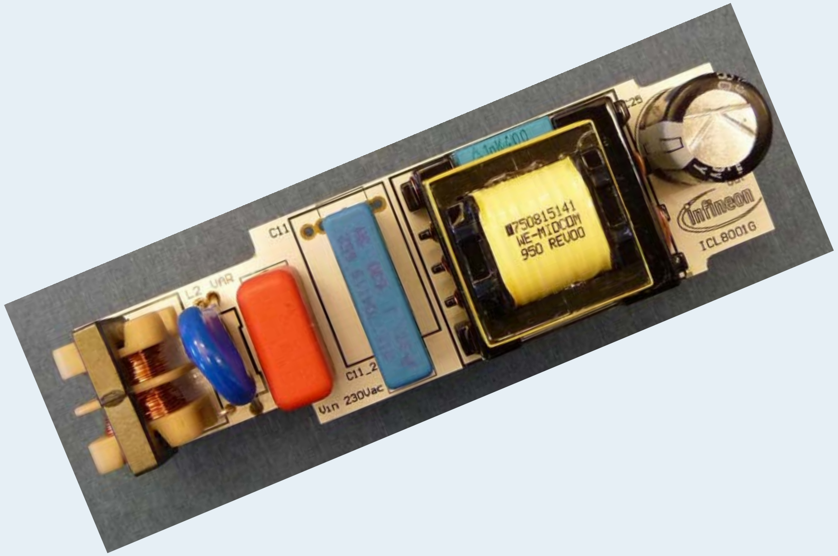
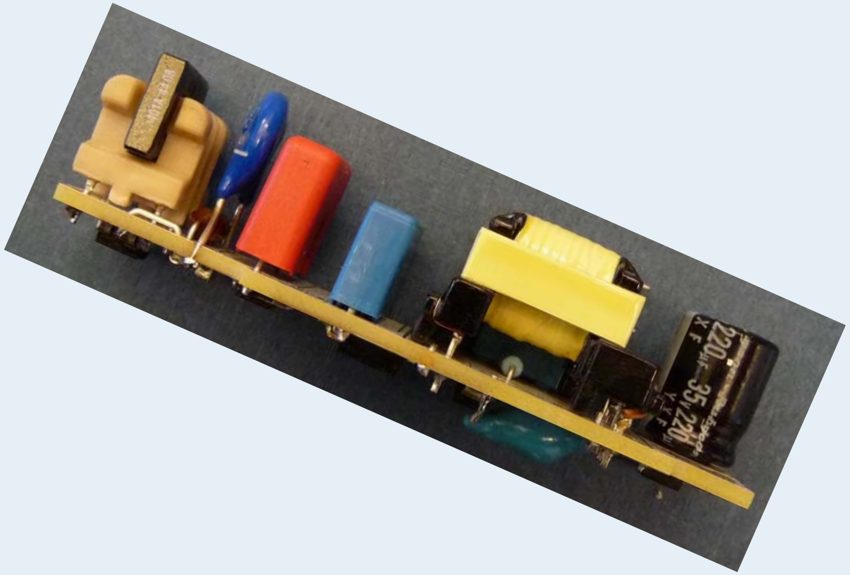
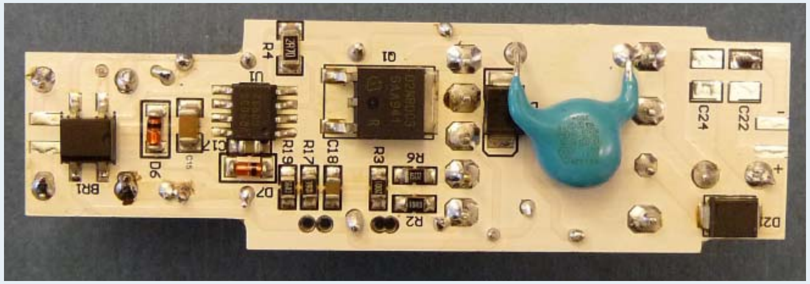
Ali Fawaz
Senior Application Engineer

POWER FACTOR CORRECTION







Infineon
Never stop thinking

Infineon‵s Rankings

Power	Industrial	Chip Card	Auto-motive
#1	#1	#1	#1
Market share 10%	Market share 8%	Market share 26%	Market share 9%
IMS Research, July 2009	Semicast, May 2008	Frost & Sullivan, October 2009	Strategy Analytics, July 2009

Agenda Overview

- Power Factor basics
- Definition of Power factor
- PF for various loads
- Total Harmonic Distortion
- PF correction methods
- ICL8001G: High PFC Dimmable LED Driver

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What is Power Factor? Why is it important for lighting?

Power Factor is a measure of how effectively the load takes power from the line (power plant)

- Alternate definition: PF provides a measure of how close your load is to a incandescent light bulb (which has a PF of 1)

- **Systems with Low PF require additional power to be generated by utilities**
- **Lighting consumes ~20% of all generated power.**
- **Much of this power is consumed by traditional bulbs with PF of 1**
- **Transition to low PF LED bulbs negates some of these savings.**

→ High power factor solutions are required for LED bulbs and fixtures

Power Factor Requirements -- Regulatory

- **DOE energy star requires PF >0.7 for energy star rating of LED light sources**
- **Europe EN61000-3-2 requires power factor to meet harmonic requirements for light sources above 25W**

These standards provide a baseline requirements!

