CB2008
CONGRESSO BRASILEIRO DE AUTOMÁTICA

An Introduction to Efficient Lighting

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Outline

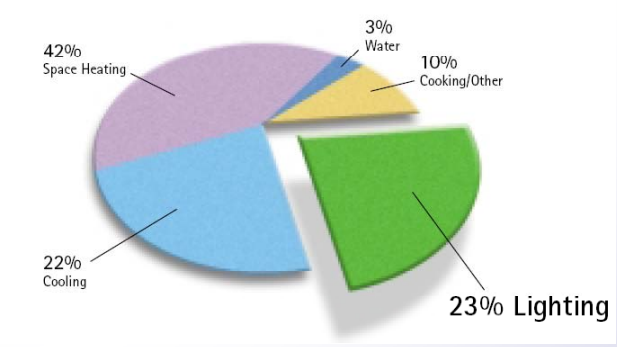
- Introduction
- Lamps
- Ballasts
- Digital Control
- Conclusions

Introduction

- First idea:
  - Light accounts for nearly 25% of the electrical energy consumption in the industrialized world

Introduction

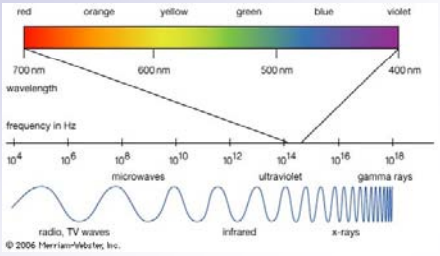
- Percentage of energy use in commercial buildings by end user



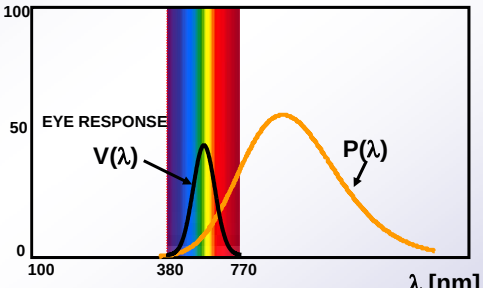
Lighting is a nice piece of the pie

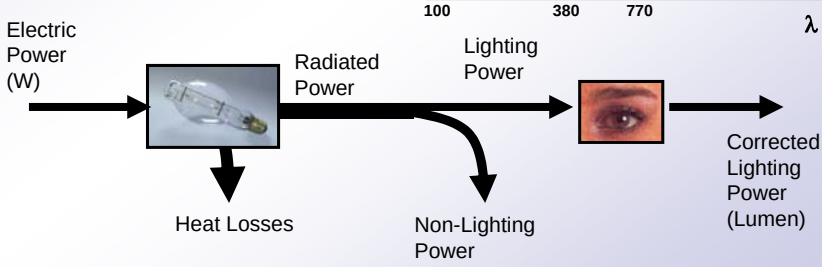
Some Basic Concepts

Electromagnetic Spectrum



Human's Eye Response



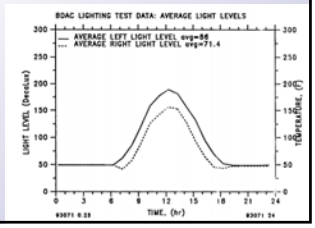


Basic hints for energy saving in lighting:

- Select the adequate light source for each application
  - Incandescent
  - Discharge

- Select the adequate auxiliary equipment:
  - Magnetic ballast
  - Electronic ballast
  - Dimming circuit

- Select the adequate control strategy:
  - Scheduling
  - Task tuning
  - Daylighting
  - Lumen maintenance
  - Presence detection …



Some countries are already taking actions:

Australia

- Traditional light bulbs will be banned by 2010 in Australia
- This will lead to a reduction of 800.000 tons of CO_2 per year
- Total CO_2 produced annually in the world is 564 Mtons (2004)

European Union

- The least efficient lamps will be phased-out from the European market by 2015
- The industry will have to switch to energy saving CFL or high-efficient halogen lamps

As a result (future):

- Reduction of 23 M tons of CO_2 emission per year
- 63,000 GWh of energy saved per year

Outline

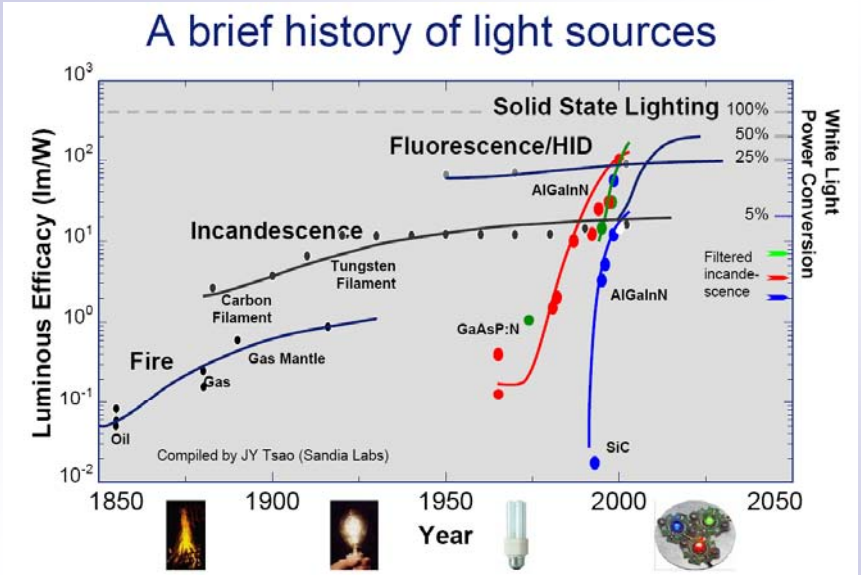
- Introduction
- Lamps
- Ballasts
- Digital Control
- Conclusions

Evolution of Lighting in History

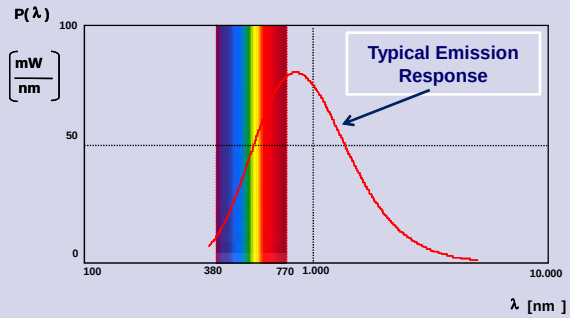
Open wood fire | Oil | Filament | Gas discharge

Solid State

- Solid state is not yet a full mature technology
- The most efficient and long-lasting lamps are still based on electrical discharge

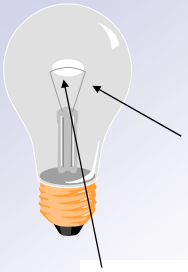


Incandescent Lamps

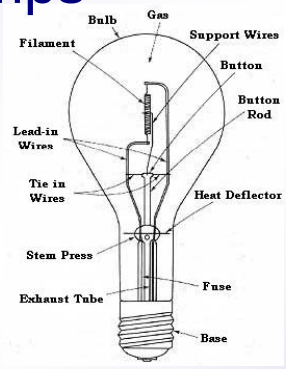


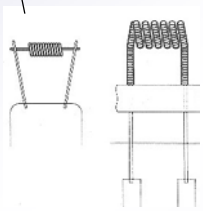
MATERIAL	MELTING TEMP. [K]	DENSITY [gr/cm³]	RESISTIVITY 20°C
Copper	1.367	8.9	0.018
Tungsten	3.668	19.1	0.04
Carbon	3.803	1.5	40.00

Incandescent Lamps



Filling gas:
Vacum for P< 40W
N + Ar, Kr, Xe: P>40W



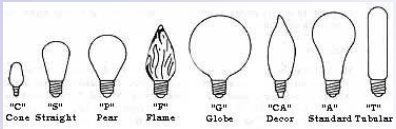


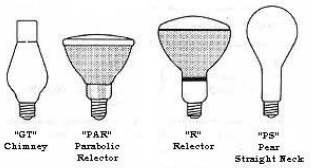
Tugnsten (Wolfram) Filament

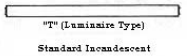
BASIC CHARACTERISTICS:

1.- Instant Ignition
2.- Very Good Color Rendering Index (CRI)
3.- Low Luminous Efficacy: 10-20 lm/W
4.- Short Life: 1000-2000 hours

