ballast that will cause the voltage across the fluorescent lamp to be below the critical operating value. When the incoming supply voltage is below 180 V, the cathode may not be sufficiently hot to generate thermionic emission to the discharge column. Therefore, the electromagnetic ballast fluorescent lamp will not operate optimally and will be switched to off-stage [9].

It is expected that the magnetic core and conducting winding losses of the electromagnetic ballast can be reduced as the function of reduction of incoming supply voltage. Figure 4.9 shows the non-distorted sinusoidal incoming supply voltages waveform for energy saving controller for the range of 230 V to 180 V RMS.

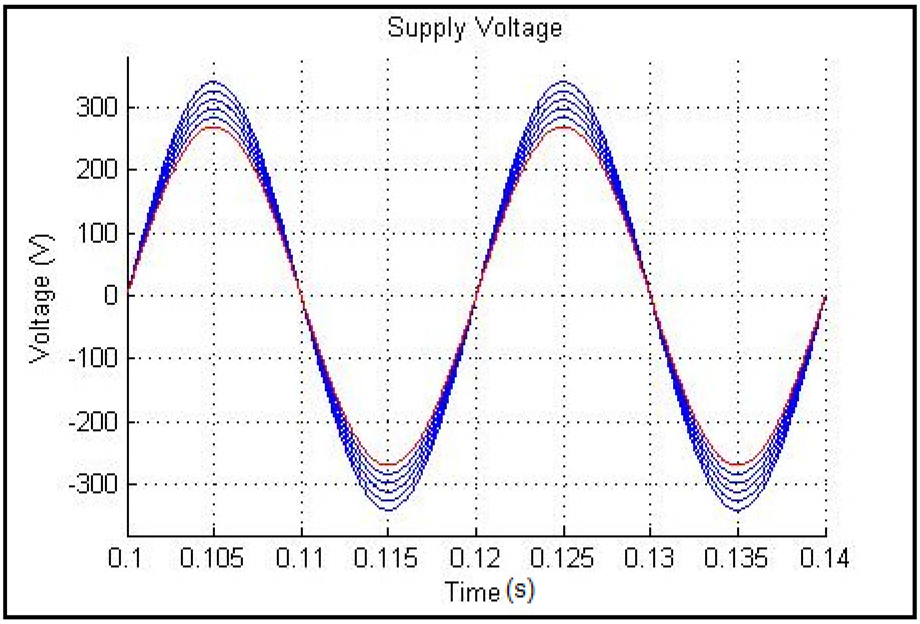


Figure 4.9: Incoming supply voltages of electromagnetic ballast fluorescent lamp.

Figure 4.10 shows that the incoming supply current decreases as the incoming supply voltage decreases. As discussed in Section 2, energy consumption of electromagnetic fluorescent lamps is proportional to the reduction of incoming supply voltage squared. The distortion of incoming supply current waveform is due to harmonic distortion in the fluorescent lamp current $I_{LAMP}(t)$ and the hysteresis of the electromagnetic ballast coil. The reduction of incoming supply voltage leads to the reduction of supply current. Therefore, the energy consumption of the electromagnetic ballast fluorescent lamp can be reduced. Since the energy consumption of fluorescent lamp system reduces much more than the fluorescent tube energy consumption, the luminous flux is reduced. Furthermore, [9] confirms that all discharge lamps can be dimmed without any significant problem down to approximate 50% illuminance output when operated on conventional electromagnetic ballast system.

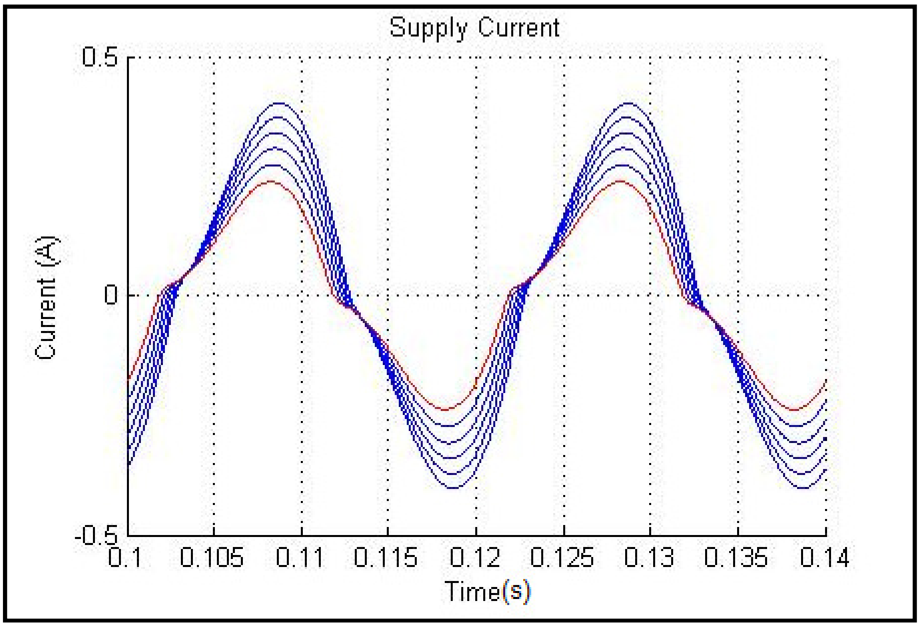


Figure 4.10: Supply currents of electromagnetic ballast fluorescent lamp.

Figure 4.11 shows the fluorescent lamps voltage $V_L(t)$ of electromagnetic ballast fluorescent lamps. The phase angle decrease when the incoming supply voltage reduces from 230 V (maximum control voltage) to 180 V (minimum control voltage). The power factor of the system is anticipated to increases as the incoming supply voltage decreases. The voltage across the electromagnetic ballast is the vectorial difference between the incoming supply voltage and the fluorescent lamp voltage. The harmonics of the fluorescent lamp appear in the fluorescent lamp voltage. As the electromagnetic ballast determines the current, there will be only odd harmonics in the fluorescent lamp voltage (even harmonics are not present). Figure 4.12 shows the fluorescent lamps current $I_L(t)$ of electromagnetic ballast fluorescent lamps

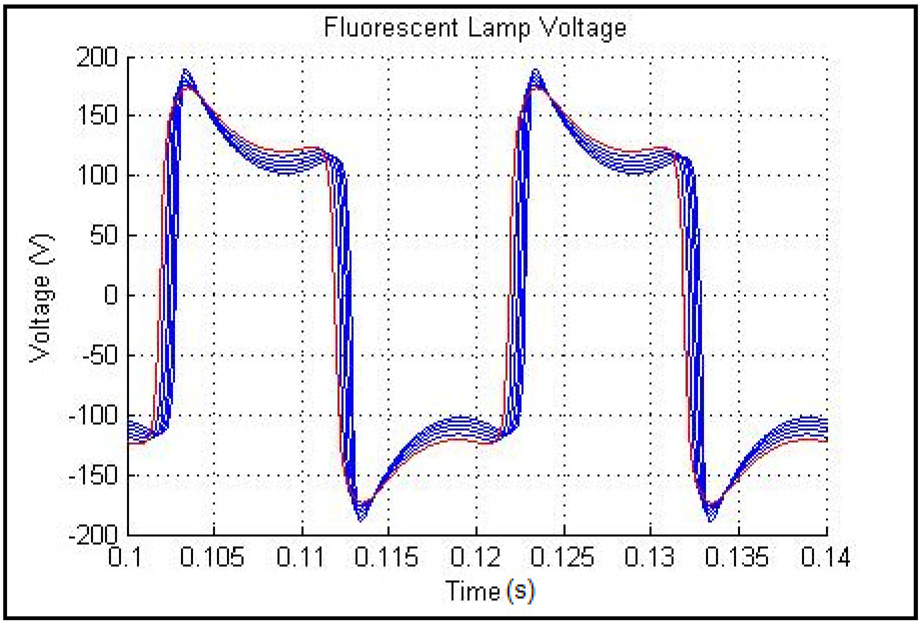


Figure 4.11: Fluorescent lamps voltage of electromagnetic ballast fluorescent lamp.

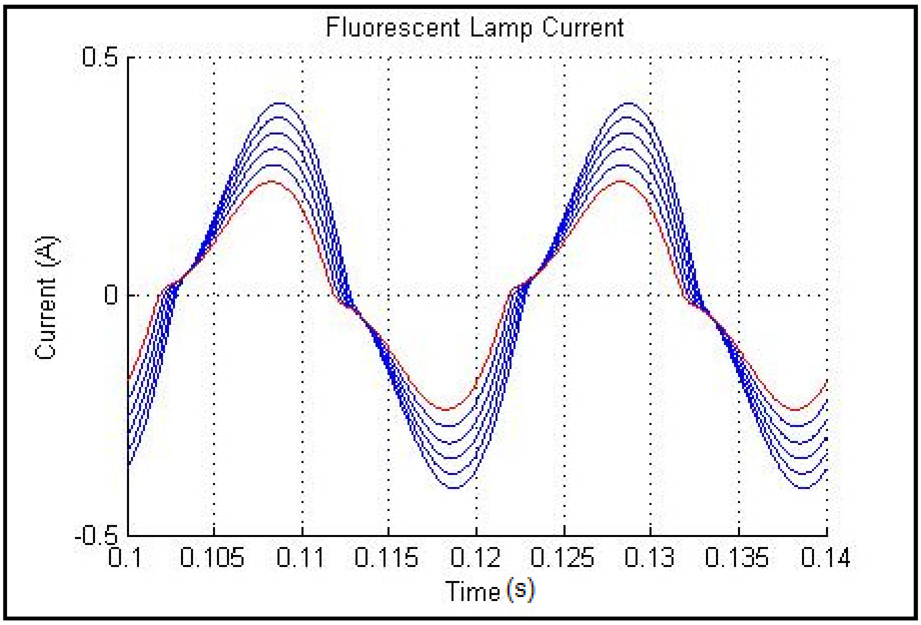


Figure 4.12: Fluorescent lamps current of electromagnetic ballast fluorescent lamp.

The relation between input energy consumption of the electromagnetic ballast fluorescent lamp and the incoming supply voltage is shown in Figure 4.13. When the incoming supply voltage is set as 230 V, the energy consumption of electromagnetic ballast fluorescent lamp is approximate 40 W. By reducing the incoming supply voltage to 180 V, the energy consumption of the electromagnetic ballast fluorescent lamp is 12 W with an energy saving of approximately 75%. Figure 4.14 illustrates the energy saving potential of the energy saving controller when the incoming supply voltage is reduced from 230 V to 180 V. The illuminance level is reduced to 67% with 75% reduction on the energy consumption of electromagnetic ballast fluorescent lamps, which is a rewarding trade-off.

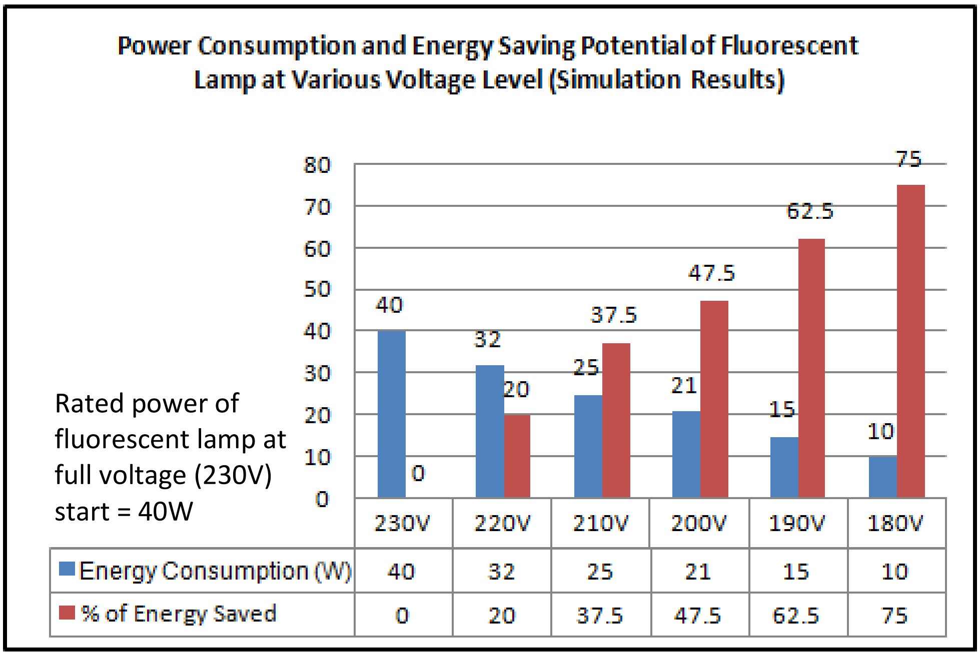


Figure 4.13: Energy consumption and energy saving potential of fluorescent lamp at various voltage level (simulation results).

4.4 Chapter summary

The following key conclusions can be drawn from the simulation in this chapter.

1. The modelling of fluorescent lamps in Matlab Simulink simulation software is based on the relationship of fluorescent lamp voltage $V_{LAMP}(t)$, fluorescent lamp current $I_{LAMP}(t)$ and dynamic resistance of fluorescent lamp $R_{LAMP}(t)$:

    a. The dynamic resistance of fluorescent lamp is expressed as a monotonically decreasing double exponential function of the low-pass filtered lamp power P_{LAMP}.

    b. The time constant of the low pass filter is related to the ionisation constant of the plasma ionisation, and affects the voltage spike of fluorescent lamp voltage $V_{LAMP}(t)$.

2. The voltage – current characteristics of electromagnetic ballast fluorescent lamp presented in this chapter are obtained from analytical models that depend on incoming supply voltage and frequency. Basically, the V-I characteristics can be divided into three stages, namely: (i) initialisation of discharge plasma; (ii) negative resistance characteristics; and, (iii) off stage. From the analysis, it can be concluded that electromagnetic ballast fluorescent lamps possess negative resistance characteristics. The resistance of the electromagnetic ballast fluorescent lamp is infinite when the electromagnetic ballast fluorescent lamp power goes to zero.

3. Simulation results show that energy saving feature of electromagnetic ballast fluorescent lamp can be achieved by reducing the incoming supply voltage from 230 V to 180 V. If the incoming supply voltage is lower than 180 V, the cathode may not be sufficiently hot to light up the fluorescent lamp.

4. The proposed energy saving controller reduces incoming supply voltage to a predetermined value after the fluorescent lamps are switched on. The incoming supply voltage and current are controlled to reduce the energy consumption of fluorescent lamps. Simulation results show that energy saving potential for electromagnetic ballast fluorescent lamp can be as high as 75%.

CHAPTER 5: SYSTEM IMPLEMENTATION

5.1 Introduction

Energy saving issue of fluorescent lamps is a matter of great concern for industry and electrical utilities. As discussed in Chapter 4, energy saving potential of electromagnetic fluorescent lamps network can be achieved by means of controlling the incoming supply voltage, optimising lighting level, reducing energy consumption and improving the efficiency of electromagnetic ballast fluorescent lamps.