→ Market requirements for LED bulbs and fixtures are driving PF >0.9 for powers as low as 5W.

Detailed of Low Power factor effects

- **A Power Factor less than 1 could result in the problems below**

  - Power is recycled from the LED Bulb/ Fixture to the power source?
  - Harmonics from LED bulb/ fixture are degrating the line and affecting the performance of other equipment on the line
  - The load is generating additional losses
  - The load is requiring that the power grid provide more power than used.

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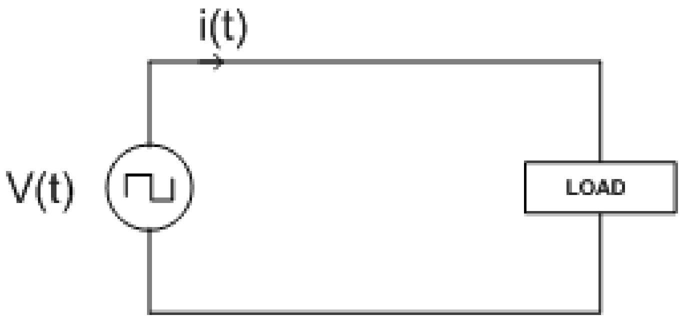
Definition of Power Factor

- Power Factor is defined as

$$P \cdot F = \frac{\text{AVERAGE POWER}}{\text{APPARENT POWER}}$$



- Derivation of Average Power

$$P_{avg} = \frac{1}{T} \cdot \int_0^T p(t)\,dt = \frac{1}{T} \cdot \int_0^T v(t) \cdot i(t)\,dt$$

A periodic voltage v(t) can be expressed in Fourier Series as:

$$v(t) = V_{dc} + \sum_{k=1}^{\infty} \left(V_k \cdot \sin\left(wt + \theta_k \right) \right)$$

Average Power

For Pure AC voltages Vdc=0

$$v(t) = \sum_{k=1}^{\infty} \left(V_k \cdot \sin\left(kwt + \theta_k\right)\right) = V_1 \cdot \sin\left(wt + \theta_1\right) + V_2 \cdot \sin\left(2wt + \theta_2\right) + V_3 \cdot \sin\left(3wt + \theta_3\right) + ...$$

Similarly a current i(t) that is periodic can be represented as:

$$\sum_{r=1}^{\infty} \left(I_r \cdot \sin\left(rwt + \phi_r\right)\right) = I_1 \cdot \sin\left(wt + \phi_1\right) + I_2 \cdot \sin\left(2wt + \phi_2\right) + I_3 \cdot \sin\left(3wt + \phi_3\right) + ...$$

$$P_{avg} = \frac{1}{T} \cdot \int_0^T p(t)\, dt = \frac{1}{T} \cdot \int_0^T v(t) \cdot i(t)\, dt$$

Average Power

$$P_{avg} = \frac{1}{T}\cdot\int_0^T V_1\cdot\sin(wt+\theta_1)\cdot(I_1\cdot\sin(wt+\phi_1)) + V_2\cdot\sin(2wt+\theta_2)\cdot(I_2\cdot\sin(2wt+\phi_2)) + V_3\cdot\sin(3wt+\theta_3)\cdot(I_3\cdot\sin(3wt+\phi_3)) + \ldots.dt$$

+

$$\frac{1}{T}\cdot\int_0^T V_1\cdot\sin(wt+\theta_1)\cdot I_2\cdot\sin(2wt+\phi_2) + V_1\cdot\sin(wt+\theta_1)\cdot I_3\cdot\sin(3wt+\phi_3) + V_1\cdot\sin(wt+\theta_1)\cdot I_4\cdot\sin(4wt+\phi_4) + \ldots\ldots dt$$

Unlike Terms (different frequencies) r ≠ k; deliver zero Average Power. Therefore,

$$P_{avg} = \frac{1}{T}\cdot\int_0^T \sum_{k=1}^{\infty} \left(V_k\cdot I_k\cdot\sin(kwt+\theta_k)\cdot\sin(kwt+\phi_k)\right) dt$$

Average Power

$$P_{avg} = \sum_{k=1}^{\infty} \left(\frac{V_k \cdot I_k}{2} \cdot \cos\left(\theta_k - \phi_k\right) \right)$$

In terms of Peak Voltage and Peak Current

$$P_{avg} = \sum_{k=1}^{\infty} \left(Vrms_k \cdot Irms_k \cdot \cos\left(\theta_k - \phi_k\right) \right)$$