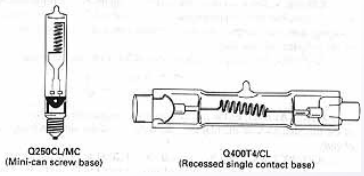
Incandescent Lamps





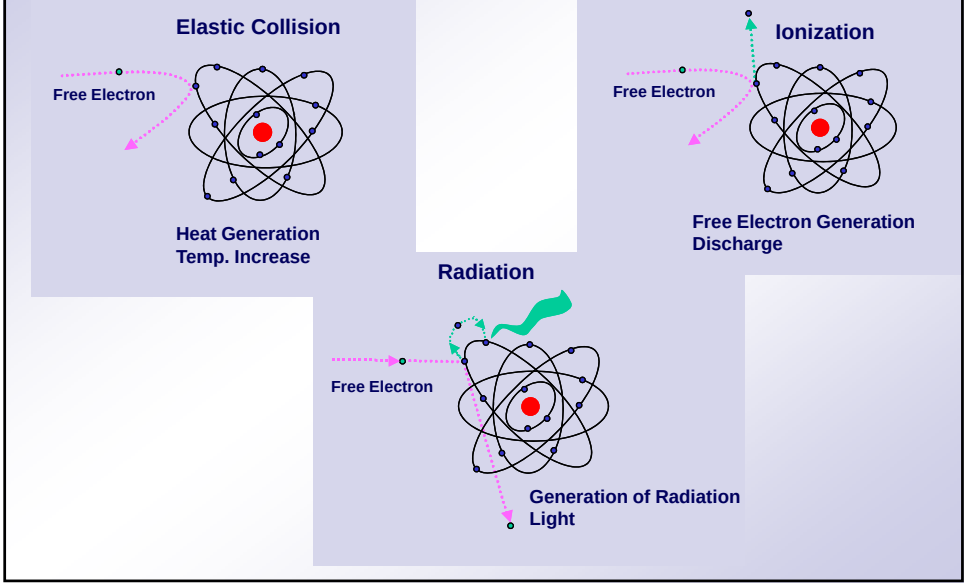


Standard Incandescent



Lamps

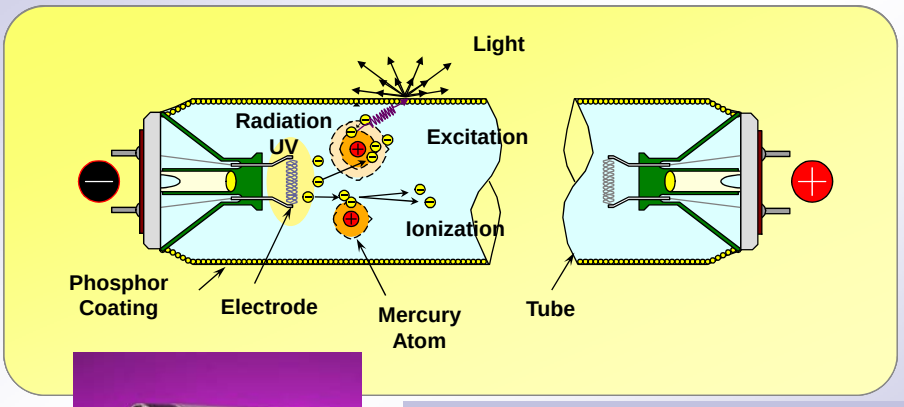
Discharge Lamps

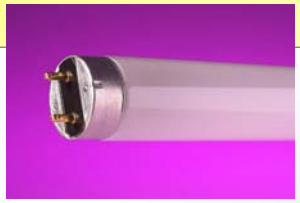


Lamps

Fluorescent Lamp

Basic Operation



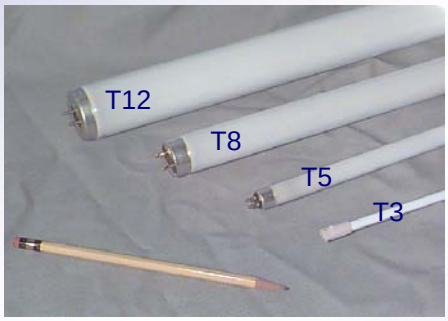


BASIC CHARACTERISTICS:

1.- Operation at 0.8-1 atm.
2.- Good Color Rendering Index (CRI)
3.- High Efficacy: 60-00 lm/W
4.- Long Life: 10,000 hours

Lamps

Linear Lamps



T12: 38 mm
T8: 25 mm
T5: 15 mm
T3: 9 mm

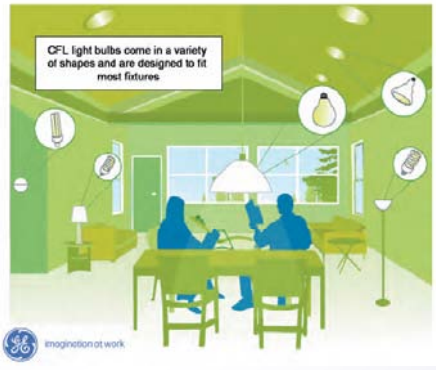
Compact Lamps

Lamps

Compact Fluorescent Lamps

With Integrated Ballast

They are a direct replacement
For Incandescent Lamps



Recommended for lighting points with burning hours higher than 1 hour per day continuously

Compact Fluorescent Lamps

With Integrated Ballast

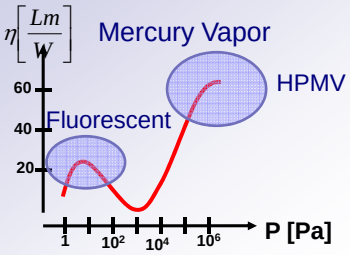
Incandescent	Energy-saving
15 W	3 W
25 W	5 W
35 W	7 W
60 W	11 W
75 W	15 W
100 W	20 W
120 W	23 W
150 W	30 W

Many different models, with different functionalities, are available

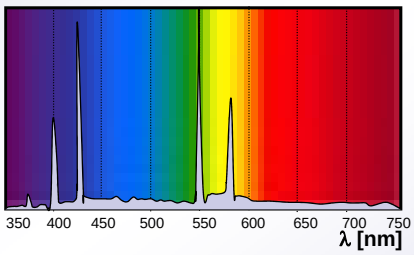
Expected Payback Time in Years for CFL

	CFL Purchase Price					
Hours used per day	$3	$6	$9	$12	$15	$18
1	2.0	4.0	5.9	7.9	9.9	11.9
2	1.0	2.0	3.0	4.0	4.9	5.9
3	0.6	1.2	1.8	2.4	3.0	3.6
4	0.5	0.9	1.4	1.8	2.3	2.7
5	0.3	0.7	1.0	1.4	1.7	2.1
6	0.3	0.6	0.9	1.2	1.5	1.8
7	0.2	0.5	0.7	1.0	1.2	1.5
8	0.2	0.4	0.7	0.9	1.1	1.3

High Pressure Mercury Vapor Lamps



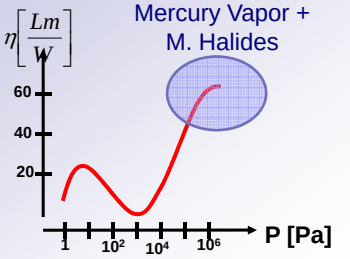
Spectrum



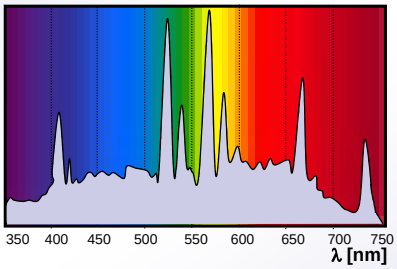
BASIC CHARACTERISTICS:

1.- Operation at 2-4 atm.
2.- Poor Color Rendering Index (CRI)
3.- Good Efficacy: 25-60 lm/W
4.- Long Life: 15,000 hours

Metal Halide Lamps



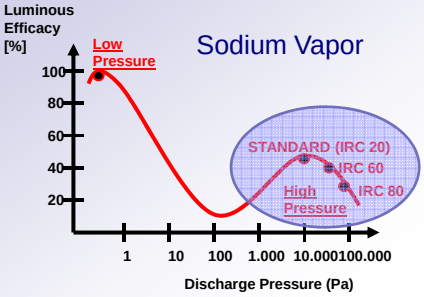
Spectrum



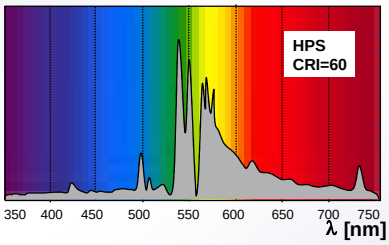
BASIC CHARACTERISTICS:
1.- Incorporate Metal Halides (Tl, Dy, Sc, etc.)
2.- Very Good Color Rendering Index (CRI)
3.- Good Efficacy: 80 lm/W
4.- Medium Life: 6,000 hours