The overall aim of this chapter is to describe the design implementation of energy saving controller for electromagnetic ballast fluorescent lamps. Furthermore, the load demand calculation and components sizing calculation are also presented in this chapter in addition to the functions of energy saving controller, energy saving control system and implementation results are propounded.

Various experiments have been conducted on the energy saving controller. Experiment results further confirmed that significant energy saving can be achieved by controlling the illuminance level of the electromagnetic ballast fluorescent lamps. Beside energy saving feature, the energy saving controller may also extend the lifetime of electromagnetic ballast in addition to the energy saving feature. [26]

5.2 Design implementation

5.2.1 Demand calculation and variable autotransformer sizing

For experimental purposes, the proposed energy saving controller is designed to control the illuminance level of 50 electromagnetic ballast fluorescent lamps. Therefore, the total energy consumption of the electromagnetic ballast fluorescent lamps can be calculated by Equation 5.1,

$$P_{TOTAL} = P_{FLS} \times Number\ of\ FLs = 40 \times 50 = 2000\ W \qquad \text{Equation 5.1}$$

Where, P_{TOTAL} represents the total power of electromagnetic ballast fluorescent lamps, P_{FLS} represents the rated power of electromagnetic ballast fluorescent lamp.

The relationship between the primary and secondary voltages is determined by the turn ratio of the variable transformer. The following guidelines have to be considered in order to determine the apparent power of the variable autotransformer.

1. According to IEC standard, the primary and secondary windings of variable transformer should not exceed 250% of full load amps. The secondary fusing should not exceed 125% of full load amps [21].

2. In order to prevent over-heating of the variable transformer, the transformer load factor should be maintained between 60% to 80%

The primary rated voltage of the variable autotransformer is 230 V while the secondary voltage is adjustable to the maximum of 230 V. The incoming supply current of electromagnetic ballast fluorescent lamp is measured to be 0.24 A. Total incoming current of the electromagnetic ballast fluorescent lamp network can be calculated by Equation 5.2.

$$I_{TOTAL} = I_{FLS} \times Number\ of\ FLs = 0.24 \times 50 = 12\ A \qquad \text{Equation 5.2}$$

Where, I_{TOTAL} represents the total current of electromagnetic fluorescent lamp network and I_{FLS} represents the fluorescent lamp current.

By considering the power factor to be 0.75 (from experimental results without capacitor compensation), the apparent power is as calculated in Equation 5.3

$$S = \frac{P}{pf} = \frac{2000}{0.75} = 2667\ VA \qquad \text{Equation 5.3}$$

Where S represents apparent power, P represents real power and pf represent power factor of the electromagnetic fluorescent lamps network

Allowing a service factor of 25%, the size of the variable autotransformer can be determined as in Equation 5.4.

$$S_{NEW} = S\ \times Service\ factor = 2667\ \times 1.25 = 3333\ VA \qquad \text{Equation 5.4}$$

Concluding from Equation 5.4 that 3.5 KVA variable autotransformer with 230 V input voltage will be used to control the incoming supply voltage of electromagnetic ballast fluorescent lamps.

5.2.2 Magnetic contactor selection

The maximum starting inrush current of electromagnetic ballast fluorescent lamps is obtained in Equation 5.5.

$$I_{max} = V_P \times \sqrt{\frac{C}{L}} = 230\sqrt{2} \times \sqrt{\frac{175\times10^{-6}}{150\times10^{-6}}} = 350\ A \qquad \text{Equation 5.5}$$

Where I_{max} represents the maximum starting current of electromagnetic ballast fluorescent lamp, V_P represents the incoming supply peak voltage, C is the capacitor for power factor compensation and L is the line inductance.

The inrush current of electromagnetic ballast fluorescent lamps at switch on can reach up to 27 times the steady state peak current. In general, the selection of magnetic contactor is based on the type of loads, applications and environment factors. IEC standard 947-4-1 regulates two standard utilisation for lighting circuit selection, namely:

1. AC-5a for switching of discharge lamps such as fluorescent lamps and high pressire sodium lamps.

2. AC-5b for switching incandescence lamps.

As electromagetic fluorescent lamps has high inrush starting current, the selection of magnetic contactor is based on AC-5a category[33]. Figure 5.1 shows the operating curve of LS AC-5a contactor. From the LS AC-5a operating curve, LS magnetic contactor GMC-9 is the preferred choice as it has a lifespan endurance of 3 million times switching.

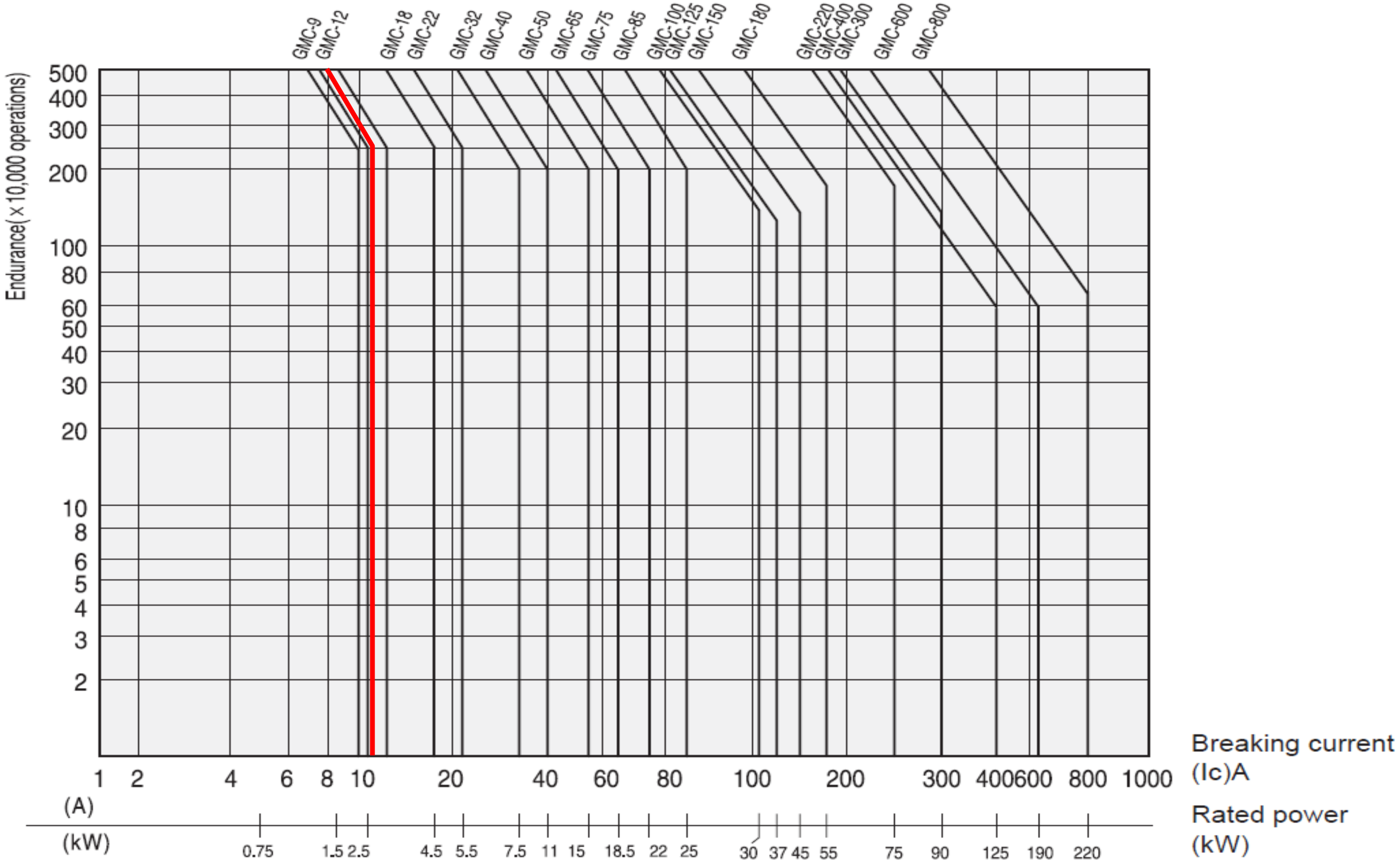


Figure 5.1: The operating curve of LS AC-5a contactor [33].

5.2.3 Programmable logic controller selection

The illuminance level control of the energy saving controller is controlled by the lux PID controller with respect to the predefine illuminance from end-user. It is preferable that this programmable logic controller can process both digital and analogue signals. The block diagram of programmable logic controller for energy saving control system is shown in Figure 5.2.

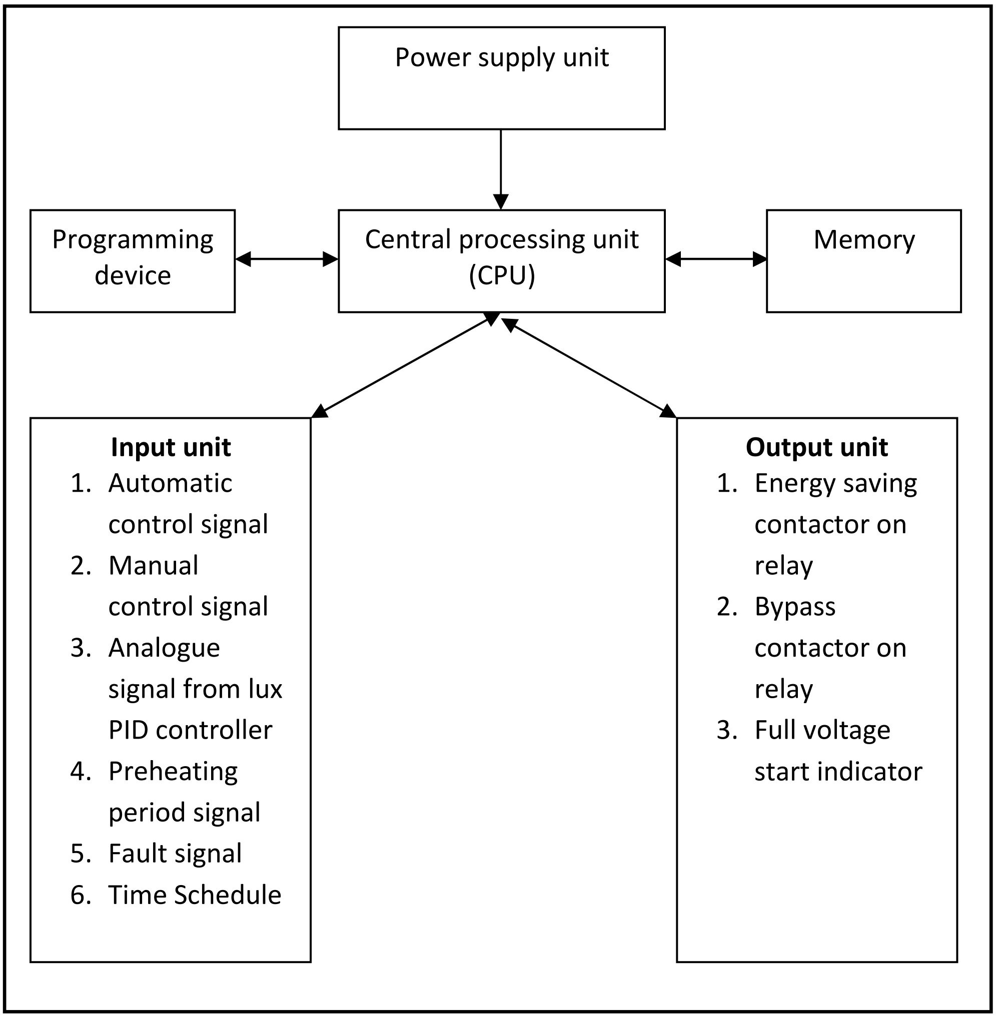


Figure 5.2: Block diagram of programmable logic controller for energy saving control system.

The programmable logic controller is controlled by six parameters, namely automatic control signal, manual control signal, output analogue of lux PID controller, preheating period signal, energy saving controller fault signal and time schedule function. Furthermore, four digital input signals and one analogue input are required for the energy saving controller. Hence, the programmable logic controller must be able support up to five inputs (four digital and one analogue) and three digital outputs. Zelio SR2B201BD programmable logic controller is selected to control the functionalities of the energy saving controller.

Zelio SR2B201BD programmable logic controller offers six digital inputs, six programmable (either as analogue or digital) inputs and eight digital outputs. Zelio SR2B122BD is designed for implementation in small automation systems in both industrial and commercial sectors, such as for chillers control systems and automation control systems for agricultural machines.

The programming of Zelio SR2B122BD is relatively simple; programming can be done by using buttons that are located at the front panel of the controller or using Zelio Soft programming software. When using Zelio software, programming can be performed either in the form of ladder diagram programming language or in function block diagrams. Figure 5.3 shows the front panel of Zelio SR2B122BD programmable logic controller, and Table 5.1 describes the front panel.

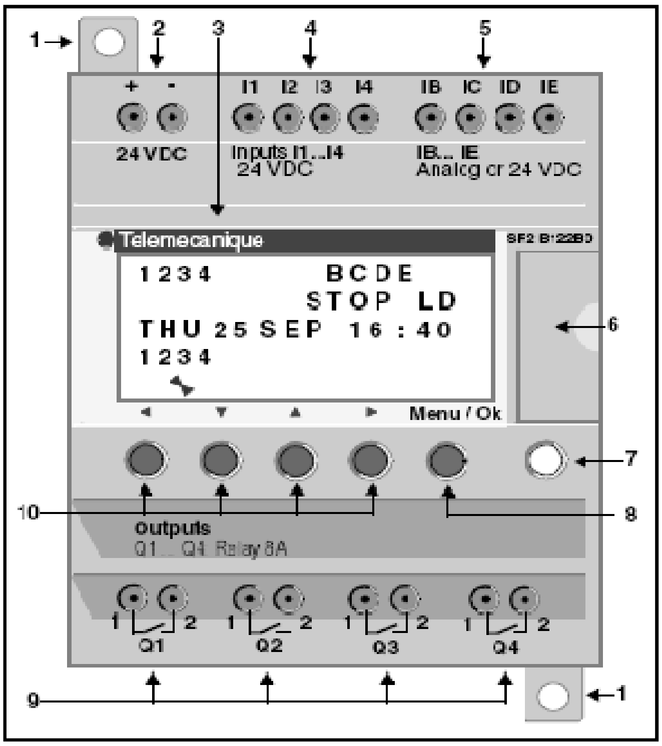


Figure 5.3: The Zelio SR2B122BD programmable logic controller.