In terms of RMS voltage and RMS current

- P.F Formulas

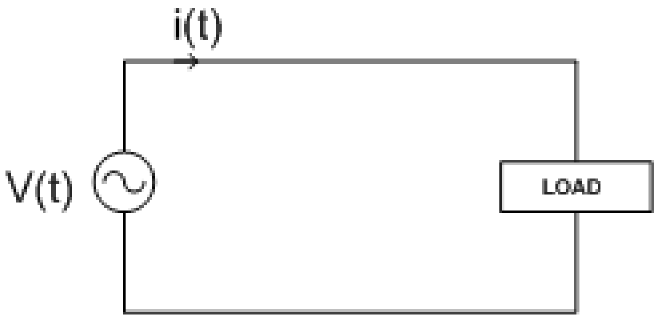
$$P \cdot F = \frac{\sum_{k=1}^{\infty} \left(Vrms_k \cdot Irms_k \cdot \cos\left(\theta_k - \phi_k\right) \right)}{Vrms \cdot Irms}$$

P.F Mother Equation

Power Factor Formulas

- Assuming V(t) is an ideal sinusoidal voltage Source:

$$P \cdot F = \frac{Vrms_1 \cdot Irms_1}{Vrms \cdot Irms} \cdot \cos(\theta_1 - \phi_1)$$



$$P \cdot F = \frac{Irms_1}{Irms} \cdot \cos(\theta_1 - \phi_1) = K_{disp} \cdot K_{dist}$$

$$K_{dist} = \frac{Irms_1}{Irms}$$ Distortion Factor

$$K_{disp} = \cos(\theta_1 - \phi_1)$$ Displacement Factor

$\theta_1 - \phi_1$ Displacement angle between V(t) and i(t) at Fundamental frequency.

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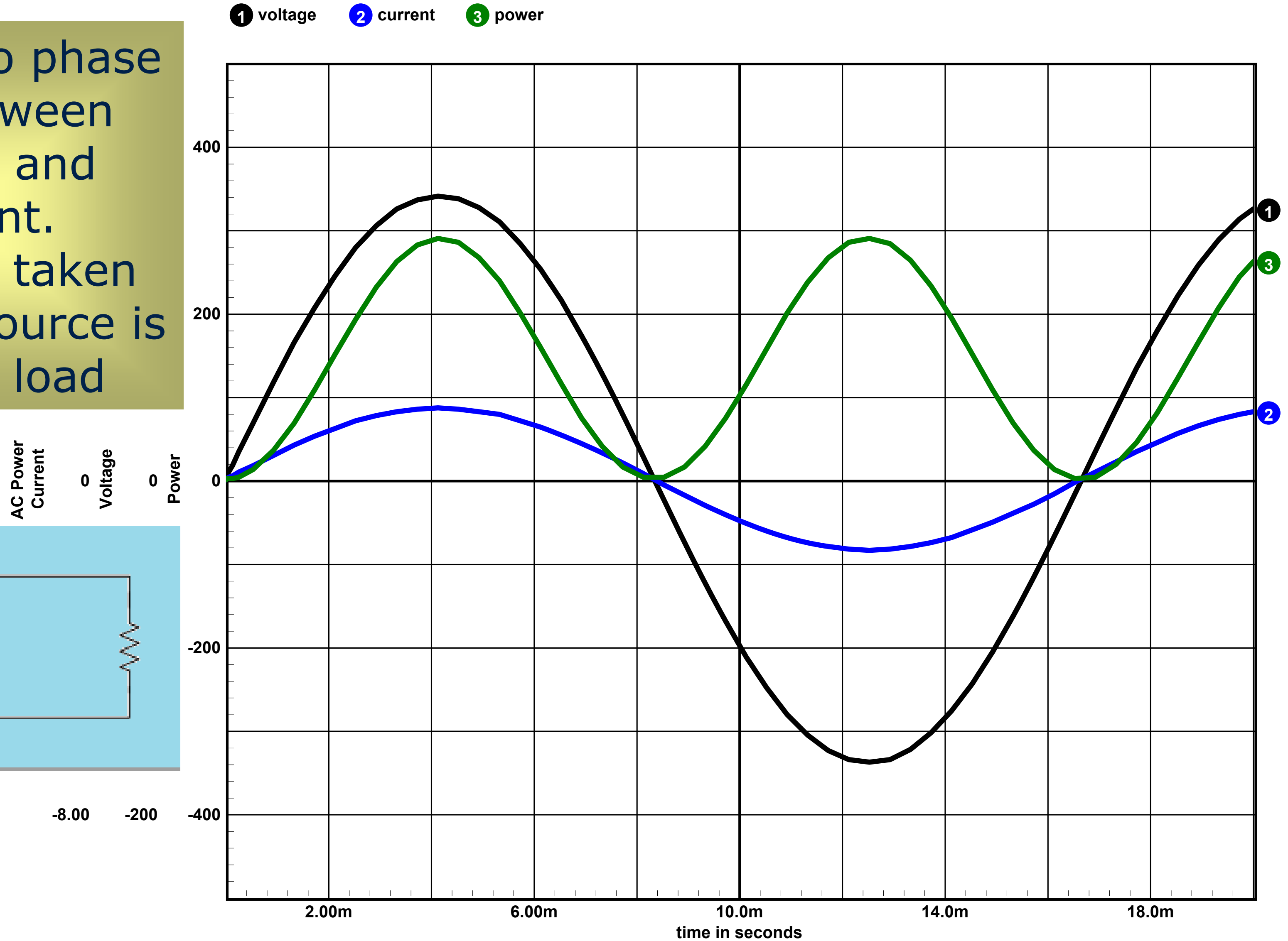
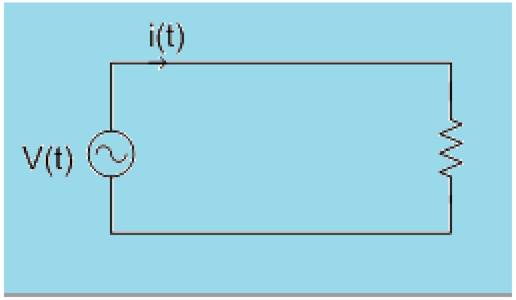
AC Power at PF =1 Resistive Load (Incandescent Light Bulb)