Lamps

High Pressure Sodium Vapor Lamps



Spectrum

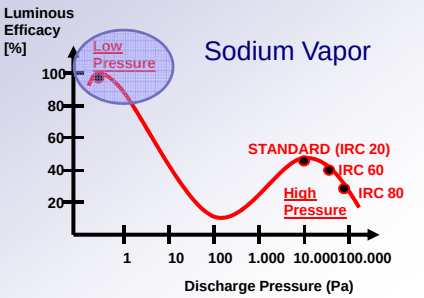


BASIC CHARACTERISTICS:

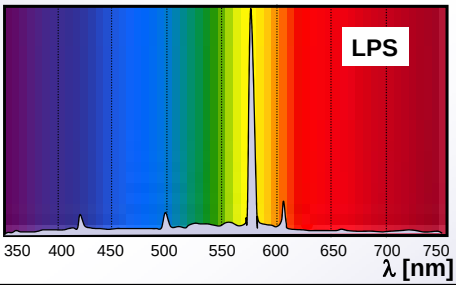
1.- Operation at 7-100 kPa
2.- Medium Color Rendering Index (CRI)
3.- Good Efficacy: 50-120 lm/W
4.- Long Life: 20,000 hours

Lamps

Low Pressure Sodium Vapor Lamps



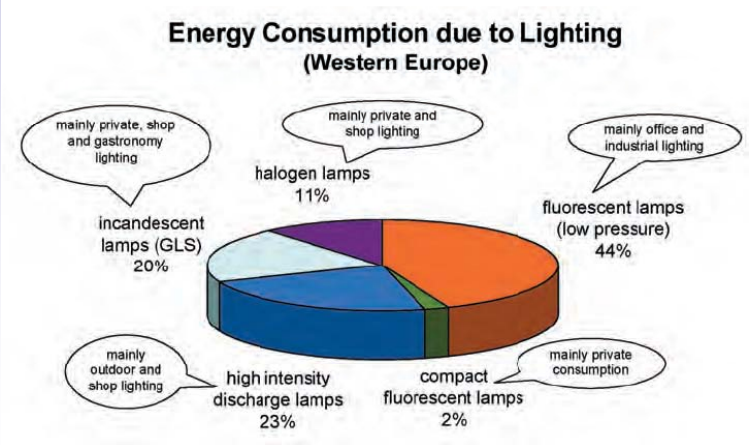
Spectrum



BASIC CHARACTERISTICS:

1.- Operation at 0.4 Pa
2.- Very Poor Color Rendering Index (CRI)
3.- Very Good Efficacy: 60-150 lm/W
4.- Long Life: 15,000 hours

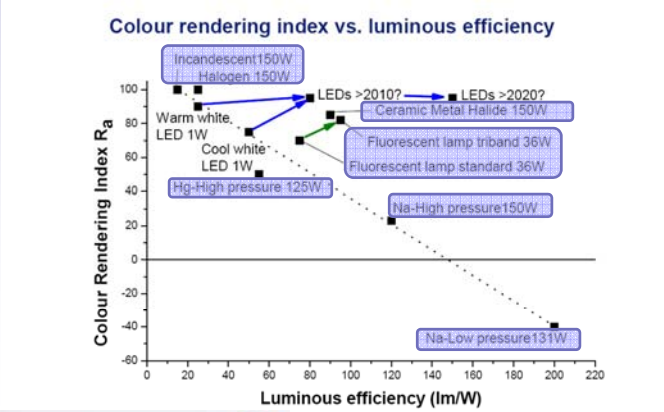
Consumption Distribution



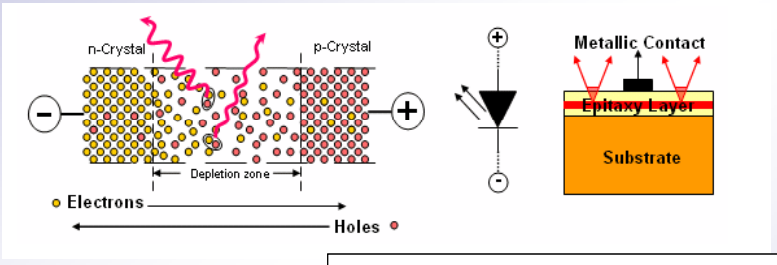
- About 70% of artificial lighting is generated by discharge lamps
- 80% of energy consumption is professional lighting

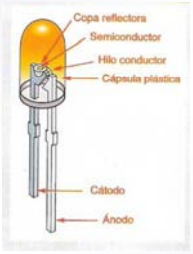
Future Light Sources: LEDs

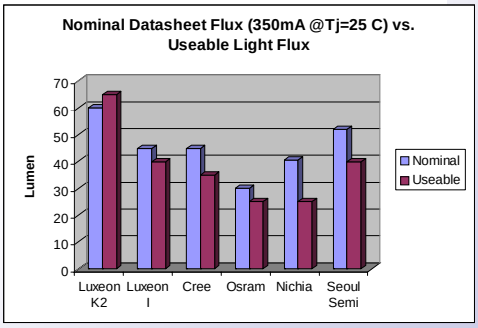
- Evolution of Light Sources: Status Quo 2007



Future Light Sources: LEDs



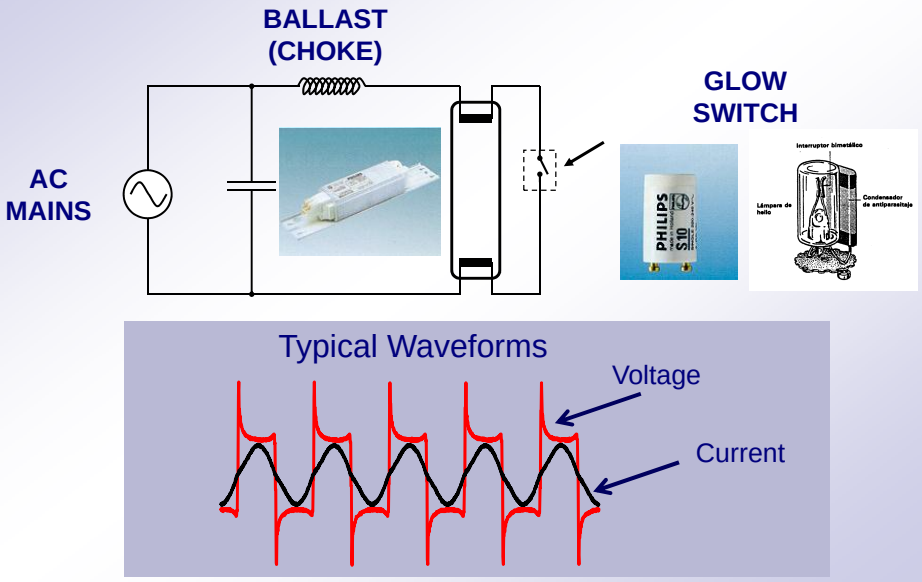




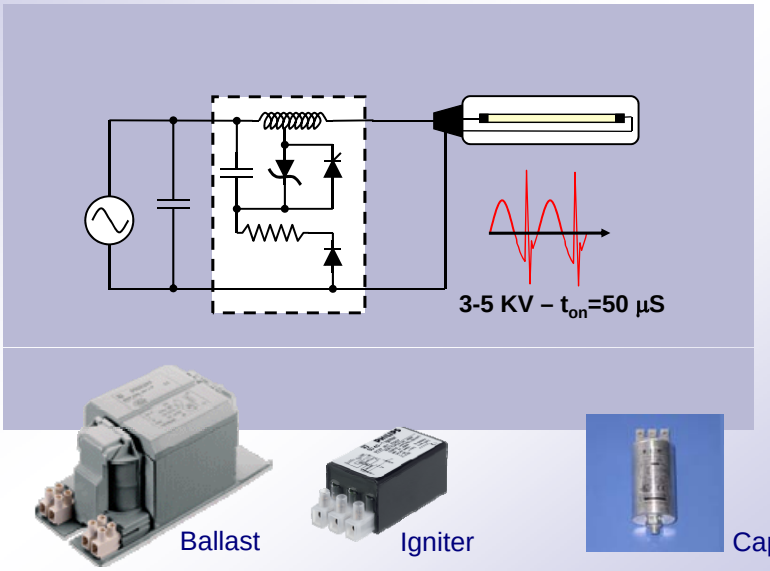
Outline

- Introduction
- Lamps
- Ballasts
- Digital Control
- Conclusions

Typical Electrical Circuit: FL



Ballast and Igniter for HPS Lamp

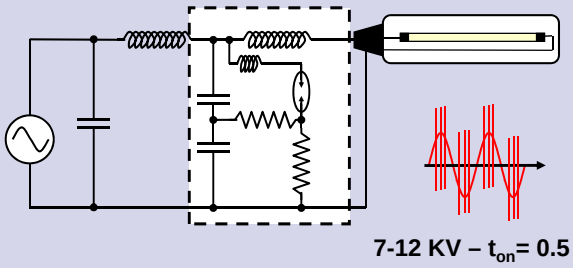


Ballast

Igniter

Capacitor

Ballast and Igniter for MH Lamp



7-12 KV – t_{on}= 0.5 µs

Ballast

Igniter

Lamp

High Frequency Operation

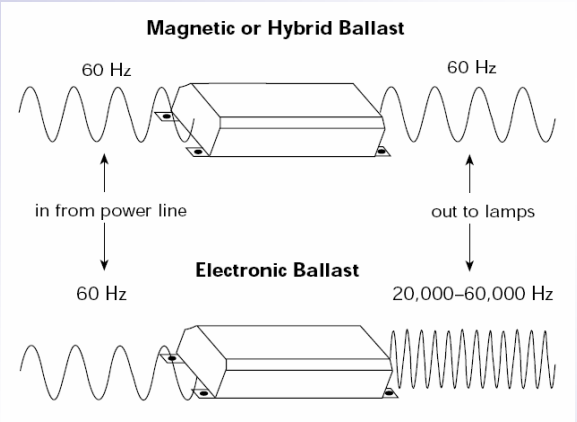
Fluorescent
(Low Pressure Mercury)