Table 5.1: Description of the front panel of Zelio SR2B122BD programmable logic controller

Reference	Description
1	Retractable mounting feet
2	Screw terminal block for the power supply
3	LCD display
4	Terminal block for input signal (24 V digital signal)
5	Programmable terminal block for digital (24 V) / analogue signal (0 – 10 V)
6	Connector for backup memory or PC connection cable
7	“Shift” function key
8	“Selection” and “Validation” function key
9	Terminal block for relay output (230 V, 8 A)
10	Arrow keys or after first configuring them, Z pushbuttons.

Two testing and simulation mode can be done in Zelio Soft2 that is simulation mode and monitoring mode. Simulation mode allows the program to be tested without connecting to a Zelio controller module. On the other hand, monitoring mode makes it possible to test the program executed from Zelio controller module. In monitoring mode, parameter settings such as time delay can be adjusted in Zelio Soft2. The input / output addresses of the energy saving controller is tabulated in Table 5.2

Table 5.2: Input / output addresses of the energy saving controller.

No	Description	Input / output	Types	Address
1	Manual control signal	Input	Digital	I1
2	Automatic control signal	Input	Digital	I3
3	Preheating period signal / reset signal	Input	Digital	I4
4	Energy saving fault signal	Input	Digital	IB
5	Analogue signal from lux PID controller	Input	Analogue	IC(Analogue)
5	Time schedule setting	Input	Digital (Set by using arrow keys)	C
6	Energy saving contactor on relay	Output	Digital	Q1
7	Bypass contactor on relay	Output	Digital	Q2
8	Full voltage start indicator	Output	Digital	Q3

5.2.4 Lux intensity sensor selection

In general, the lux intensity sensor has a loop power of 0 to 10 V which corresponds to illuminance level of 0 to 1000 lux. As a result, the output signal of the lux intensity sensor increases proportional to the room illuminance level. Figure 5.4 shows the characteristic of lux intensity sensor with respects to illuminance level.

Illuminance level is measured by a silicon photodiode light sensor in a hermetical sealed case, which is specially designed for high precision linear applications. The lux intensity sensor has a flat glass window with a built in colour correction filter, providing a close approximation to the spectral response in the human eye [29]. Figure 5.5 shows the photograph of the lux intensity sensor used in the energy saving controller. Refer to Table A.2 (Appendix A1) for the technical speciciation of lux intensity sensor.

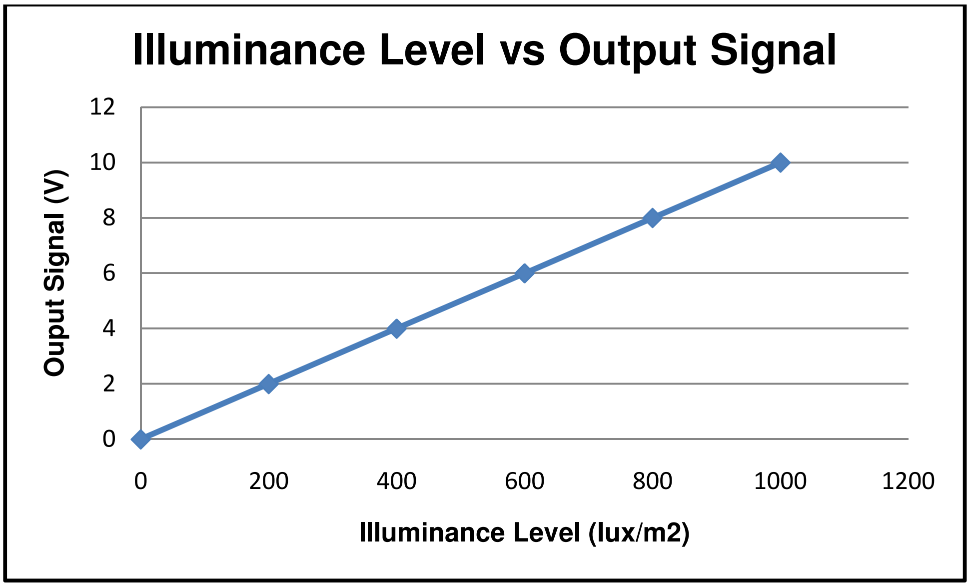


Figure 5.4: Characteristic of lux intensity sensor correspond to the illumiance level.

Figure 5.5: The 0 – 1000 lux intensity sensor.

Since Zelio programmable logic controller does not accept analogue current signal, the output of the lux intensity sensor must be converted to an useable voltage signal. The conversion from current to voltage signal can be done by connecting a 250 Ω resistor at the output terminal of lux intensity sensor. This resistor used in the control system is of a high accuracy, which produces a 0 – 5 V dc signal that corresponds to the illuminance level of 0 – 1000 lux. Appendix A1, Figure A.1 shows the connection diagram for input and ouput signal of lux intensity sensor.

5.2.5 Features of energy saving controller

The energy saving controller for electromagnetic ballast fluorescent lamp is the central control unit that can provide an adjustable incoming supply voltage at 50 Hz frequency for a network of electromagnetic ballast fluorescent lamps. The proposed energy saving controller works on single phase alternating current supply varying from 180 V to 230 V. All electromagnetic ballast fluorescent lamps installed in this project are based on 230 V and 50 Hz specification. The energy saving controller system consists of lux PID controller, programmable logic controller, lux intensity sensor and one variable autotransformer to reduce the incoming supply voltage to predefine value after the electromagnetic ballast fluorescent lamps are switched on. Table 5.3 shows the detailed components listing of the energy saving controller.

Table 5.3: Component list of energy saving controller

Item	**Brand**	**Description**	**Quantity require**
1	Honeywell	230V /24V motor actuators	1
2	LS Industrial	BKN-b Type C 20 A 6 KA single pole miniature circuit breaker	1
3	LS Industrial	RKN6240100 40 A 2P 100 mA earth leakage circuit breaker	1
4	LS Industrial	BKN-b Type C 16 A 6 KA single pole miniature circuit breaker	1
5	LS Industrial	GMC-9 three pole electromagnetic contactor	2
6	Meanwell	230 V/24 V 2.1 A DC power supply	1
7	NESB	0 – 230 V 3.5 KVA variable transformer	1
8	Salzer	Auto / Off / Manual three pole selector switch	1
9	Schneider	RXM-2 230 V control relay	1
10	Schneider	Zelio programmable logic controller SR2B122BD	1
11	Shimaden	Digital lux proportional integration and derivative controller	1
12	Twinlux	Lux intensity sensor. Measurement range: 0 – 1000 lux , Output signal: 0 – 10 V	1

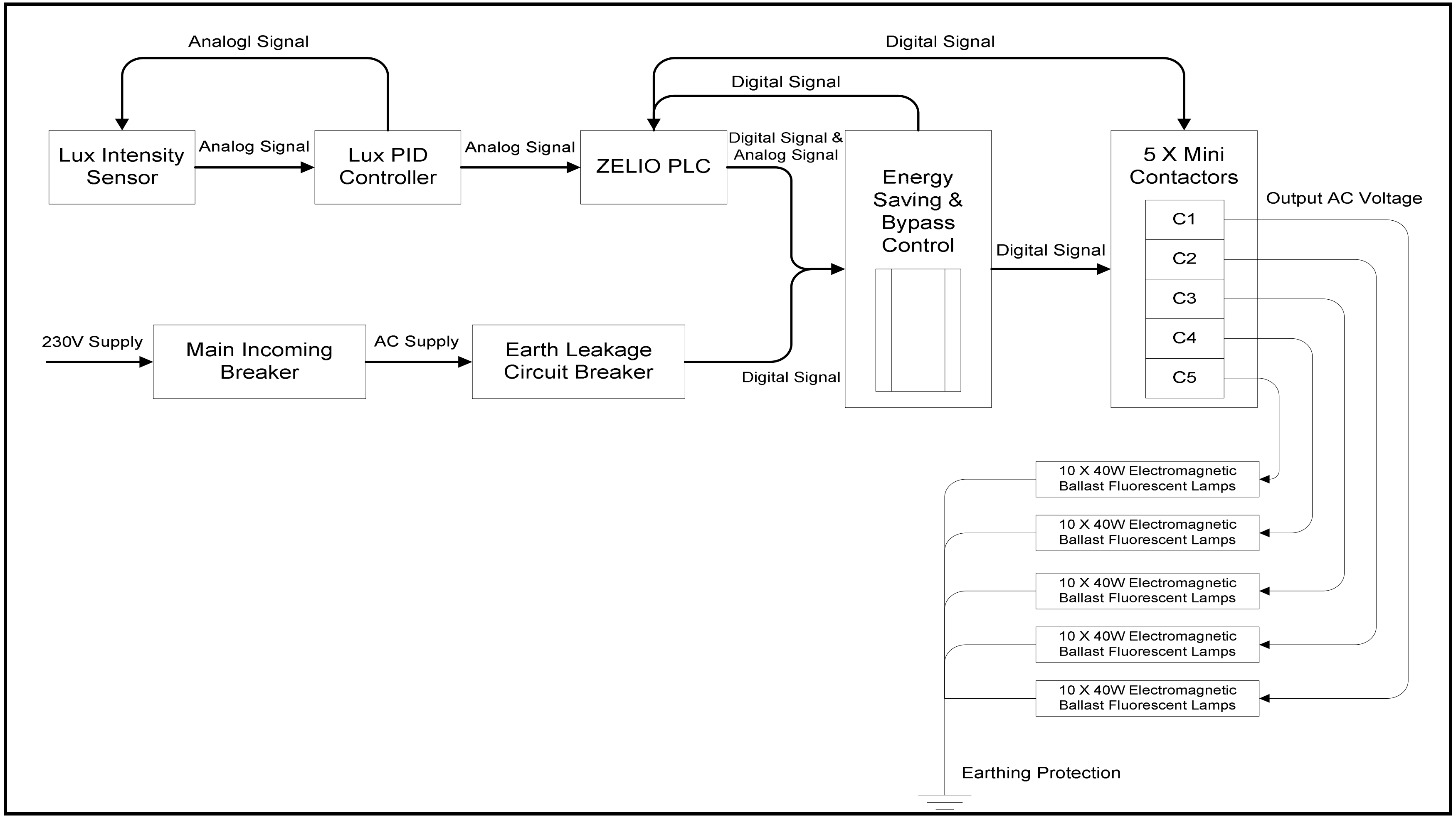


Figure 5.6: Block diagram of the energy saving controller for electromagnetic ballast fluorescent lamp network.

Figure 5.6 shows the block diagram of the energy saving controller for electromagnetic ballast fluorescent lamp network. The functions of the energy saving controller are as listed as follows:

1. **Dimmable illuminance control**

   Energy saving controller provides dimmable illuminance control for electromagnetic ballast fluorescent lamp. The energy control may dim the fluorescent lamp when its surrounding is sufficiently bright. A significant amount of energy can be saved from this feature. Essentially, the energy saving controller will turn on all fluorescent lamps at full voltage of 230 V in order to preserve the life time of electromagnetic ballast fluorescent lamp. Energy saving control is activated only after the preheating period. Moreover, the controller controls analogue input / output signals, incoming supply voltage and the operation of electromagnetic ballast fluorescent lamps. Lux intensity sensor provides stable and accurate illuminance level sensing for the energy saving controller.

   Traditionally, illuminance control of fluorescent lamp can only be done by using dimmable electronic ballast. However there are various shortcomings in using dimmable electronic ballast such as short life time, high installation cost and it only provide individual control to one fluorescent lamp per ballast. The new energy saving controller for electromagnetic ballast fluorescent lamp turns the non-dimmable electromagnetic ballast into dimmable illuminance control.

2. Voltage reduction method

Energy saving feature is achieved by controlling the incoming supply voltage to predefined voltage level. Simulation results prove that the controllable range of incoming voltage is between 180 V to 230 V. When the incoming supply voltage is below 180 V, electromagnetic ballast fluorescent lamp will switch to “off-stage”.

3. Earth leakage protection

The energy saving controller provides earth leakage protection to the electromagnetic ballast fluorescent lamp network system. The protection provided follows Malaysia Electricity Act 1990 and IEC standard 61008. According to Malaysia Electricity Act 1990, the protection against earth leakage current shall be afforded for any final circuit. Either individually or in a group, by an earth leakage circuit breaker having a rated residual operating current not exceeding 100 milli-amperes expects the following situation: (a) it is impractical to provide earth leakage protection for functional reasons or (b) it is unsafe or even dangerous to provide earth leakage protection [39].

4. Backup power system

In order to ensure system stability, the energy saving controller provides automatic backup power system. In case of failure in the energy saving controller, the backup system will be switched on automatically, and provide full voltage of 230 V to electromagnetic fluorescent lamp lighting network. Furthermore, it is also possible to connect the energy saving controller to an uninterruptible power supply (UPS). The UPS may provide emergency electricity to the electromagnetic fluorescent lamp lighting network when the input power supply fails.

The under-voltage detection relay inside the UPS will turn on the DC-AC inverter when the incoming supply voltage falls below 20% of the rated voltage. i.e. 192 V. The DC-AC inverter is powered by a set of DC battery bank. According to [27], the changeover time of UPS can be as long as 25 milliseconds, depending on the amount of time it takes for the UPS control system to detect the under-voltage. The block diagram showing connection of energy saving controller to a UPS is as shown in Figure 5.7.

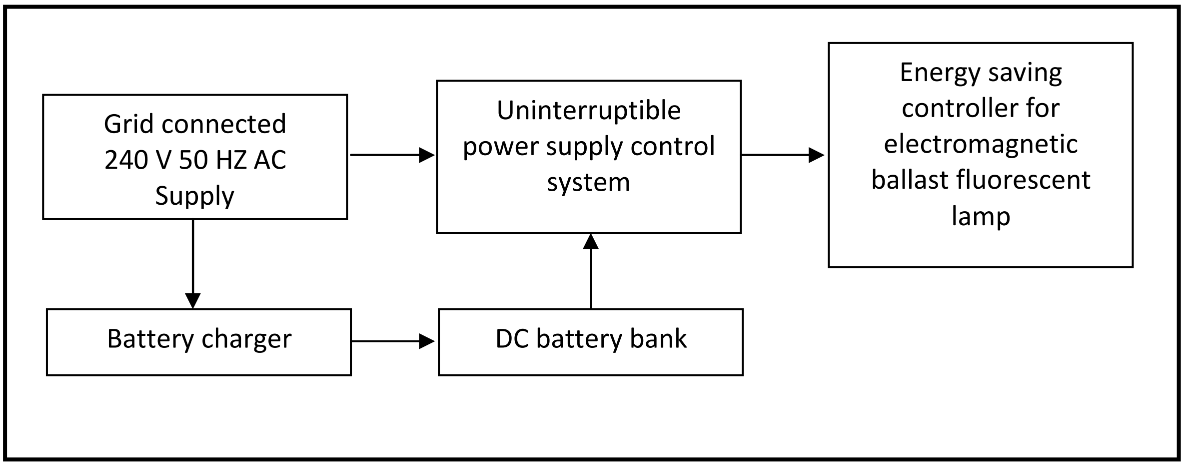


Figure 5.7: Cooperate uninterruptible power supply in energy saving controller.