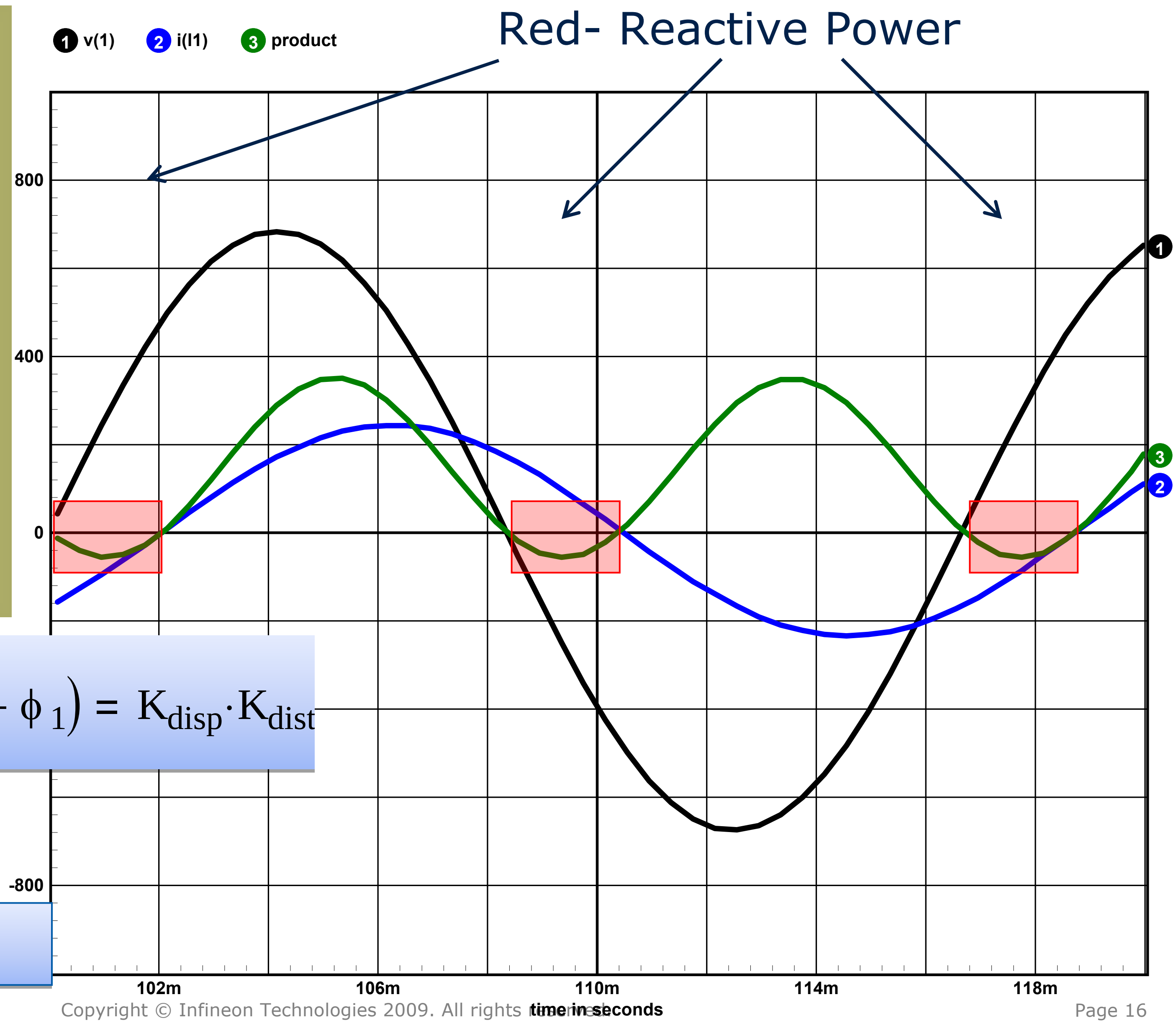
There is no phase shift between Voltage and Current.
All power taken from the source is used by load