Low Pressure Sodium

- In these lamps the increase of frequency provides and increase of luminous efficacy

Ballasts

Electronic Ballast Vs. Magnetic Ballasts

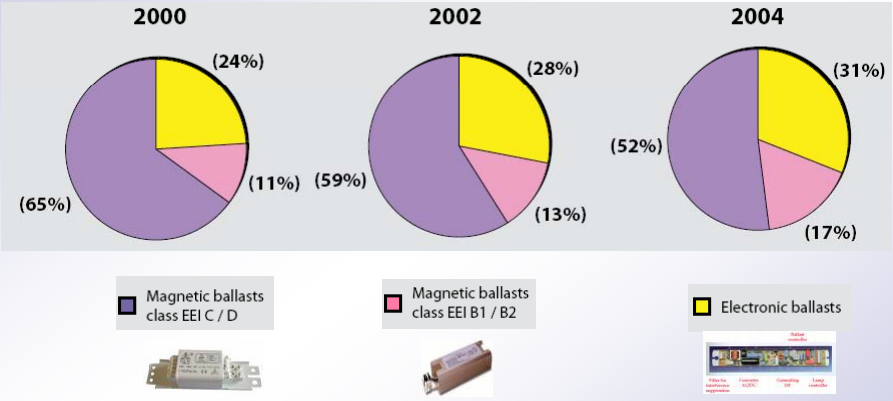


- Operation at low frequency
- High losses, poor efficiency
- Stroboscopic effect
- Acoustic noise (humming)
- High volume and weight

- Operation at high frequency
- Low losses, good efficiency
- No Stroboscopic effect
- No Acoustic noise
- Low volume and weight

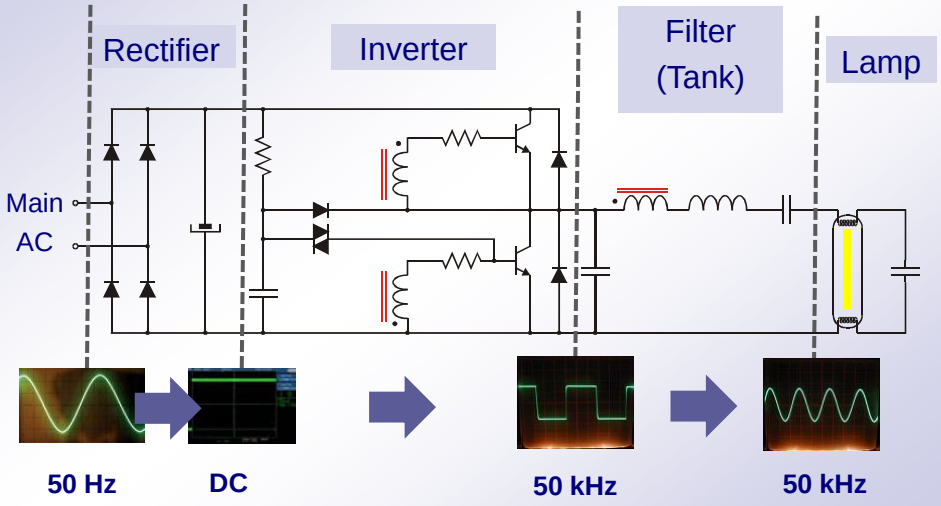
Ballasts

Market share of ballast

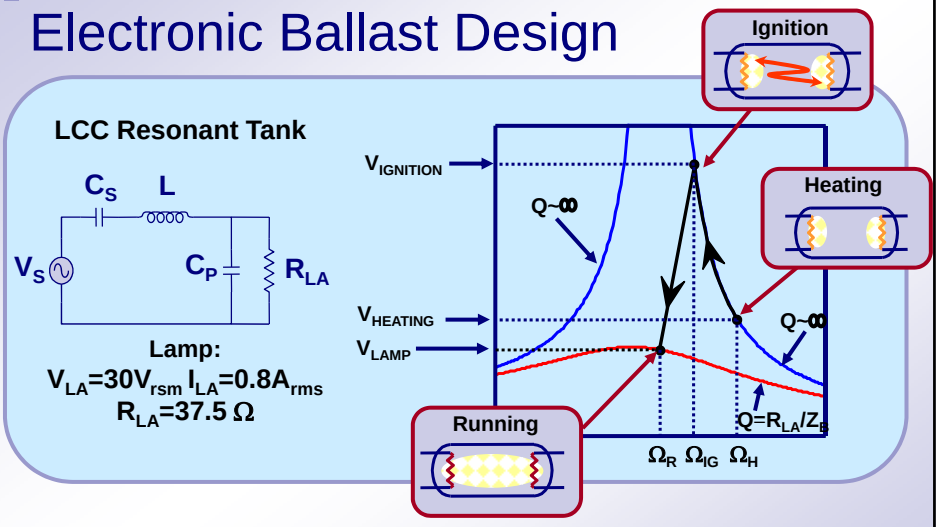


- The market share of electronic ballasts is growing: From 24 % in 2000 to 31% in 2004

Typical Circuit of Electronic Ballast



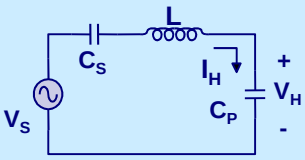
Electronic Ballast Design

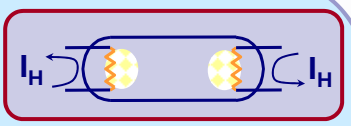


- An LCC resonant tank is used to ignite and supply the lamp
- A soft-starting strategy is implemented in order to increase lamp's life

Electronic Ballast Design

Heating





- The frequency needed for a given heating current I_H is:

$$\Omega_H = \frac{V_S}{2Z_B I_H} + \sqrt{1+\left(\frac{V_S}{2Z_B I_H}\right)^2}$$

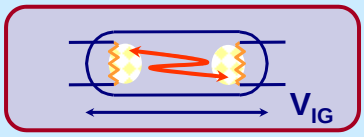
- The heating voltage at this operating point:

$$V_H = \frac{\alpha V_S}{\Omega_H^2 - 1}$$

Ignition

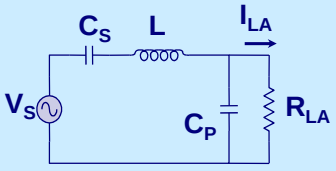
- The ignition voltage is obtained at the following frequency:

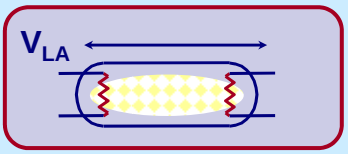
$$\Omega_{IG} = \sqrt{1+\alpha\frac{V_S}{V_{IG}}}$$



Electronic Ballast Design

Running





- At natural resonant frequency (Ω=1), the circuit behaves as a current source:

$$I_{LA} = \frac{V_S}{\alpha Z_B}$$

Electronic Ballast Design

Lamp Data @ 50kHz
V_{LA}=30V_{rsm}
I_{LA}=0.8A_{rms}
R_{LA}=37.5 Ω

α = 0.9 →

Base Impedance

$$Z_B = \frac{V_S}{\alpha I_{LA}} = \frac{4(320/2)/\pi/\sqrt{2}}{0.9 \cdot 0.8} = 200\Omega$$

Resonant Elements

$$L = \frac{Z_B}{2\pi f_S} = \frac{200}{2\pi 50 \cdot 10^3} = 0.63mH$$

$$C_P = \frac{1}{2\pi f_S \alpha Z_B} = \frac{1}{2\pi 50 \cdot 10^3 \cdot 0.9 \cdot 200} = 17.7nF$$