5. Preheating feature

Preheating feature is added to energy saving controller in order to preserve the lifetime of electromagnetic ballast fluorescent lamp. The preheating feature is initialised when “automatic control mode” has been selected. The preheating period has a run-up time of 10 minutes for electromagnetic ballast fluorescent lamp. After the preheating period, energy saving control algorithm will be switched on. [10] claimed that the starting temperature of fluorescent tube can be maintained by providing full incoming supply voltage i.e. 230 V when switching on. As a result, the energy saving controller does not have negative impact on the lifespan of fluorescent lamps.

In addition, various researches showed that the lifespan of fluorescent lamps can be affected by fluorescent lamps current crest factor (CCF) and electrode starting temperature. The energy saving controller installed controls the incoming supply voltage to fluorescent lamps and reduces their CCF, thus extending the lifespan of fluorescent lamps [26].

6. Time schedule function

The time scheduling system in the energy saving controller controls the switching schedule of electromagnetic ballast fluorescent lamps. In addition, the dimmable illuminance feature is able to work with this time schedule control. This time scheduling settings can be adjusted by using either the specific programming software or the function key located at the LCD display of programmable logic controller.

Figure 5.8 shows the overall control sequence of the energy saving controller for electromagnetic ballast fluorescent lamp.The flow process shown served as the design for implementing the controller into a PLC ladder program.

The energy saving controller is programmed to operate under two different mode of operation, namely automatic or manual control mode by using the PLC program shown in Figure 5.9. From Figure 5.9, it can be seen that I3 represents automatic control system. When I3 is activated, time delay relay T2 (located at rung 3) will energise and after the predefined delay time, the open contact of T2 (located at rung 4) becomes close contact. Hence, the automatic relay M2 (located at rung 4) will be energised, and the energy saving controller is activated.

On the other hand, I1 is selected, the relay T1 (located at rung 1) will energise and start the time delay function. After predetermined time delay, the fluorescnet lamps system will operate under manual control scheme.Under this scheme, the energy saving controller is bypassed. The electromagnetic ballast fluroescent lamps will be connected to 230 V incoming supply voltage without any voltage. For protection of the energy saving controller, manual relay M1 (located at rung 2) and automatic relay M2 (located at rung 4) are connected in the form of mutually excluive to prevent automatic and manual operation mode from being activated at the same time.

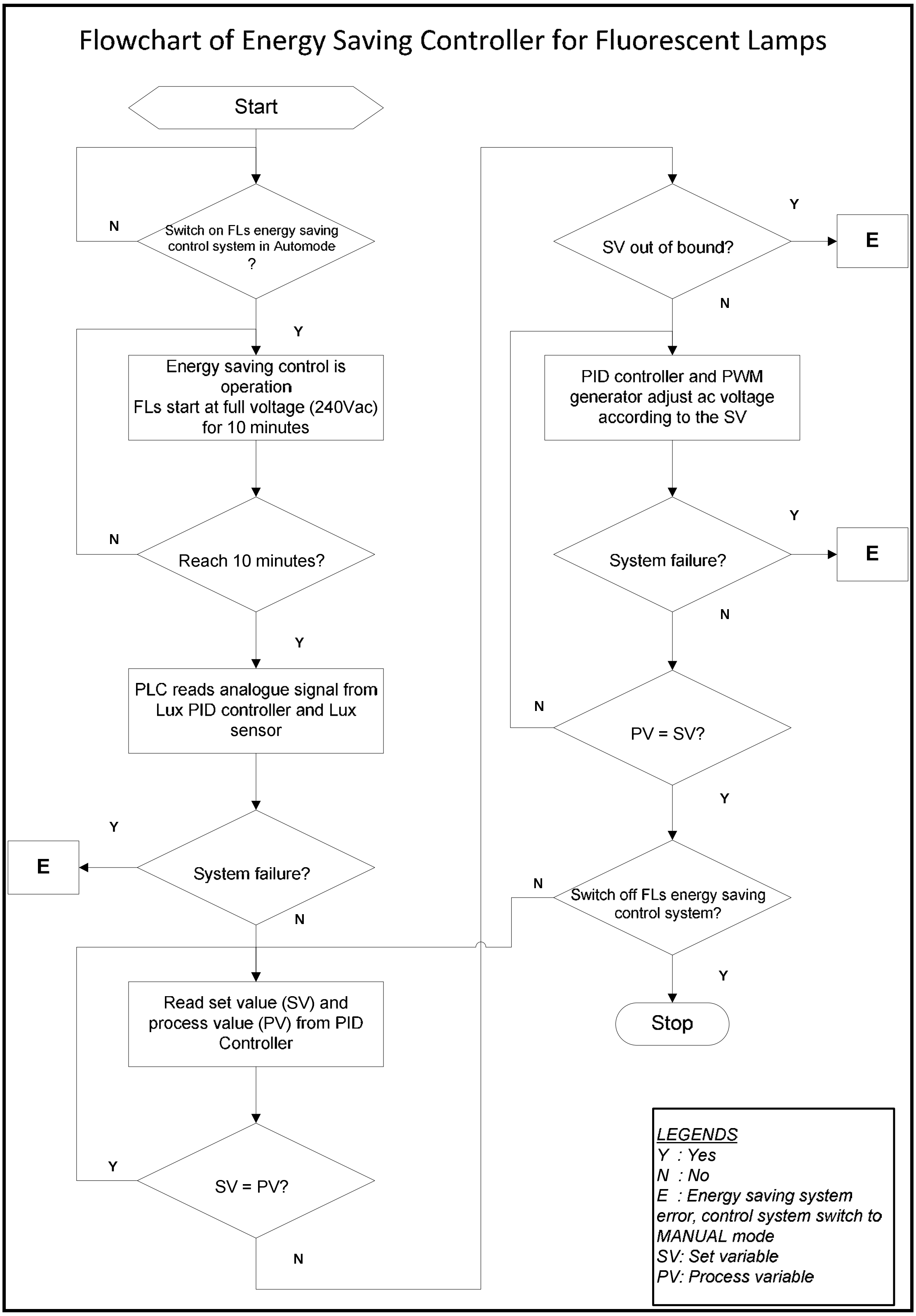


Figure 5.8: Flow chart of the energy saving controller for electromagnetic ballast fluorescent lamp.

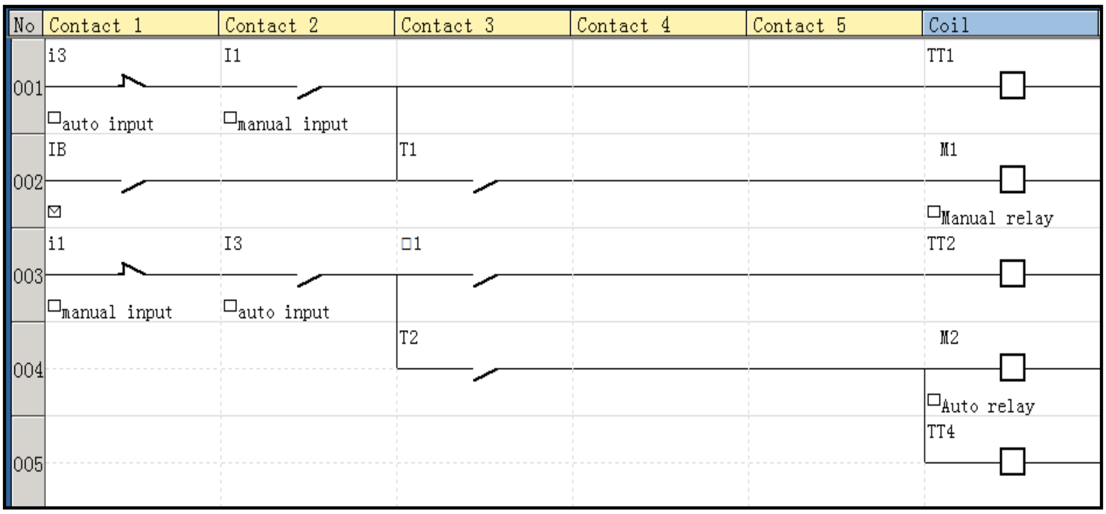


Figure 5.9: Lader diagram of automatic / off / manual control system.

As automatic relay M2 (located at rung 4) is energised, the associated normally open contact of M2 (located at rung 8), Figure 5.10, becomes close contact. The output coil Q2 (located at rung 8) and preheating time delay relay T4 (located at rung 5 check this) are energised by the closed contact of M2. The time delay relay T4 is used to control the preheating period of energy saving controller and the output Q2 indicates start / stop control of energy saving controller in automatic control mode.

During the preheating period, preheating output Q3 (located at rung 9), Figure 5.11, is energised and electromagnetic fluorescent lamps are started in full voltage. In general, the preheating period has a run-up time of 10 minutes for electromagnetic ballast fluorescent lamps. After the time delay of T4, Q3 will switch to off-stage so that the incoming supply voltage of energy saving system can be controlled by the lux PID controller. Figure 5.10 shows the ladder diagram for automatic control mode.

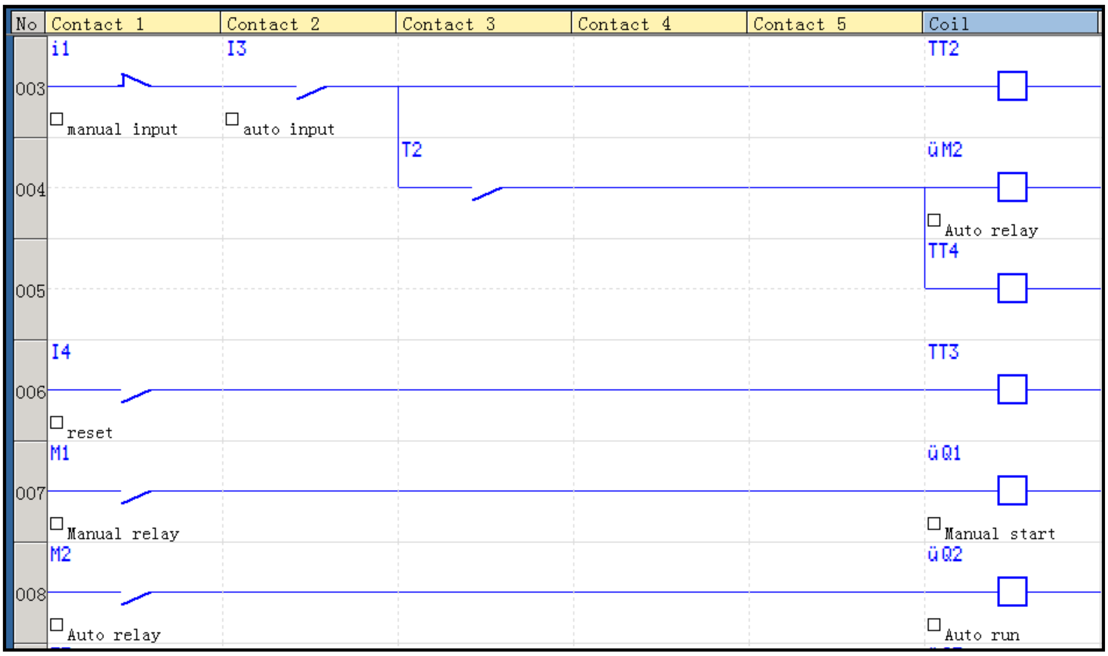


Figure 5.10: Lader diagram of automatic control mode.

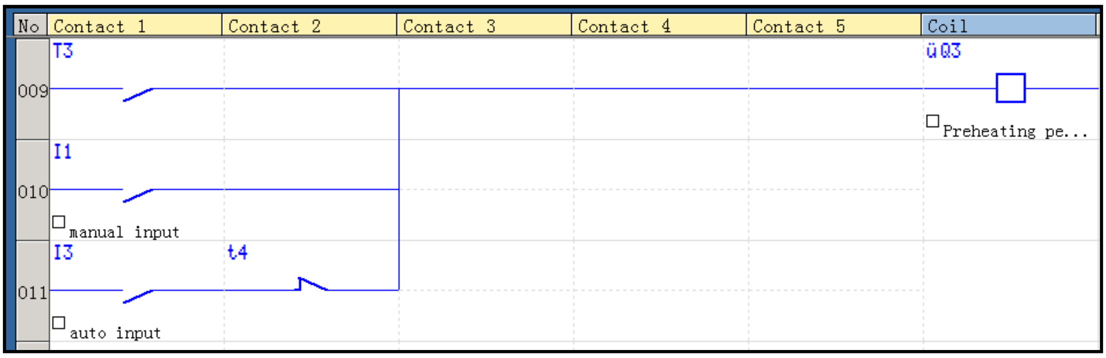
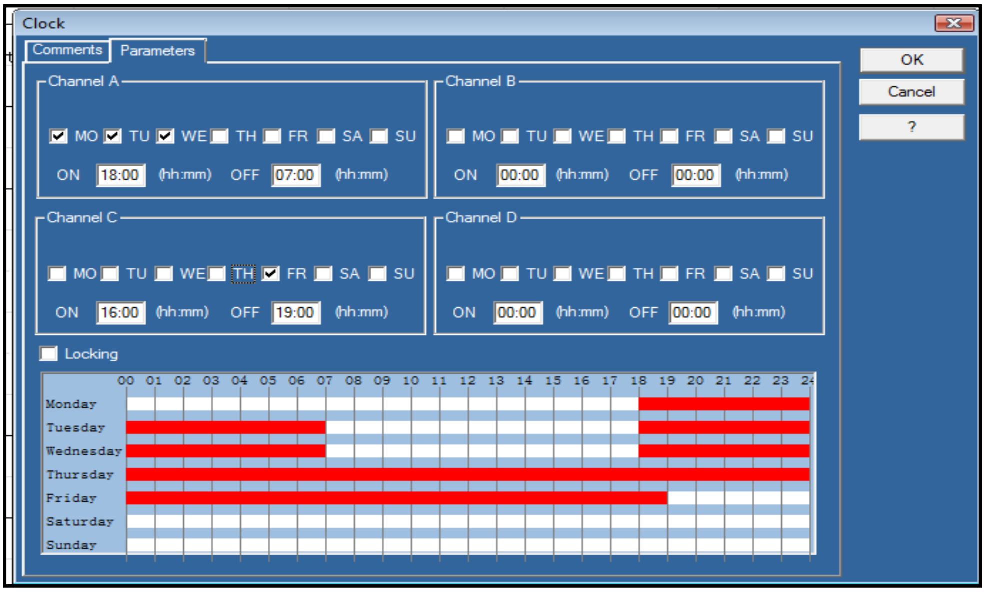


Figure 5.11: Ladder diagram of preheating period.

Preheating period also can be started manually by pressing the "preheating period start" button at the energy saving controller. Refer to Figure 5.11, when the preheating period start button is pressed, normally open contact of I4 (located at rung 6) becomes close contact, and timer delay relay T3 (located at rung 6) is energised. The normally open contact of T3 (located at rung 9) will switch on the preheating output Q3 (located at rung 9) for 10 minutes.