Sinusoidal v(t) & Sinusoidal i(t) with PF < 1

Reactive power Oscillates between Source and reactive part of load (cap or inductor) Current Phase Shift
Cap (0<Φ <90)
Ind (-90<Φ<0)



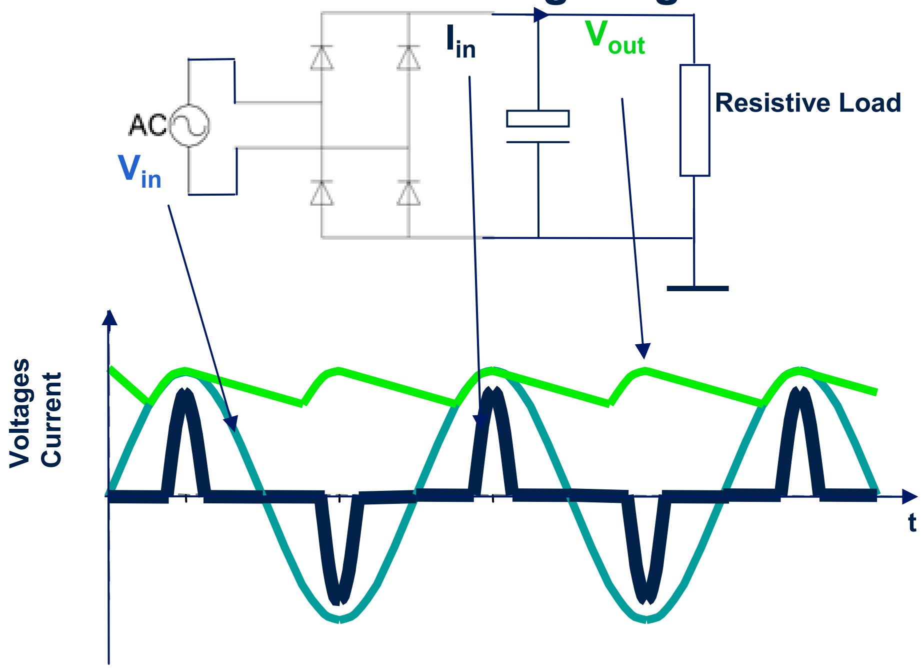
$$P{\cdot}F = \frac{Irms_1}{Irms}\cdot\cos\left(\theta_1 - \phi_1\right) = K_{disp}\cdot K_{dist}$$