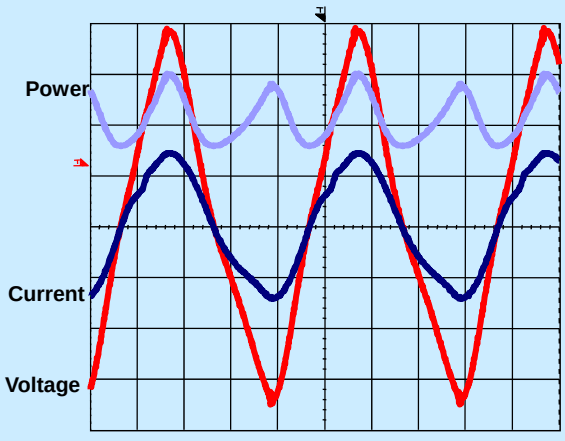
$$C_S = \frac{1}{2\pi f_S (1-\alpha) Z_B} = \frac{1}{2\pi 50 \cdot 10^3 \cdot 0.1 \cdot 200} = 159.1nF$$

Heating Frequency and Voltage (I_H=0.7 A_{rms}):

$$\Omega_H = \frac{144}{2 \cdot 200 \cdot 0.7} + \sqrt{1 + \left(\frac{144}{2 \cdot 200 \cdot 0.7}\right)^2} = 1.64 \qquad V_H = \frac{\alpha V_S}{\Omega_H^2 - 1} = \frac{0.9 \cdot 144}{1.77^2 - 1} = 60.7\, V_{RMS}$$

√

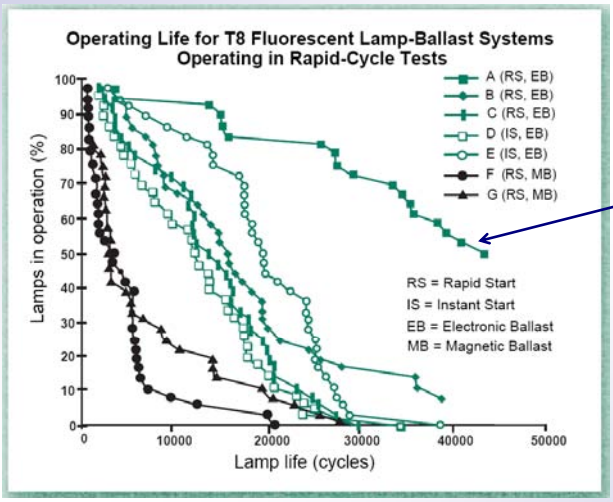
Lamp Waveforms



P_{LA} 23W

20 V/DIV, 0.5 A/DIV, 5 µs/DIV

Life extension of fluorescent lamps



The winner is:

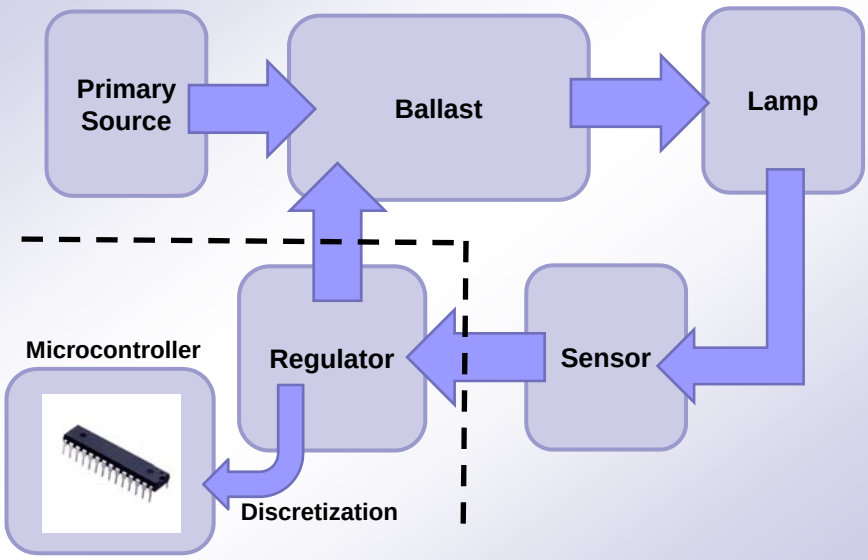
Electronic Ballast with Rapid Start

THE IGNITION OF FLUORESCENT LAMPS

Outline

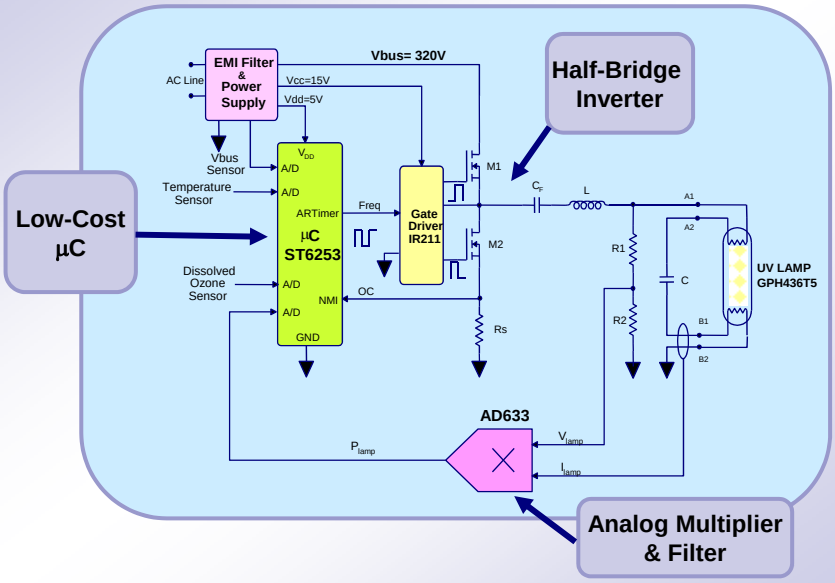
- Introduction
- Lamps
- Ballasts
- Digital Control
- Conclusions

Digital Control of Electronic Ballasts



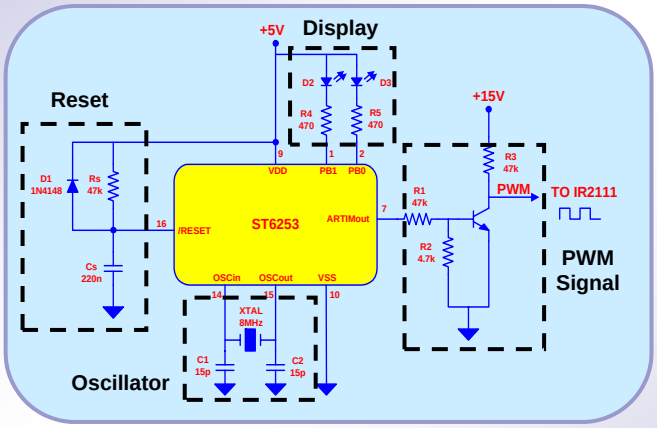
Digital Control

General Diagram of the UV Ballast



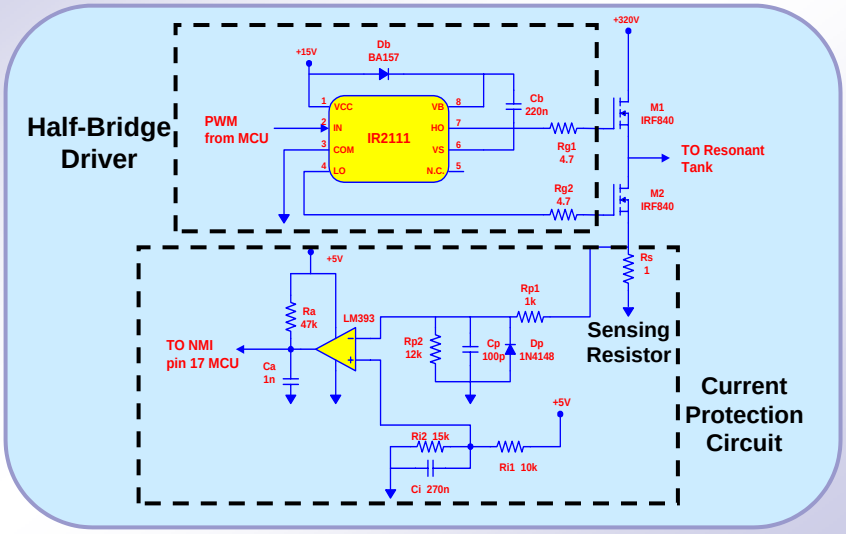
Digital Control

Basic Microcontroller Circuitry

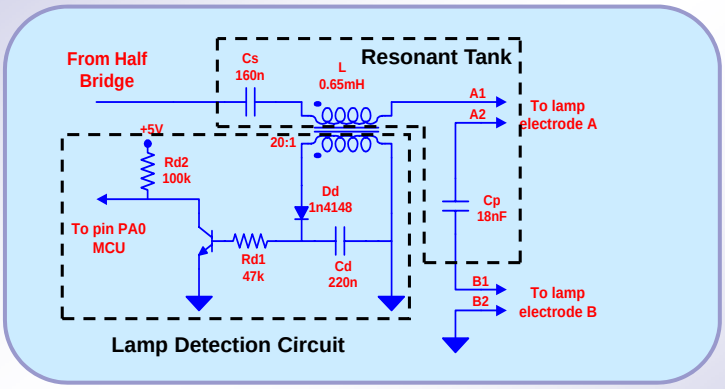


- Low cost microcontroller ST6253 with high noise immunity
- Power switches are driven directly from the MCU
- A 8MHz crystal is used for the MCU oscillator