If the energy saving controller is faulty, a fault signal will be sent to IB (located at rung 2). This will switch on the manual relay M1 (located at rung 2), causing the energy saving controller to be bypassed. When this happens, the incoming voltage supply of electromagnetic ballast fluorescent lamps becomes 230 V static voltage, without any voltage variation control. When a fault signal is cleared from the system, the energy saving controller will automatically switch back to automatic mode.

In automatic mode, the switching schedule for electromagnetic ballast fluorescent lamps can be controlled by the time schedule program. The time schedule can be set by using either Zelio programming software, Figure 5.12 or the front panel of Zelio programmable logic controller, Figure 5.13. The Zelio programmable logic controller used offers 4 separate time schedule output channel namely A, B, C and D. In order to activate the schedule for each channel, the days of week desired must be checked and the start and end time must be specified.



Channel A
☑ MO ☑ TU ☑ WE ☐ TH ☐ FR ☐ SA ☐ SU
ON 18:00 (hh:mm) OFF 07:00 (hh:mm)

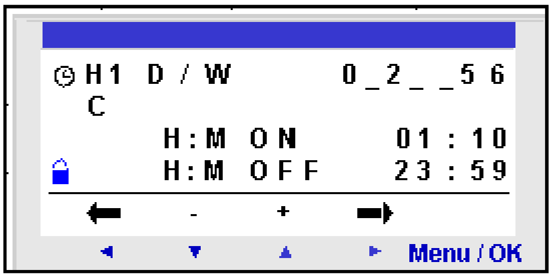
Channel B
☐ MO ☐ TU ☐ WE ☐ TH ☐ FR ☐ SA ☐ SU
ON 00:00 (hh:mm) OFF 00:00 (hh:mm)

Channel C
☐ MO ☐ TU ☐ WE ☐ TH ☑ FR ☐ SA ☐ SU
ON 16:00 (hh:mm) OFF 19:00 (hh:mm)

Channel D
☐ MO ☐ TU ☐ WE ☐ TH ☐ FR ☐ SA ☐ SU
ON 00:00 (hh:mm) OFF 00:00 (hh:mm)

☐ Locking

Figure 5.12: Setting parameter of time schedule function in programming software.



H1 D/W 0_2__56
C
H:M ON 01 : 10
H:M OFF 23 : 59

Figure 5.13: Setting parameter of time schedule function by using front panel of Zelio programmable logic controller.

5. 3 System configuration and implementation results

5.3.1 System configuration

For the hardware implementation of energy saving controller, GE T9 40 W fluorescent lamps and electromagnetic ballast are used to verify the energy saving feature and illuminance level control of the controller. A variable autotransformer with output voltage ranging from 180 V to 230 V is used as an adjustable voltage supply to the electromagnetic ballast fluorescent lamp. The output voltage of the variable autotransformer is controlled by an actuator and lux PID controller. Illuminance level measurement is carried out by using Kyoritsu digital light meter model 5202, and it is installed at around 1.5 meters below the electromagnetic ballast fluorescent lamps. Tektronix digital real time oscilloscope TDS 200 and Fluke power analyser are used for experimental measurements.

Figure 5.14 shows the panel layout of energy saving controller for electromagnetic ballast fluorescent lamps outside the box door. The devices that are located at the front panel of the controller consist of lux PID controller, manual/bypass mode indicator, energy saving on indicator, full voltage start indicator, start preheating period pushbutton and automatic/off/manual selector switch. Appendix A1, Table A.1 shows the parameter setting of lux PID controller.

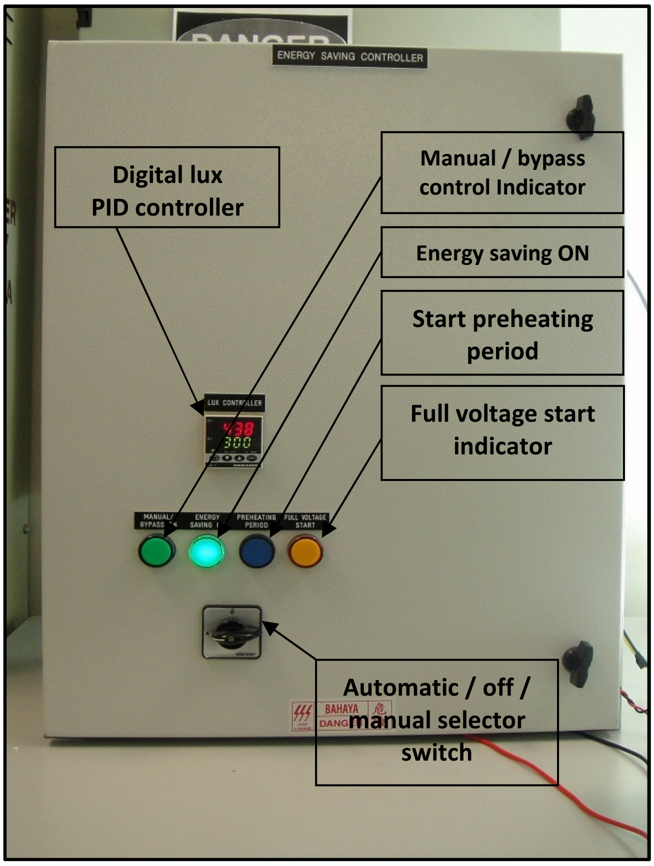


Figure 5.14: Panel layout of the energy saving controller.

Figure 5.15 shows the internal wiring connection of energy saving controller. The main incoming circuit breaker, earth leakage circuit breaker, automatic-manual changeover contactor, variable transformer, motorise actuator, Zelio SR2B122BD programmable logic controller and DC power supply are located inside the energy saving controller box. Figures 5.16 and 5.17 present a zooming components of Figure 5.15. In addition, Figure 5.18 shows the wiring of the feedback path of digital lux PID controller. The lux is measured by the lux intensity sensor and feedback to the digital lux PID controller. The digital lux PID controller will compare the SV with the PV and reduce the difference between these two variables.

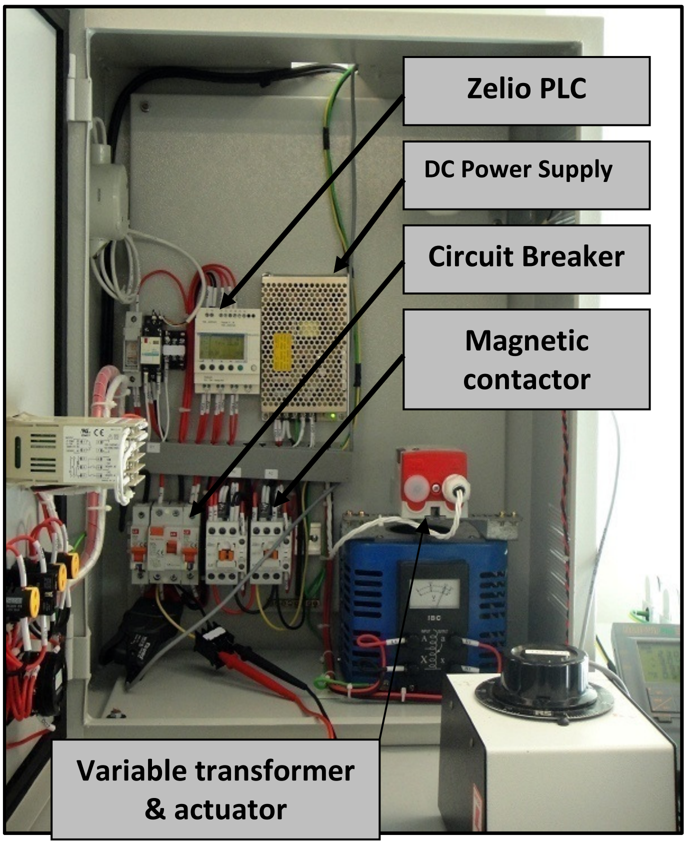


Figure 5.15: Internal wiring connection of energy saving controller.

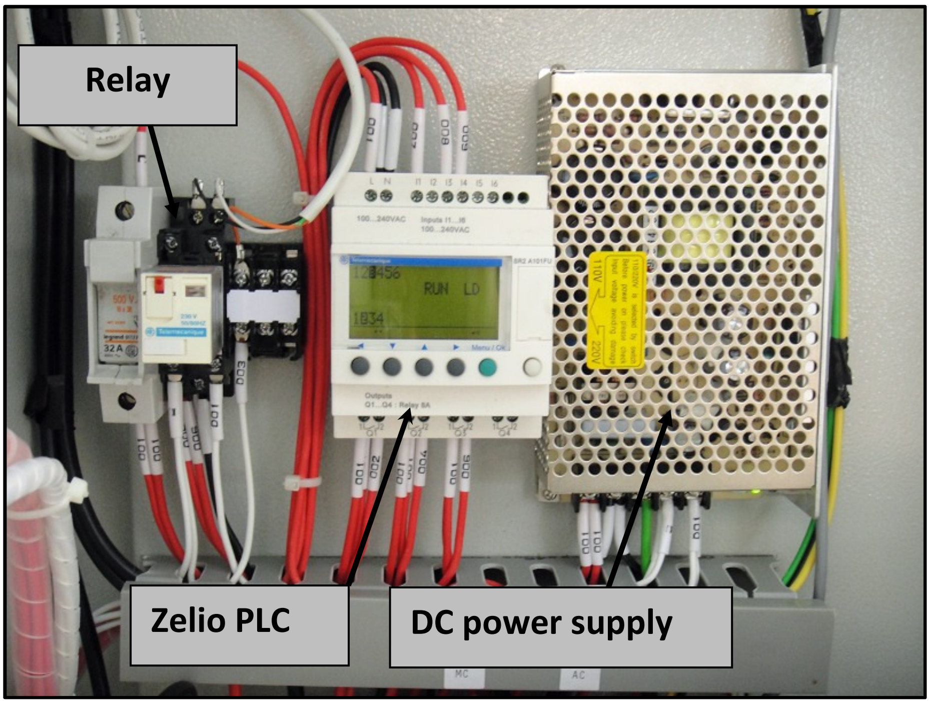


Figure 5.16: The Zelio SR2B122BD programmable logic controller and DC power supply.

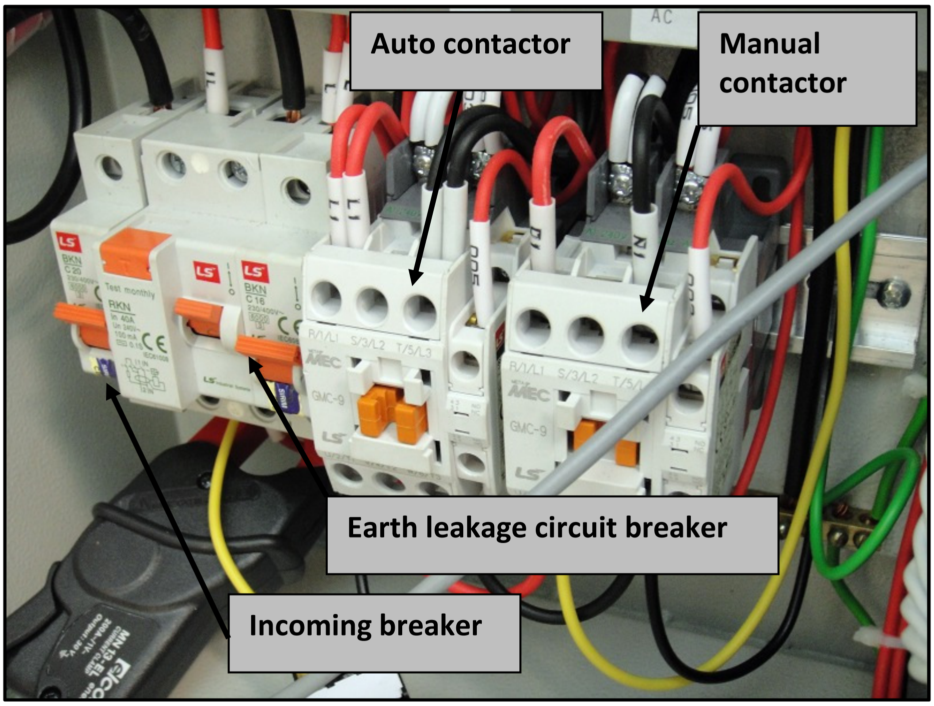


Figure 5.17: Protection system of enegry saving controller.

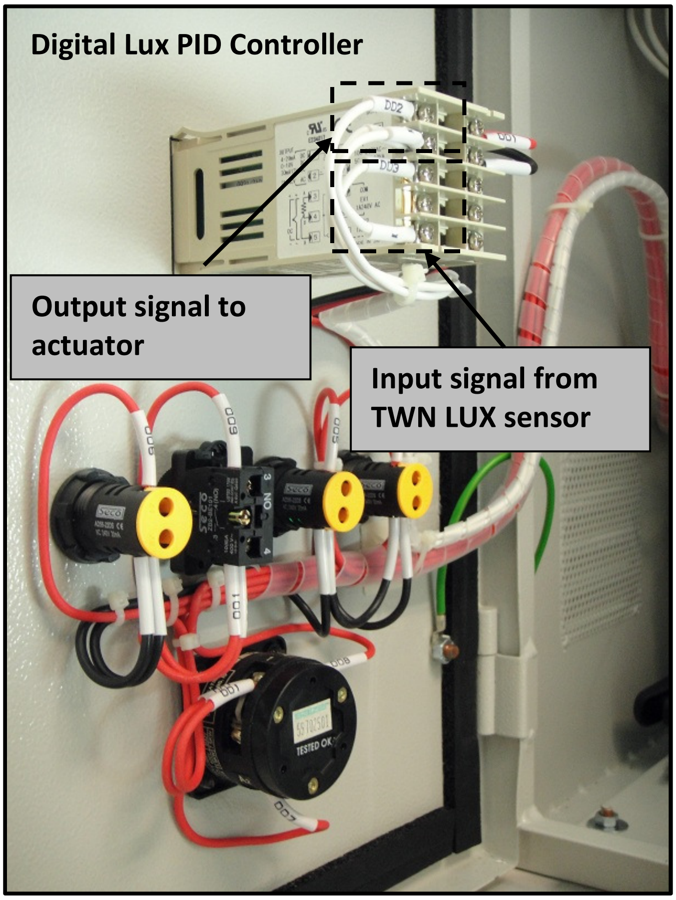


Figure 5.18: Wiring of the feedback path of digital lux PID controller.