$$K_{dist} = \frac{Irms_1}{Irms} = 1$$

$$P.F = K_{disp}$$

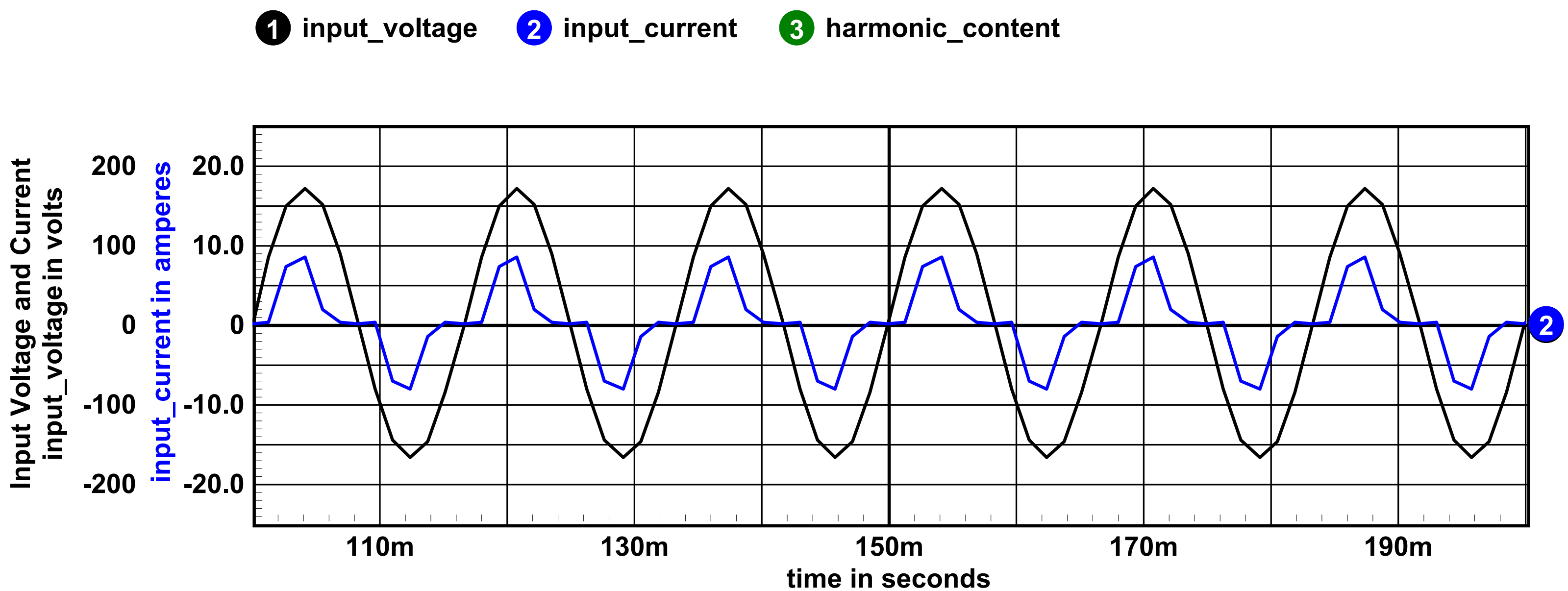
Non-Linear Load and Power Factor

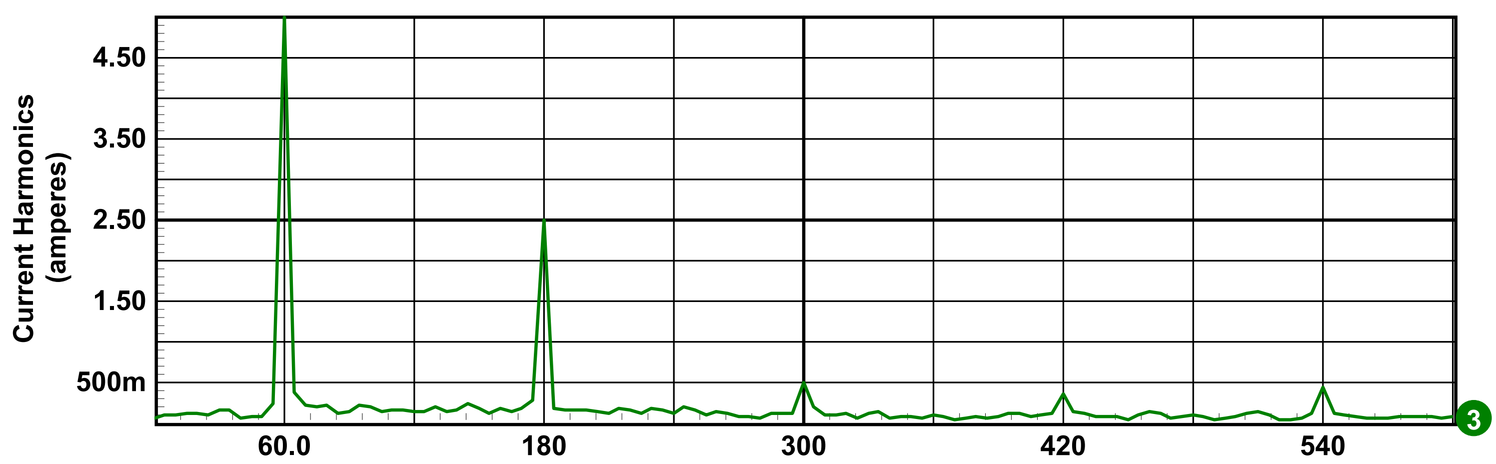
☹ **The input current in a system with diode rectifier followed by a capacitor is nonsinusoidal: This is observed in Lighting Solutions**



- **Problems:**
  - **- a large harmonic component in the distorted input current leads to an increasing pollution of the mains voltages**
  - **- the amount of reactive power is dramatically increased (a 100W TV set consumes 90W reactive power => The input power is only partly transferred to the output)**