Half-Bridge Driver and Current Protection Circuit



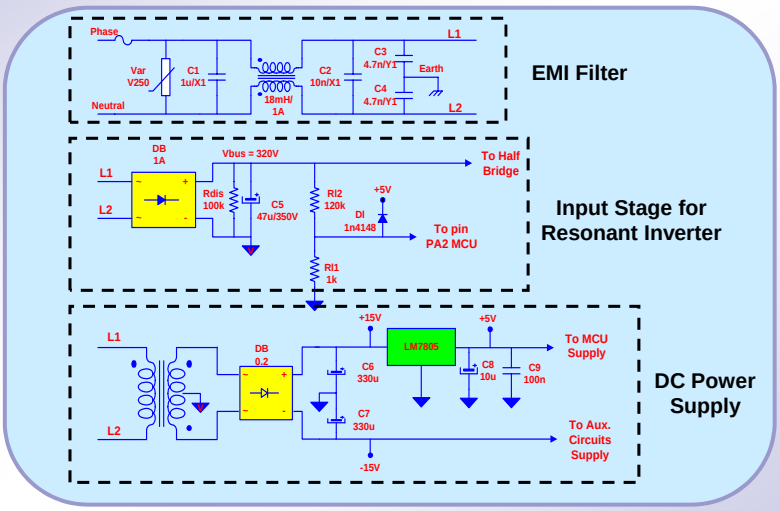
Resonant Tank and Lamp Detection



- A LCC resonant tank is used
- An additional winding is used in the inductor to detect lamp presence

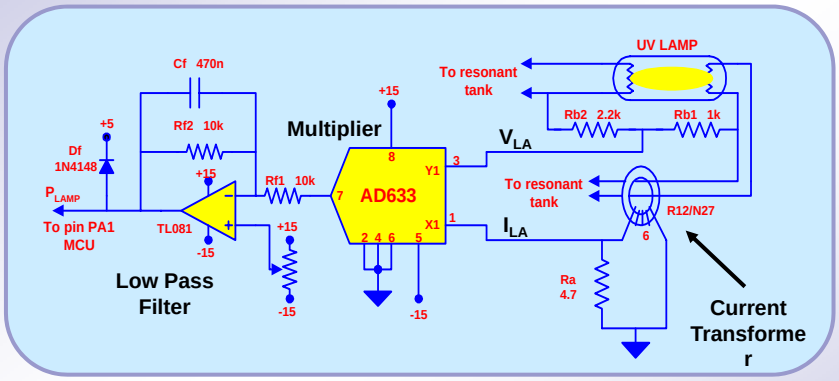
Digital Control

Power Supply and EMI Filter



Digital Control

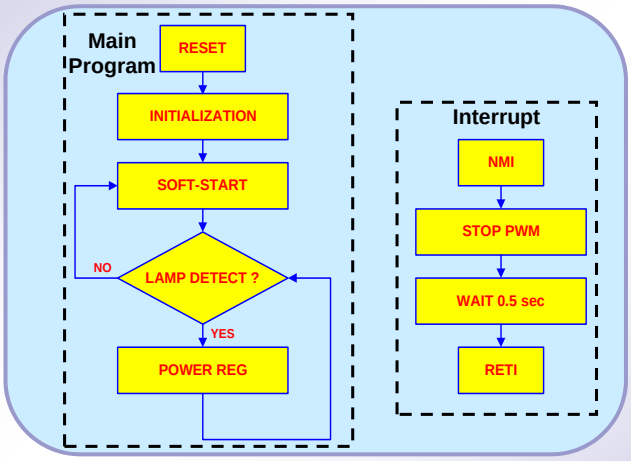
Lamp Power Sensing Circuit



- Lamp current is measured using a current transformer
- An AD633 multiplier is used to obtain the lamp instantaneous power
- A low pass filter is used to obtain the lamp mean power

Digital Control

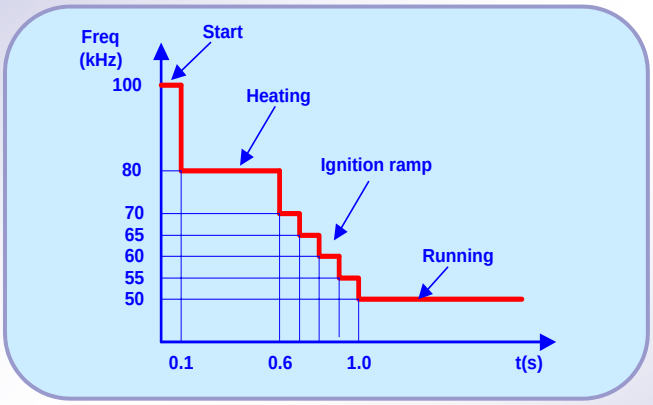
Microcontroller Programming



- Watchdog register is programmed to increase robustness (T_R=24.5 ms)
- Main routines are Soft-Start and Power Regulation
- NMI interrupt is used to implement overcurrent protection

Digital Control

Soft-Start Routine



- Autoreload register is used to generate PWM
- Two registers are used, reload (RC) and compare (CP):

$$f(kHz) = \frac{8000}{255 - RC} \qquad Duty = \frac{CP - RC}{255 - RC}$$

Power Regulation Routine

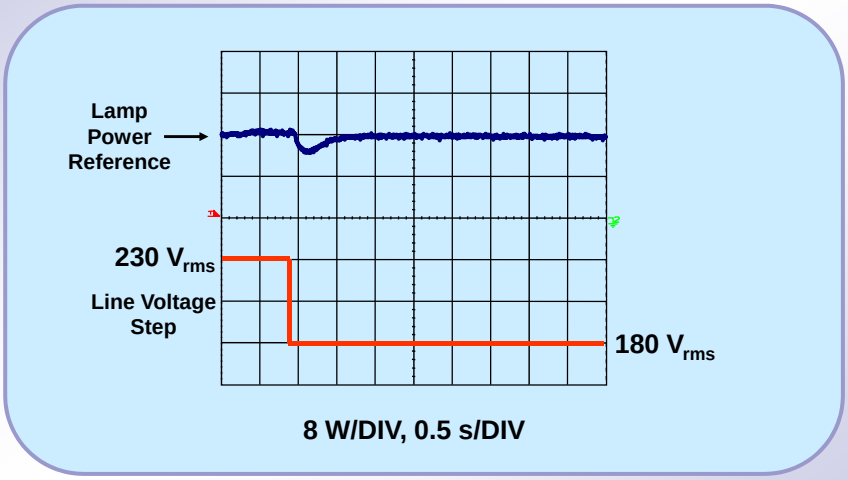
- A simple regulation routine is used in order to be feasible its implementation in the selected low cost microcontroller
- The reload register is modified in a value proportional to the error signal:

$$RC_k = RC_{k-1} + A \cdot e_k$$

$$f(kHz) = \frac{8000}{255 - RC} \quad \rightarrow \quad \frac{df}{d(RC)} = \frac{f^2}{8000}$$

- If e_k>0 (P_{LA}>P_{REF}) $\Rightarrow$ RC $\uparrow$ $\Rightarrow$ f $\uparrow$ $\Rightarrow$ P_{LA} $\downarrow$
- The regulation routine has been adjusted experimentally, final values are: A=0.5 and sample time of 0.1s
- The switching frequency is limited within the range: 45-80 kHz

Power Response

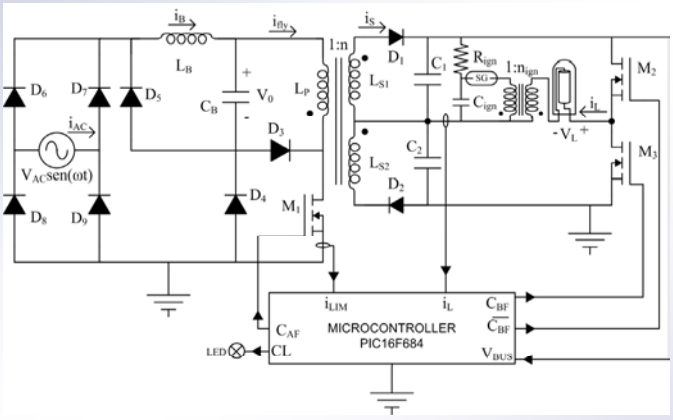


Digital Control

Laboratory prototype

Digital Control

Electronic Ballast for HID Lamp with Digital Control



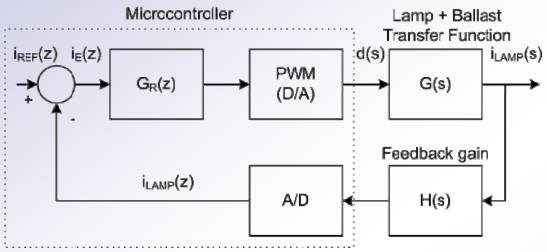
Microcontroller:

PIC16F684 from Microchip, 14 pins, low cost.