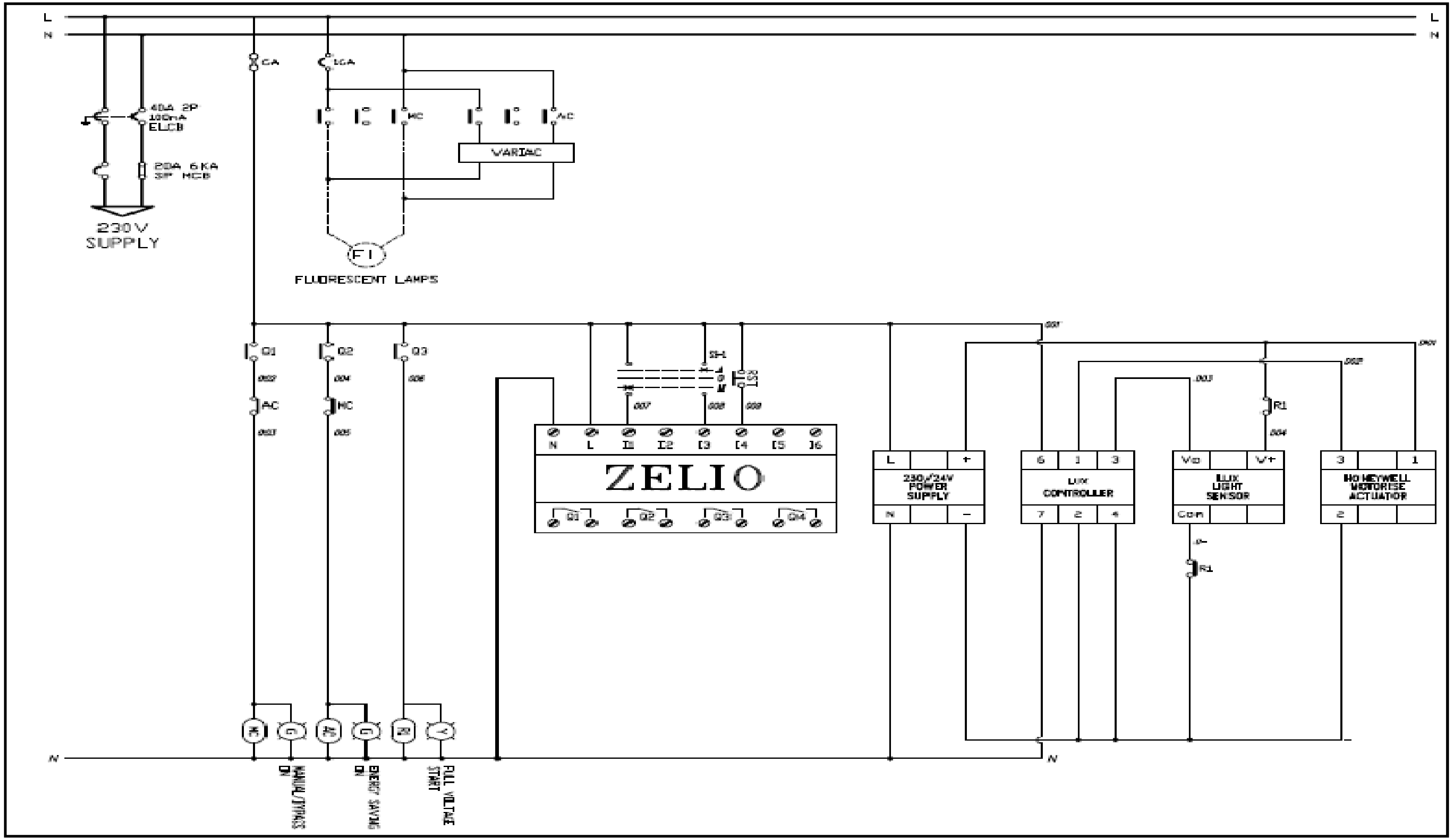
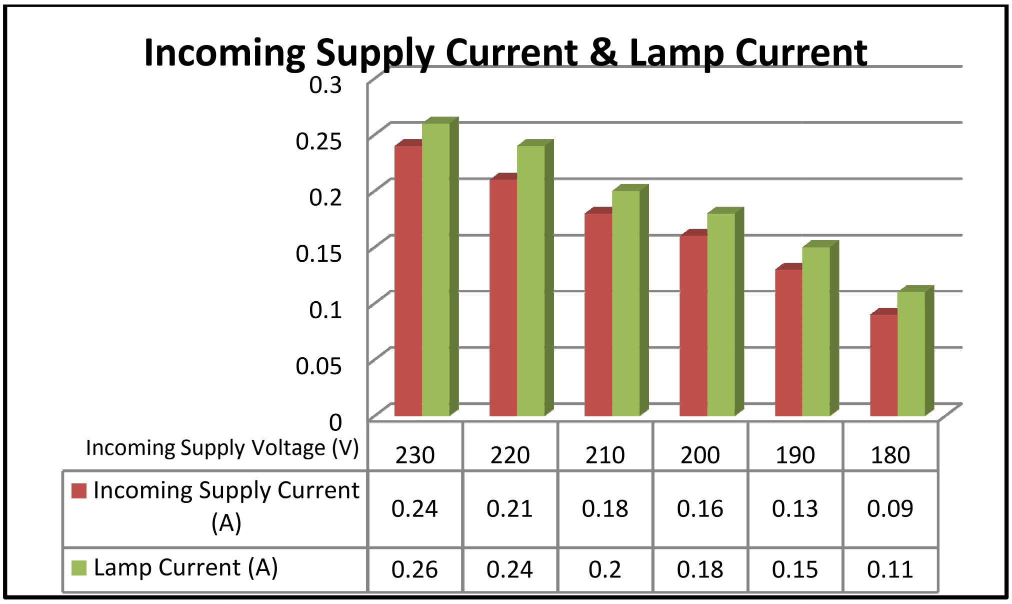


Figure 5.19: Circuit configuration of energy saving controller

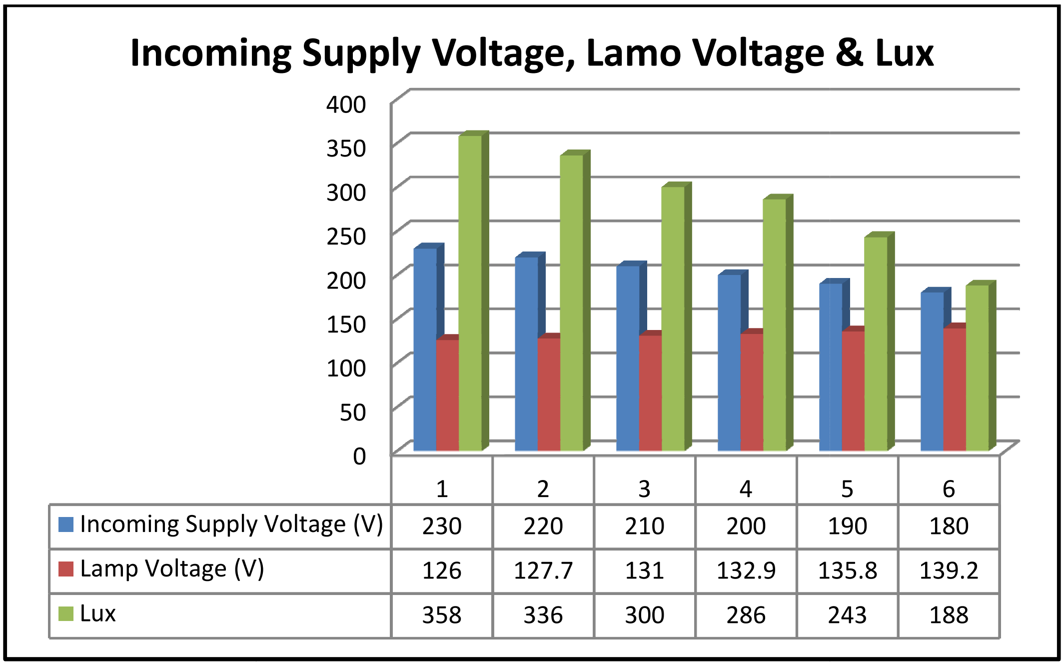
Figure 5.19 shows the block diagram of the forward path and components connection of the controller of Figure 5.15 (the dc supply, PLC, actuator, lux intensity sensor, as well as the contactors, ac supply and florescent lamps)

5.3.2 Implementation results



Incoming Supply Voltage (V)	230	220	210	200	190	180
🟥 Incoming Supply Current (A)	0.24	0.21	0.18	0.16	0.13	0.09
🟩 Lamp Current (A)	0.26	0.24	0.2	0.18	0.15	0.11

Figure 5.20: Incoming supply voltage versus incoming supply current and fluorescent lamp current.



	1	2	3	4	5	6
🟦 Incoming Supply Voltage (V)	230	220	210	200	190	180
🟥 Lamp Voltage (V)	126	127.7	131	132.9	135.8	139.2
🟩 Lux	358	336	300	286	243	188

Figure 5.21: Relationship between incoming supply voltage, fluorescent lamps voltage and illuminance level.

Figure 5.20 shows that the incoming supply voltage has a linear relationship with incoming supply current as well as the fluorescent lamp current. Experimental results prove that the reduction of incoming supply voltage leads to reduction of incoming supply current. Hence, the energy consumption of energy saving controller can be reduced by controlling the incoming supply voltage to predefined value after the preheating period of electromagnetic ballast fluorescent lamps.

Figure 5.21 confirms that the illuminance level of electromagnetic ballast fluorescent lamp can be controlled by using voltage reduction method. Experiment results show that by reducing the incoming supply voltage from 230 V to 180 V, 67% reduction on illuminance level and 75% reduction on the energy consumption of electromagnetic ballast fluorescent lamp can be achieved. It can be concluded that reduction on incoming supply voltage has a huge impact on the input power as well as the fluorescent tube power.

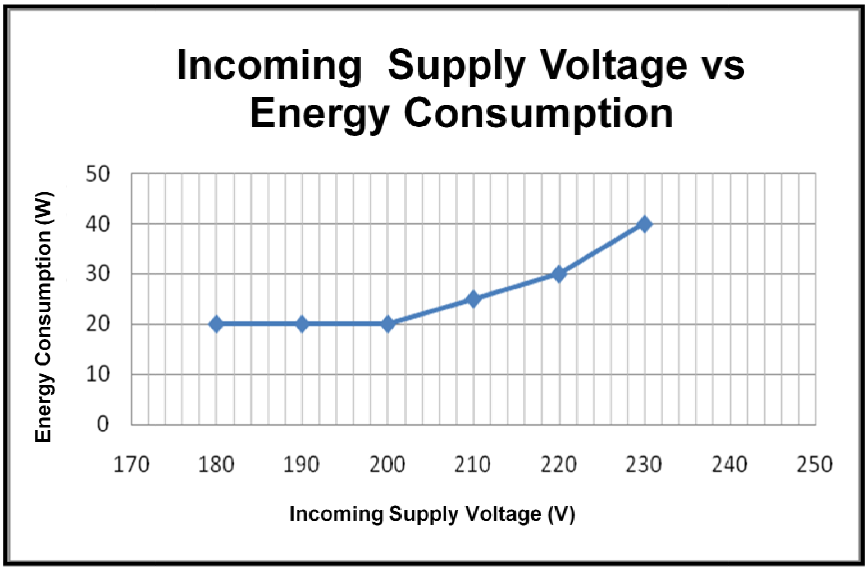
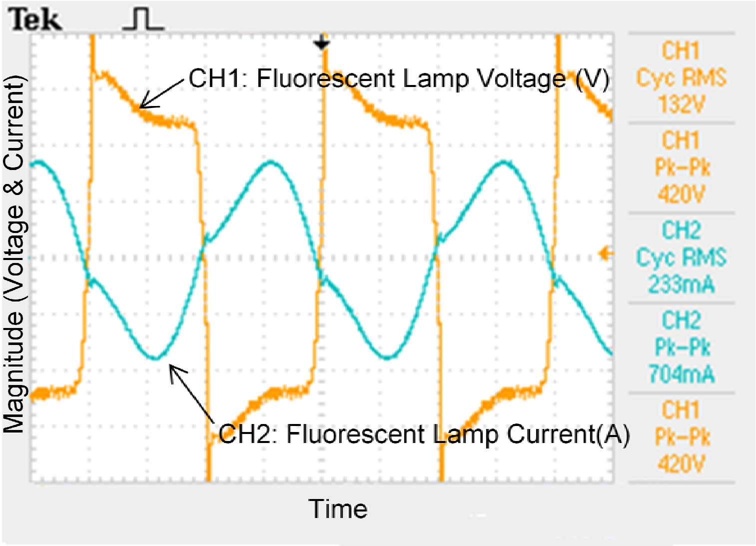


Figure 5.22: Incoming supply voltage versus energy consumption of fluorescent lamps.

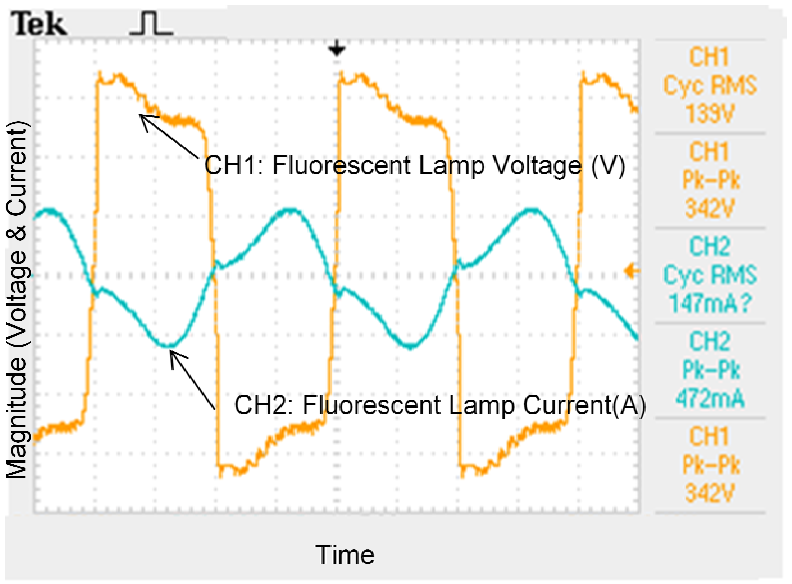
Figure 5.22 shows the relationship between input power (energy consumption of the GE fluorescent lamps) and the incoming supply voltage. When incoming supply voltage is set to 230 V, the energy consumption of GE fluorescent lamps is 40 W. By reducing the supply voltage to 180 V, the energy consumption of GE fluorescent lamps drops to 20 W, results in 50% power saving.

Based on the experimental results in Figure 5.23 and Figure 5.24, it can be concluded that at least 37.5% of energy can be saved by reducing incoming supply voltage to 210 V (optimum voltage). The illuminance level at 210 V is 300 lux, which is only 16% lower than 358 lux at 230 V. This small difference in the luminous flux is not detectable by human eyesight.