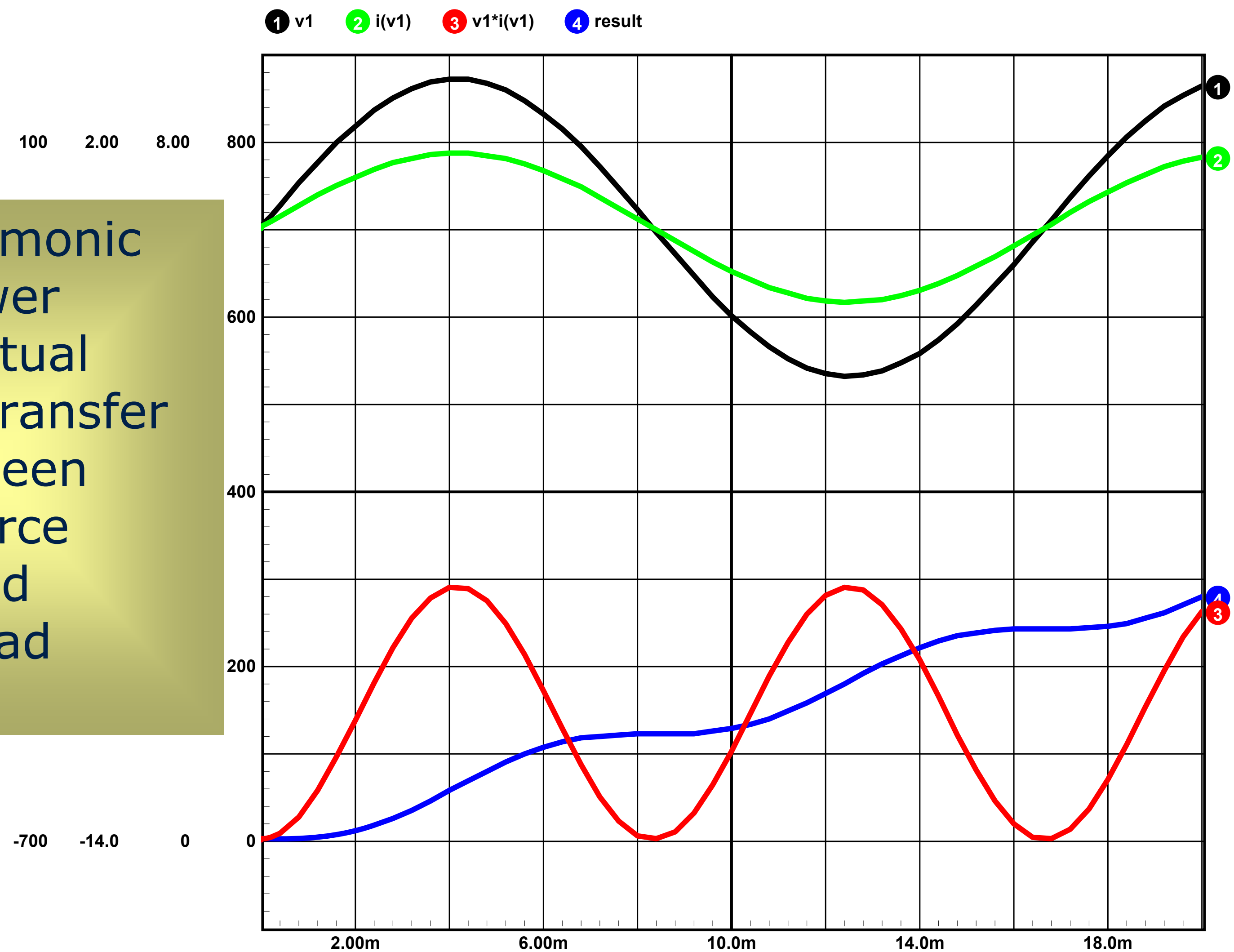
Harmonic Content





1st Harminic Power

1rd Harmonic Power Is actual Power Transfer between Source and Load

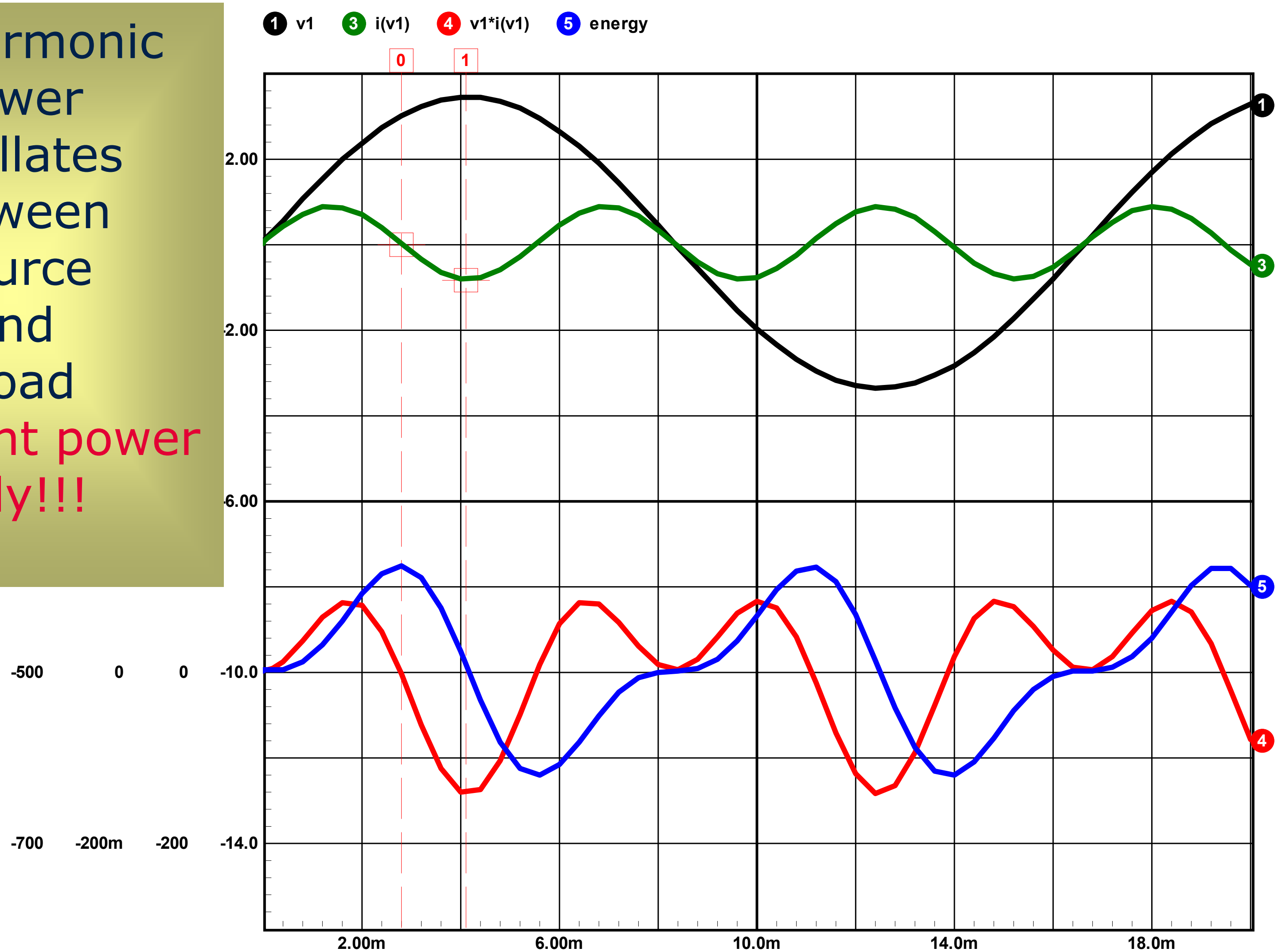


Total energy transfer is positive all the time.

3rd Harmonic Power

3rd Harmonic Power Oscillates between Source and Load

Apparent power only!!!



Total energy transfer after each half period is equal zero “0”

Power Factor Formula for Non-Linear Loads:

- Power Factor Formula:

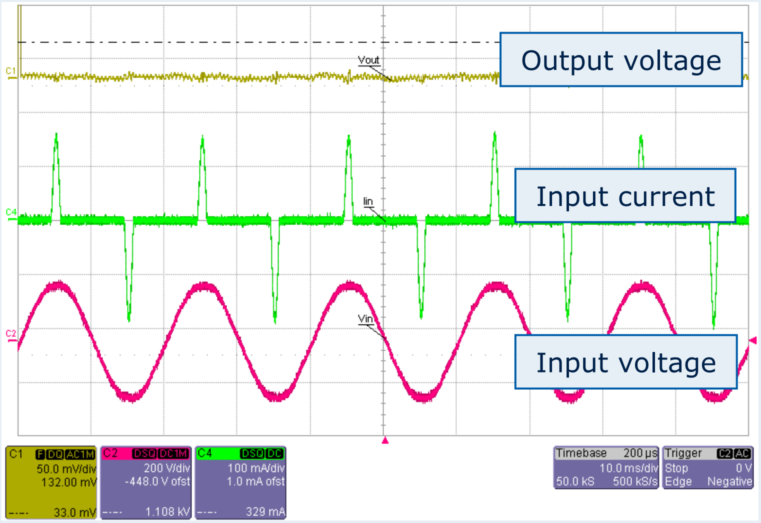
$$P \cdot F = \frac{Irms_1}{Irms} \cdot \cos(\theta_1 - \phi_1) = K_{disp} \cdot K_{dist}$$

- V(t) and i(t) fundamental components are in phase;

$$\cos(\theta_1 - \Phi_1) = K_{disp} = 1$$