8 bits, internal oscillator (8MHz), PWM module, A/D converter, and timers.

Digital Control

Block Diagram



Lamp Model

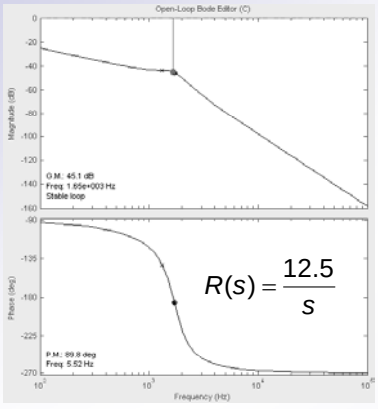
$$z_L(s) = \frac{v_L(s)}{i_L(s)} = k\frac{s+z}{s+p}$$

$$G(s) = \frac{I(s)}{D(s)} = \frac{2{,}454s + 26240}{9{,}9\cdot 10^{-9}s^3 + 1{,}387\cdot 10^{-4}s^2 + 1{,}612s + 9654}$$

- ❑ **Lamp current regulation in closed loop**
- ❑ **The model includes lamp and ballast dynamic behavior**

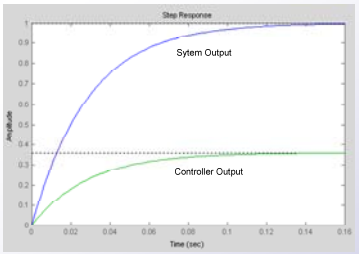
Digital Control

Designing the Closed Loop



$$R(s) = \frac{12.5}{s}$$

Design by SISOTOOL (Matlab):
- A=12.5 →
- Phase Margin: 90º
- Response Time: 100ms



Discretization (Tm=10ms):

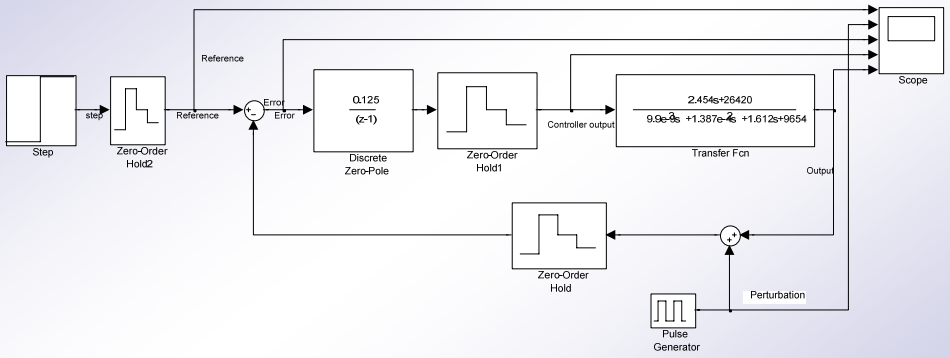
$$R(z) = \frac{D(z)}{E(z)} = \frac{A\cdot T_m}{z-1} = \frac{A\cdot T_m\cdot z^{-1}}{1-z^{-1}}$$

Difference Equation:

$$D_k = D_{k-1} + \frac{1}{8}\varepsilon_{k-1}$$

Digital Control

Simulation with Matlab Simulink



Digital Control

Simulation Results

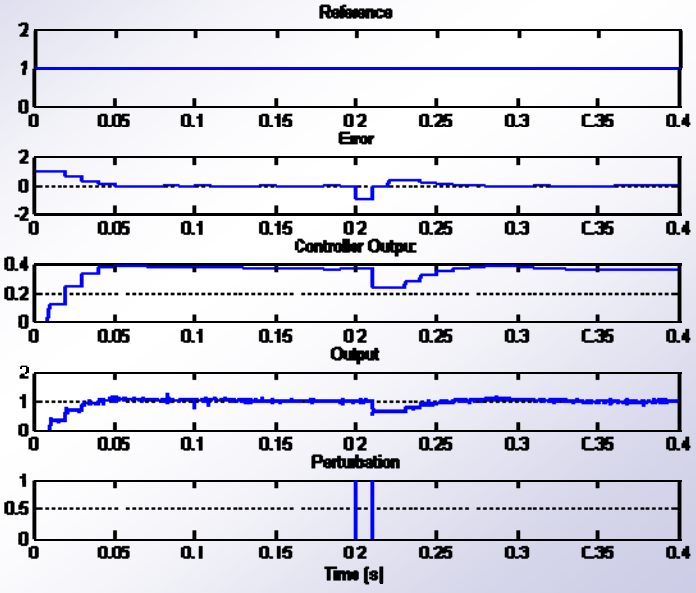
Reference

Error

Regulator

Output

Perturbation

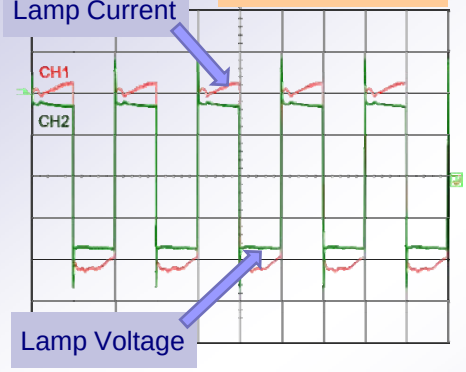


Digital Control

Experimental Results

Steady State

Lamp Current

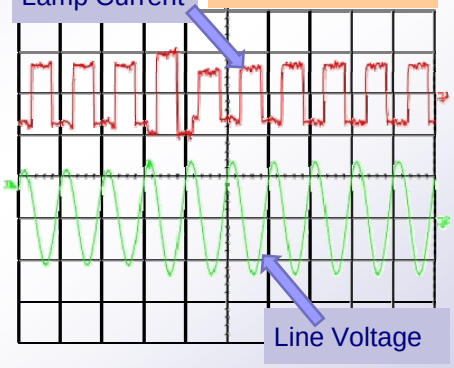


Lamp Voltage

50 V/div – 0.2 A/div – 5 ms/div

Transient

Lamp Current

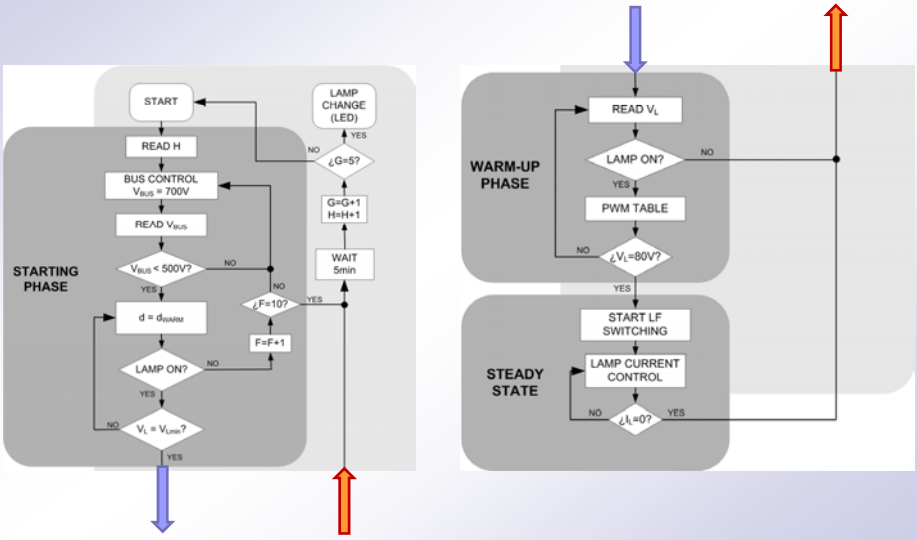


Line Voltage

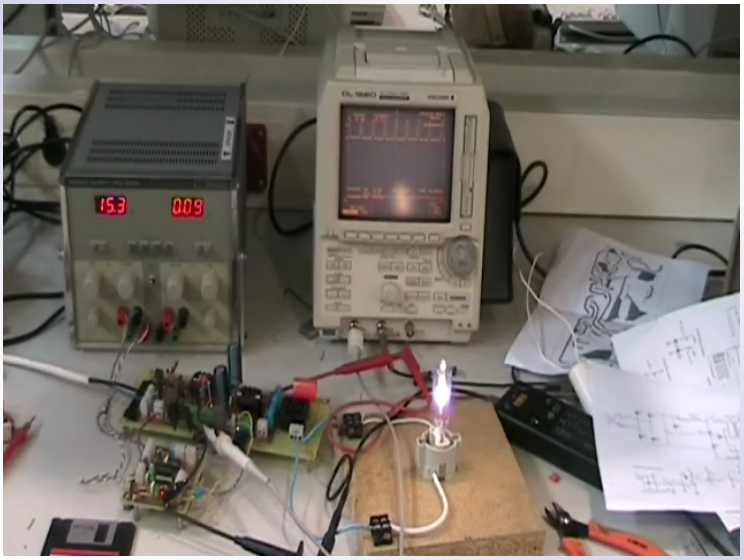
250 V/div – 0.5 A/div – 20 ms/div

Digital Control

Program Flowchart

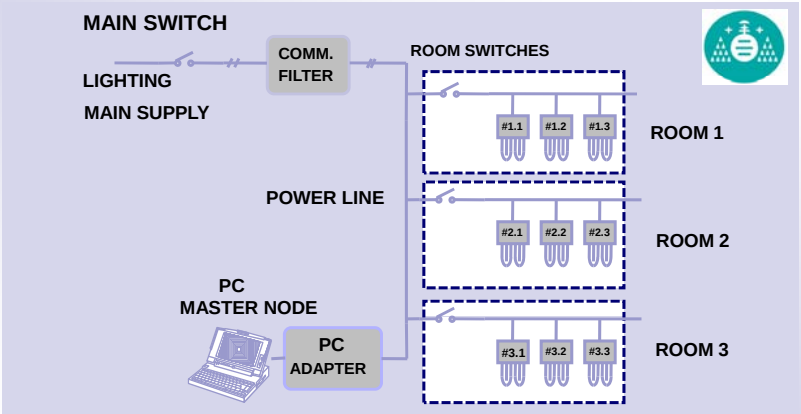


Laboratory prototype



Lighting system with power line control

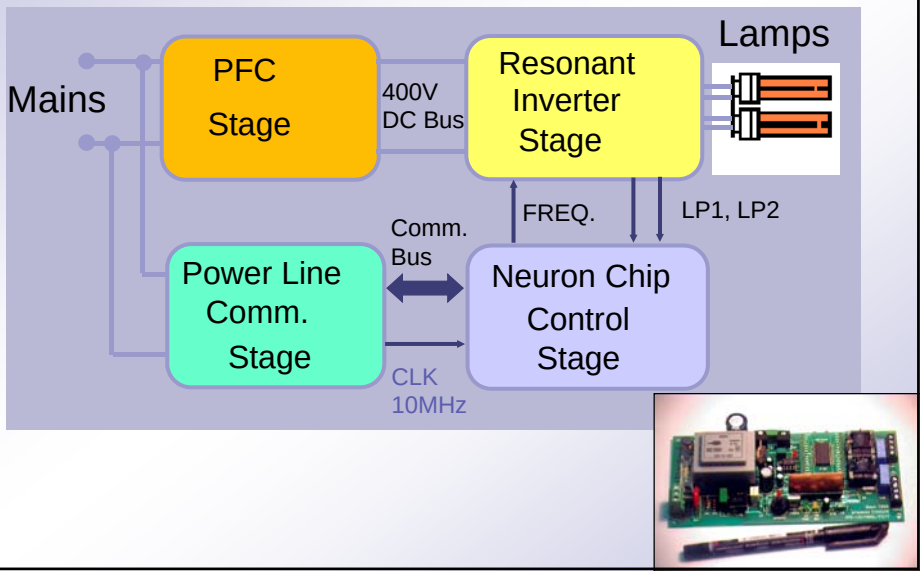
- Developed by University of Oviedo



- Power Line is used as communication medium
- Simple installation procedure
- Able to implement any control strategy

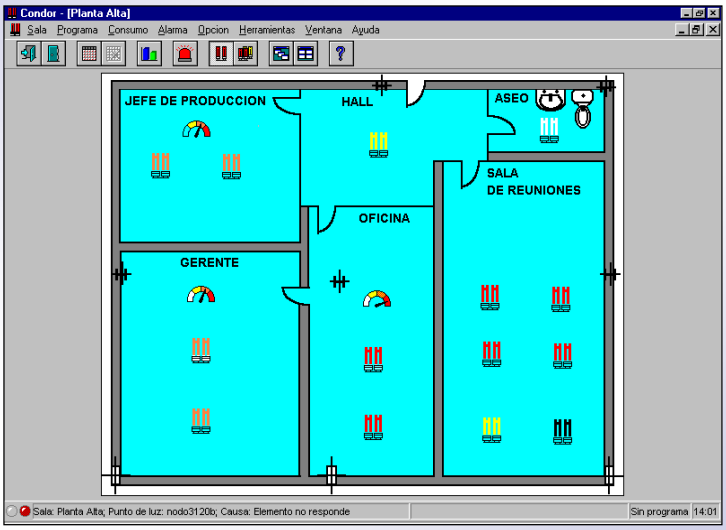
Digital Control

Ballast Block Diagram



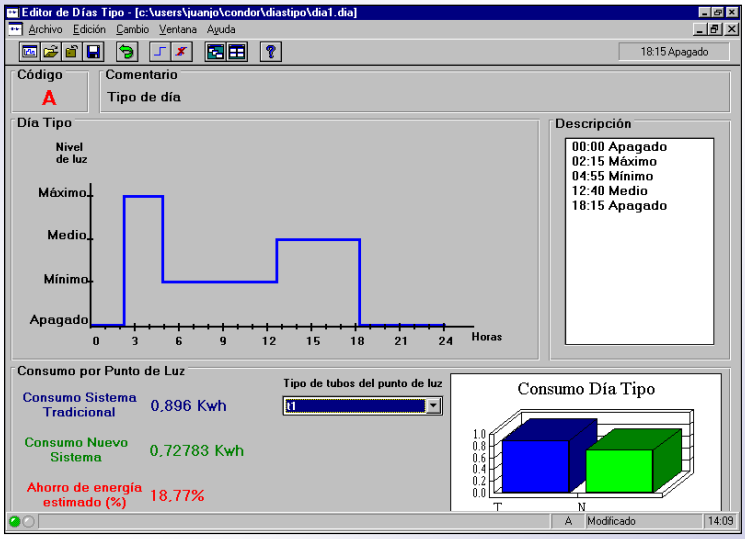
Digital Control

Management software



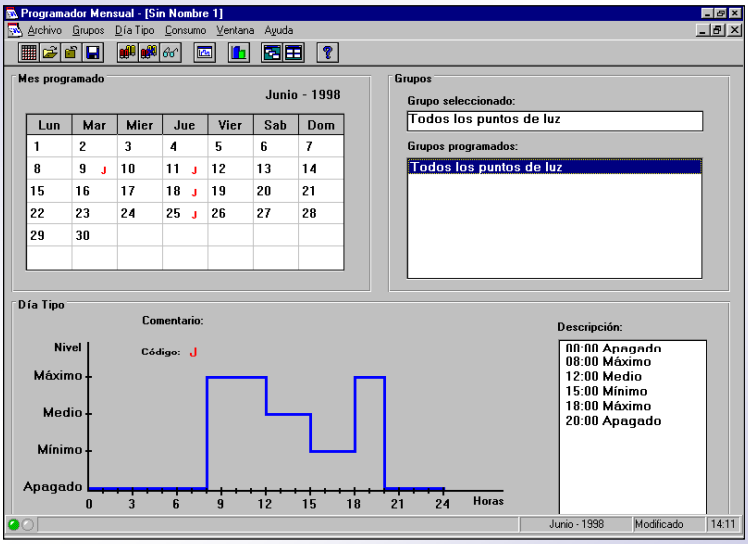
Digital Control

Scheduler



Digital Control

Scheduler



Conclusions

- Nowadays much energy is wasted in lighting due to the use of non-adequate lamp types or ballasts.
- Lighting technology existing today allows saving up to 30-60% of energy.
- Any good action taken or control strategy implemented, even being initially costly, will be paid back by the saving in electric consumption.
- For large investments an economic study is crucial to determine the payback time

Thank you !