Lux PID controller setting	**Experimental results**
Set variable: 300 lux	Energy saving controller output voltage: 210 V
Process variable: 310 lux	Fluorescent lamp voltage: 132 V
Transient period: 6 s	Fluorescent lamp current: 0.23 mA

Figure 5.23: Voltage reduction with lux PID illuminance level control at 300 lux.



Lux PID controller setting	**Experimental results**
Set variable: 190 lux	Energy saving controller output voltage: 180 V
Process variable: 182 lux	Fluorescent lamp voltage: 139 V
Transient period: 23 s	Fluorescent lamp current: 0.15 mA

Figure 5.24: Voltage reduction with lux PID illuminance level control at 190lux.

5.4 Chapter summary

In this chapter, an energy saving controller for electromagnetic ballast fluorescent lamps has been developed. The key element of the energy saving controller is Zelio programmable logic controller SR2B122BD which controls the interaction between the lux intensity sensor, lux PID controller, energy saving and bypass control system. Experiment results show that the energy saving controller may turn the “traditional” non-dimmable electromagnetic ballast into dimmable with energy saving feature and illuminance level control.

The function of energy saving controller includes controlling the illuminance level of working environment lightings under different conditions (when the surrounding is dark or bright). From this, the illuminance level of working environment lightings can be maintained and energy consumption of electromagnetic ballast fluorescent lamps can be reduced. The experimental results in this chapter clearly indicate the energy saving potential of electromagnetic ballast fluorescent lamps.

In addition, the energy saving controller is extended with time scheduling control capability, where the switching of lighting systems can be controlled at predetermined times based on occupancy schedule. Moreover, the lighting occupancy schedule can be programmed by using Zelio soft2 programming software or using front panel of Zelio programmable logic controller.

In order to ensure power system stability, the energy saving controller provides automatic backup power system to electromagnetic ballast fluorescent lamps network. In case of automatic system failure, the controller is bypassed and the fluorescent lamps will operate at full rated voltage.

CHAPTER 6: COST ESTIMATION OF ENERGY SAVING CONTROLLER

6.1 Introduction

In order to demonstrate the practicability and to further support the energy saving potential of energy saving controller, the cost estimation and break even analysis of the energy saving controller is highlighted in this chapter.

6.2 Estimate energy consumption of electromagnetic ballast fluorescent lamps

A scenario based on a 24 hours manufacturing factory with 50 numbers of electromagnetic ballast fluorescent lamps is considered to facilitate the calculations and appropriate comparison of estimated energy consumption and electricity costs with and without energy saving controller. According to Tenaga Nasional Berhad Tarrif D:033, [40] electricity cost for factory A (without energy saving controller) will cost RM 517.82 monthly. In contrast, electricity cost for factory B with same capacity and operating hours, but installed with energy saving controller only cost RM 323.64 per month.

By installing this controller, the electricity cost can be significantly reduced by at least RM 194.18 per month, which is equivalent to 37.5% of energy consumption. For small and medium enterprise (SME), this saving will definitely reduce the operation cost and therefore, lower the overhead cost and maximise profit gained. The energy consumptions of electromagnetic ballast fluorescent lamps are calculated as follows:

Existing energy consumption Equation 6.1

$$\frac{Number\ of\ FLS \times PFL \times Operating\ hour \times Number\ of\ days}{1000}$$

$$\frac{= 50 \times 40 \times 24 \times 31}{1000}$$

$= 1488\ KWH/$Month

Where FLS represents the number of electromagnetic ballast fluorescent lamps, PFL represents the power of one set electromagnetic ballast fluorescent lamp.

New energy consumption Equation 6.2

$$\frac{ESF \times No\ of\ FLS \times PFL \times Operating\ hour \times Number\ of\ days}{1000}$$

$$= \frac{0.625 \times 50 \times 40 \times 24 \times 31}{1000}$$

$= 930\ KWH/$Month

Total potential energy saved Equation 6.3

$= 1488\ KWH - 930\ KWH$

$= 558\ KWH\ (RM\ 194.18)/$Month

Where ESF represents energy saving factor (based on experimental results of section 5, at least 37.5% energy can be saved by reducing 15% of the incoming supply voltage). FLS represents the number of electromagnetic ballast fluorescent lamps; PFL represents the power of one set electromagnetic ballast fluorescent lamp.

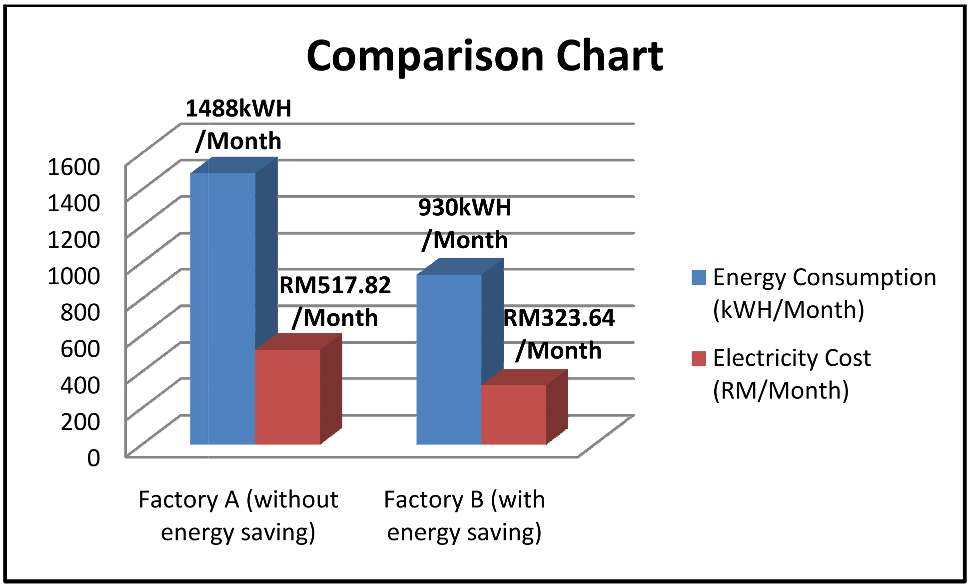


Figure 6.1: Comparison chart of energy consumption and electricity cost.

6.3 Installation cost of energy saving controller

In general, the lifespan of energy saving controller is more than 10 years. However the energy saving controller should not be used in any of the working environments below, as it may cause instruments damage, fire or have its lifespan shortened.

1. Flammable gas, corrosive environment, corrosive gas and oil mist can deteriorate electrical insulation are generated or abundant.
2. The operating temperature is below -10℃ or above 50 ℃.
3. The operating relative humidity should not exceed 90%.
4. Operating conditions where highly intense vibration or impact is generated or transferred.
5. Places exposed to direct sunlight.

The installation is a onetime cost which is cost efficient especially for small and medium enterprises (SME). The installation cost of RM 5000 will include the following components:

Table 6.1: Estimate installation cost of 3.5 KVA Energy saving controller

Item	**Description**	**Cost (RM)**
1	IP21 indoor wall mounted energy saving control panel c/w :- 3.5 KVA variable autotransformer Lux intensity sensor Lux PID controller Programmable logic controller	3500.00
2	Site modification job :- To modify existing fluorescent lamps wiring into energy saving control	500.00
3	Installation and wiring works for lux intensity sensor	1000.00
	Total	**5000.00**

By installing energy saving controller, 558 KWH of energy and 3620 kg of CO_2 emission can be avoided annually. As a result, the controller can also contribute to environment friendly and global warming from reducing the emission ofCO_2 when the lighting power consumption is reduced, and consequently the gas emission of power source will reduce.

6.4 Break-even analysis of energy saving controller

The break even period of the energy saving controller

$$= \frac{Installation\ cost}{Projected\ electricity\ charge\ saved\ per\ month} \qquad \text{Equation 6.4}$$

$$= \frac{RM\ 5000.00}{RM\ 194.18/Month}$$

$\approx$ 26 Months

The installation cost of energy saving controller is RM5000.00. However by comparing the installation cost against projected saved electricity, the break even period of the energy saving controller is around 26 months. After the breakeven period, the investor can enjoy the direct benefits of energy and cost saving from the energy saving controller.

CHAPTER 7: CONCLUSION

7.1 Conclusion

Fluorescent lamps technology has proven to be one of the most efficient and cost effective lightings. However, most of the fluorescent lamp systems are over designed to ensure that the lamps can generate a minimum illuminance for commercial buildings. This minimum illuminance assurance comes with a high price that is huge amount of excess energy consumption. Therefore illuminance level of the working environment should be minimised and maintained based on Australia Standard Authority (ASA).

The energy consumption issue has been addressed in this study. A complete model of energy saving controller for electromagnetic ballast fluorescent lamps has been designed and simulated in Matlab Simulink simulation software. The fluorescent lamp model was derived based on the relationship of fluorescent lamp voltage, fluorescent lamp current and also the dynamic resistance characteristics of electromagnetic ballast fluorescent lamps. Simulation results show that energy saving feature of electromagnetic ballast fluorescent lamps can be achieved by reducing the incoming supply voltage from 230 V to 180 V.

Beside simulation evaluation, the energy saving controller had been implemented in order to confirm the energy saving potential of electromagnetic ballast fluorescent lamps. The major components of energy saving controller consist of lux PID controller, lux intensity sensor, programmable logic controller and one variable autotransformer. The functions of the energy saving controller include process control of the dimmable illuminance level, voltage reduction control, preheating feature, earth leakage protection, backup power system and time schedule function.

The energy saving controller controls the incoming supply voltage of electromagnetic ballast fluorescent lamps. The reduction in incoming supply voltage leads to reduction in current drawn by the lamps. As a result, the energy consumption of electromagnetic ballast fluorescent lamps can be reduced (energy consumption of fluorescent lamps is proportional to the square of the reduction voltage). The hardware implementation results in this study clearly indicate that at least 37.5% energy can be saved by reducing 15% of the incoming supply voltage.

Unlike individual electronic dimmable ballast fluorescent lamps, the energy saving controller can provide centralised control for electromagnetic ballast fluorescent lamps networks. Besides, it is compatible to the existing electromagnetic ballast fluorescent lamps network, thus major modification of electrical wiring is unnecessary. As a result, large electromagnetic fluorescent lamps networks can be controlled by installing only one central energy saving controller. Other advantages of the energy saving controller are as follow:

1. Provide dimmable illuminance level control to electromagnetic ballast fluorescent lamps.
2. With the help of energy saving controller, the lifespan of electromagnetic ballast can be extended. This has been confirmed by US environment agency.
3. Energy saving controller is suitable to operate in extreme weather condition.
4. Low initial cost.

5. Low maintenance cost as the components of energy saving controller are common and easily available in the market.
6. The reduction of energy consumption leads to the reduction of power plant's carbon dioxide emission.
7. High robust and reliability

The estimated installation cost of the energy saving controller for 50 electromagnetic fluorescent lamps is RM 5000.00. From economic point of view, the break even period of the energy saving controller is around 26 months. After the breakeven period, the investor will gain profit and electricity cost saving from the energy saving controller. Experiment results indicate that installing energy saving controller in electromagnetic fluorescent lamps can diminish fossil fuel dependence and reduce green house gas emission from significant reduction in energy consumption.

Overall, the objectives of this study had been achieved. The system that was analysed has given a big picture of the design of energy saving controller for electromagnetic ballast fluorescent lamps. This successful design will bring in new and great ideas for energy saving in the use of electromagnetic ballast fluorescent lamps, and it also provides a global environmental friendly solution for the future.

7.2 Recommendation for future work

A centralised energy saving controller for electromagnetic ballast fluorescent lamps had been developed in this study. In order to improve the performance of energy saving controller, the following recommendations for future work are proposed:

1. Integrate the energy saving controller with building management system (BMS). As a result, the switching of fluorescent lamps and illuminance level can be controlled and monitored by using computer based software or human machine interface (HMI) touch screen.

2. Currently the energy saving controller is only applicable for electromagnetic ballast fluorescent lamps. However the design can be extended to provide energy saving feature for other types of discharge lamps such as metal halide lamps, mercury vapour lamps and sodium lamps.

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APPENDICES

A1 Parameter setting of lux PID controller

Appendix A1 contains the parameter setting of lux PID controller under study. The lux PID controller of this system is a microprocessor controller instrument, that is configurable as auto & manual PID controller, where the microprocessor will performs automatic computation and adjust the proportional band setting, integral time setting and derivative time setting of the lux PID controller. On the other hand, these parameters can also be set manually by the end user. Table A.1 presents the parameter setting of lux PID controller for the energy saving controller.

Table A.1: Parameter setting of lux PID Controller

Mode no.	Screen Title	Setting range	Setting
1 - 0	Initial screen	Initial screen	Initial screen
1 – 1	Key lock setting	Off, 1 ~ 3	2
1 – 2	Proportional band setting	Off, 0.1 ~ 999.9%	300
1 – 3	Hysteresis setting	1 ~ 999 unit	NA (PID control)
1 – 4	Internal time setting	Off, 1 ~ 6000 sec	150
1 – 5	Derivative time setting	Off, 1 ~ 3600 sec	50
1 – 6	Manual reset setting	-50 ~ 50%	3
1 – 7	Target value function setting	Off, 0.01 ~ 1.00	0.4
1 – 8	Lower limit output limiter setting	0.0 ~ 99.9%	0
1 – 9	Higher limit output limiter setting	0-L+0.1 ~ 100.0%	100
1 – 10	Proportional cycle time setting Y, P is output	1 ~ 120sec (Y:30, P:3)	NA
1 – 11	EV1 type code setting	Off, Hd ~ So	Off
1 – 12	EV1 hysteresis setting	1 ~ 999 unit	NA
1 – 13	EV1 standby action setting	1 ~ 4	1
1 – 14	EV2 type code setting	Off. Hd ~ So	Off
1 – 15	EV2 hysteresis setting	1 ~ 999 unit	NA
1 – 16	EV2 standby action setting	1 ~ 4	1
1 – 17	Control output characteristics setting	rA / dA	dA
1 – 18	SV lower limiter setting	0 ~ 800	0
1 – 19	SV higher limiter setting	0 ~ 800	500

1 – 20	PV bias value setting screen	-1999 ~ 2000 unit	0
1 – 21	PV filter time setting screen	0 ~ 100sec	10
1 – 22	Measuring range code setting screen	81 ~ 86	85
1 – 23	Input unit setting screen	C / F	C
1 – 24	Input scaling lower limit value setting	-1999 ~ 9999 unit	0
1 – 25	Input scaling higher limit value setting	-1999 ~ 9999 unit	1000
1 – 26	Input scaling decimal point setting	None ~ 0.001 digit on right of decimal pint	0.0

A2 Technical specification of lux intensity sensor

Lux intensity sensor is a device that converts a measured illuminance level into an analogue signal. Table A.2 shows the technical specification of lux intensity sensor. The power supply of lux intensity sensor is 12 – 24 V DC voltage., The lux intensity sensor support two types of analogue signal, it can be in the form of voltage signal (0 – 10 V) or current signal (4 – 20 mA). However only one analogue signal needs to be connected as presented in Figure A.1. Beside the discussion of the technical specifications and connection of the sensor, this section also discusses the mounting instruction, wiring and commissioning procedures in details.

A2.1 Specification

Table A.2: Technical specification of lux intensity sensor

Function	Description
Input	Adjustable from 1 – 10 lux to 0 – 1000 lux nominal, standard calibration. Turn pot fully clockwise = 0 – 10 lux nominal, standard calibration. Turn pot fully anticlockwise = 0 – 1000 lux nominal, standard calibration Note: Pot requires 25 turns to go from one end to the other.
Output	Voltage: 0 – 10 V. Output impedance = 1 kΩ Note: with a 12 V supply output may only rise within approximate 95% FSO Current: 4 – 20 mA, 3 wire. Maximum load = 300 Ω@12 V, Maximum load = 900 Ω@24 V.
Power supply	12 – 24 V
Current draw	Voltage output: 20 mA @ 24 V P/S with 10 V out Current output: 40 mA @ 24 V P/S with 20 mA out
Operating temperature & Humidity	0 - 60°C (Storage temperature: -20 – 80°C) 5 – 85% RH Maximum. None Condensing.
Enclosure	Conduit two way J-box 20 mm

A2.2 Connection diagram

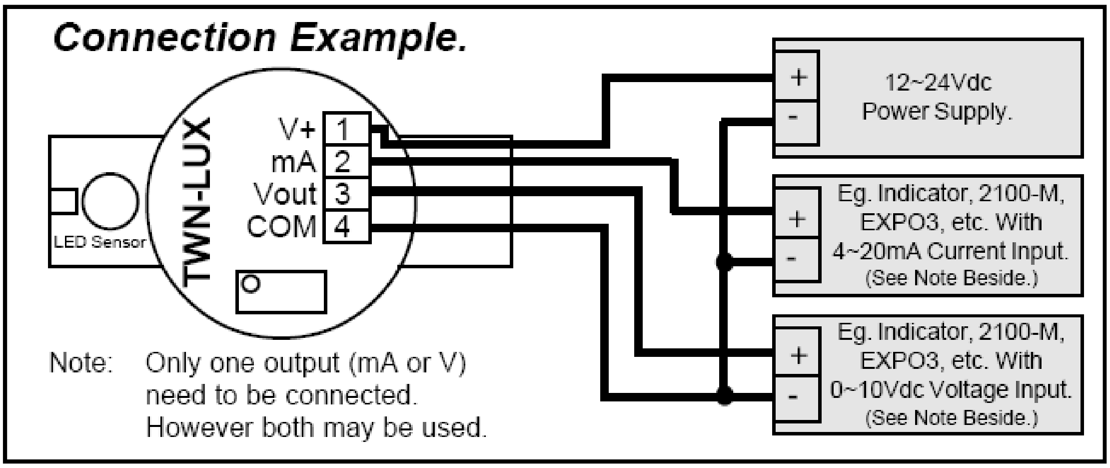

Figure A.1: Connection of lux intensity sensor

A2.3 Mounting instruction

1. Mount in a clean environment away from power control equipment. Be mindful of positioning the light sensor, (mounted at the end of the enclosure) so that the desired level of illumination reaches the sensor. Do Not mount the sensor in direct light or sunlight - measure reflected light.

2. Do not subject to vibration or excess temperature or humidity variations.

A2.4 Wiring

1. All cables should be good quality overall screen instrumentation wire only with the screen earthed at one end only.

2. Signal cables should be laid a minimum distance of 300mm from any power cables.

3. For 2 wires current loops Austral Standard Cables B5102ES is recommended. For three wire transmitters, RTD's and Resistance Probes, Austral Standard Cables B5103ES is recommended.

4. It is recommended that do not ground current loops and use power supplies with ungrounded outputs.

5. Lightning arrestors should be used when there is a danger from this source.

A2.5 Commissioning

1. Once all the above conditions have been carried out and the wiring checked apply power to the TWN-LUX and allow five minutes for it to stabilise.

2. It is advised to adjust the output of the TWN-LUX to the lux level required using a calibrated lux meter, once the "room" being measured is completed. This is necessary as every installation has a unique reflective pattern, depending on colours, windows, positioning of walls, furniture, etc. Turn the Trimpot clockwise to increase the output reading, and anticlockwise to decrease the output reading.

A3 Technical specification of Shimaden controller

A strong motivation for using automatic PID controller is to correct the error between the SV and PV. Generally the error is caused by disturbance inputs, parameter variations and imperfect modelling [27]. In order to reduce the energy consumption of electromagnetic ballast fluorescent lamps, the Shimaden PID controller is used to regulate the illuminance level of the workspace. Technical specification of Shimaden PID is shown in Table A.3. The SV, which is the reference illuminance level, is set on the front panel of Shimaden PID controller. In addition, beside display the SV, the front panel of Shimaden PID controller also displays PV value at the front panel as shown in Figure A.2. The front panel of Shimaden PID controller consists of measured value (PV) display, target set value (SV) display, actions display lamps and operating keys. The functions of these parts are listed in Table A.4.

A3.1 Specification

Table A.3: Technical specification of Shimaden controller

Function	Description
Display accuracy	± (0.3% FS + 1 digit)
Display accuracy maintaining	23 ± 5 °C
Measured value display range	Input range or -10 – 110% of measuring range
Setting method	By operating 4 keys on the front panel
Setting limiter	Within the measuring range, individual setting for higher and lower limits. (lower limit < higher limit)
Input type	Multi input, (TC, PT100, JPT100, mV) V (in case of mA input connect receipt resistance between the input terminals)
PV bias	-1999 – 2000 unit
PV filter	0 – 100 seconds
Control mode	Auto tuning PID control, manual control
Type of control output	Relay contact, SSR drive voltage, voltage and current
Output control characteristics	RA / DA switching

Output limiter	Lower limit: 0.0 – 99.9% Upper limit: lower limit + 0.1 – 100.0%
Output event	2 points, EV1 and EV2
Output rating	240 V AC 1A (resistive load)
Event type	Absolute values, deviations, (higher, lower, higher/lower, within, outside)
Event action	On – off action
Standby action	Selectable from 3 types standby mode
Ambient temperature for operational condition	-10 °C - +50 °C
Supply voltage	100 – 240 V ±10% 50/60 Hz
Energy consumption	Approximately 10 VA

A3.2 Names and functions of parts on front panel

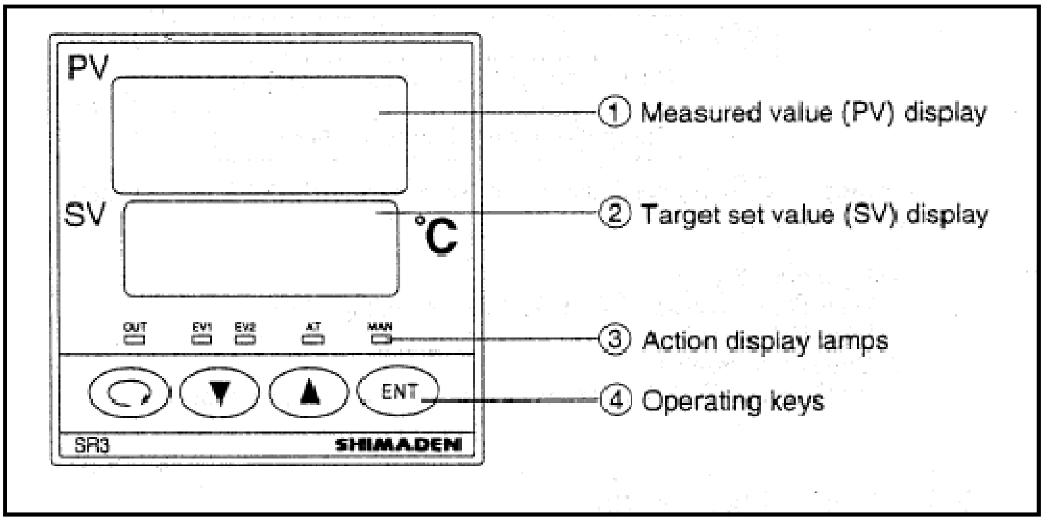

Figure A.2: Front panel of Shimaden controller

Table A.4: Functions of parts on front panel

Function	Description
Measured value display	Display measured value (PV) or each type of parameter signs (red)
Target set value display	Display target set value (SV), each type of parameter set value. Output value is displayed by % on control output monitor screen of the screen group 0 (green)
Action display	1. **Out (green) / control output display:** Lights when output turns on during contact or SSR drive output contact. Turn off when output is 0% during voltage or current and flashes continuously when output is 100%. 2. **EV1, EV2 (orange) / event output display:** Light during event output. 3. **AT (green) / auto tuning action display:** Flashes when ON key is selected by “up key” pm the AT action selection screen and AT is executed by “registration key” and goes out when AT terminates automatically release. 4. **MAN (green) / manual control action display:** Flashes when manual control action mode is selected.
Operating keys	1. **Parameter key:** Pressing this key on any screen of the screen group 0 and the screen group 1 call the next screen onto display. When pressed continuously for 3 seconds, this key function to move toward the basic screen of screen group 0 and the initial screen of screen group 1. 2. **Down key:** When pressed on each of the screen, the decimal point of the rightmost digit flashes and the set data decreases or moves backward. 3. **Up key:** When pressed on each of the screen, the decimal point of the rightmost digits flashes and the set data increases or moves forward. 4. **Registration (entry) key:** Used to register a set data changed by means of “up key” or “down key” on a parameter screen. (The flashing right most digit turn off). When press continuously for 3 seconds on the control output screens (mode 0 to 1), this key functions to switch between the manual control mode (Man flashes) and the automatic control mode (Man turns off)

A4 Technical specification of Honeywell actuator

The motorised actuator control system is a closed- loop to control the motion of non-spring return direct-coupled actuator, in close correspondence to a reference DC voltage analogue signal (typically 0 – 10 V). Figure A.3 shows the non-spring return actuator. In the energy saving controller, the non-spring return actuator is coupled with the variable autotransformer in order to regulate the output voltage of energy saving controller. As a result, the output voltage of variable autotransformer varies as a function of actuator's motion. Beside the application of non-spring return actuator, section A4.1 covers the technical specification of the actuator. In addition, section A4.2 and A4.3 provide a brief description on the control methods of non-spring return actuator control system.

The non-spring return direct-coupled damper actuator provides modulating and floating / 2-positions control for the following application:

1. Air dampers
2. VAV units
3. Air handlers
4. Ventilation flaps
5. Louvers
6. Reliable control for air damper applications with up to 10 square feet / 44 lb-in. (5 Nm) and 20 square feet / 88 lb-in (seal-less damper blades; air friction-dependent)

The functions non-spring return direct-coupled damper actuator provides as listed below,

1. Declutch for manual adjustment.
2. Adjustable mechanical end limits.
3. Removable access covers for direct wiring.
4. Mountable in any orientation.
5. Function selection switching for selecting modulating or floating / 2 positions control.

Figure A.3: Non-spring returns direct-coupled actuator

A4.1 Specification

Table A.5: Technical specification of Honeywell actuator

Function	Description
Supply voltage	24 V/dc -15% / +20%, 50/60 Hz
Nominal voltage	24 V/dc 50/60 Hz
Modulating control signal	0(2) – 10 V
Floating / 2 positions control	24 V/dc
Ambient operating limits	20 – 60 °C
Ambient storage limits	-30 – 80 °C
Relatively humidity	5 – 95% non-condensing
Protection standard	IP54
Protection class	II as per EN 60730-1
Over voltage category	II
Lifetime	Full strokes: 60000 Repositions: 1.5 million

A4.2 Floating and 2 positions control method

1. Without feedback signal: If, however, the function selection switch has been set to one of the two floating/2-position control settings - but the actuator has not been wired for a feedback signal, then as soon as operating power is applied, the shaft adapter will run according to the control signals applied.

2. With feedback signal: If the function selection switch has been set to one of the two floating/2-position control settings - and if the actuator has been wired for a feedback signal (see Figure A.4 and Figure A.5.) - then as soon as operating power is applied, the shaft adapter will likewise run first completely counter clockwise and then completely clockwise (see also section "Adaption" [32] page 4), after which it will run according to the control signals applied.

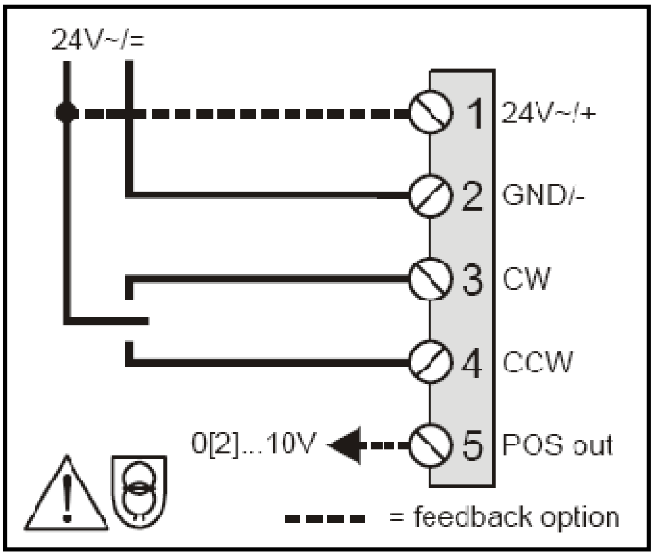

Figure A.4: Actuator connection for floating mode control

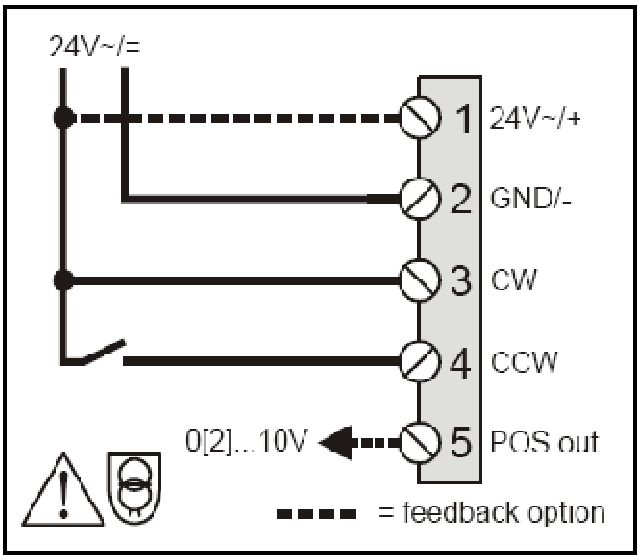

Figure A.5: Actuator connection for 2 positions mode control

A4.3 Modulating control method

If the function selection switch has been set to one of the four modulating control settings - and if the actuator is wired correspondingly, then as soon as operating power is applied, the shaft adapter will run first completely counter clockwise and then completely clockwise after which it will run according to the control signals applied.