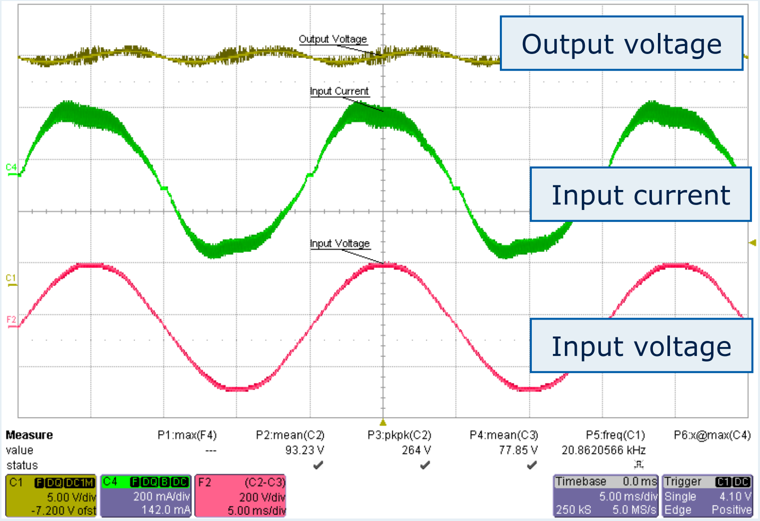
- P.F= $K_{dist} = \frac{Irms_1}{Irms} < 1$

AC-DC conversion with and without PFC



Without Power Factor Correction

Power factor: 0.43



With Power Factor Correction

Power factor: >0.90 !

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Total Harmonic Distortion

- **A frequently-used measure of harmonic levels is total harmonic distortion (or distortion factor), which is the ratio of the rms value of the harmonics (above fundamental) to the rms value of the fundamental, times 100%, or:**

$$THD_I = \frac{I_{rms}(Distorted)}{I_{rms1}} \times 100$$

I_{rms}(Distorted) is the sum of all the harmonics other than the fundamental.

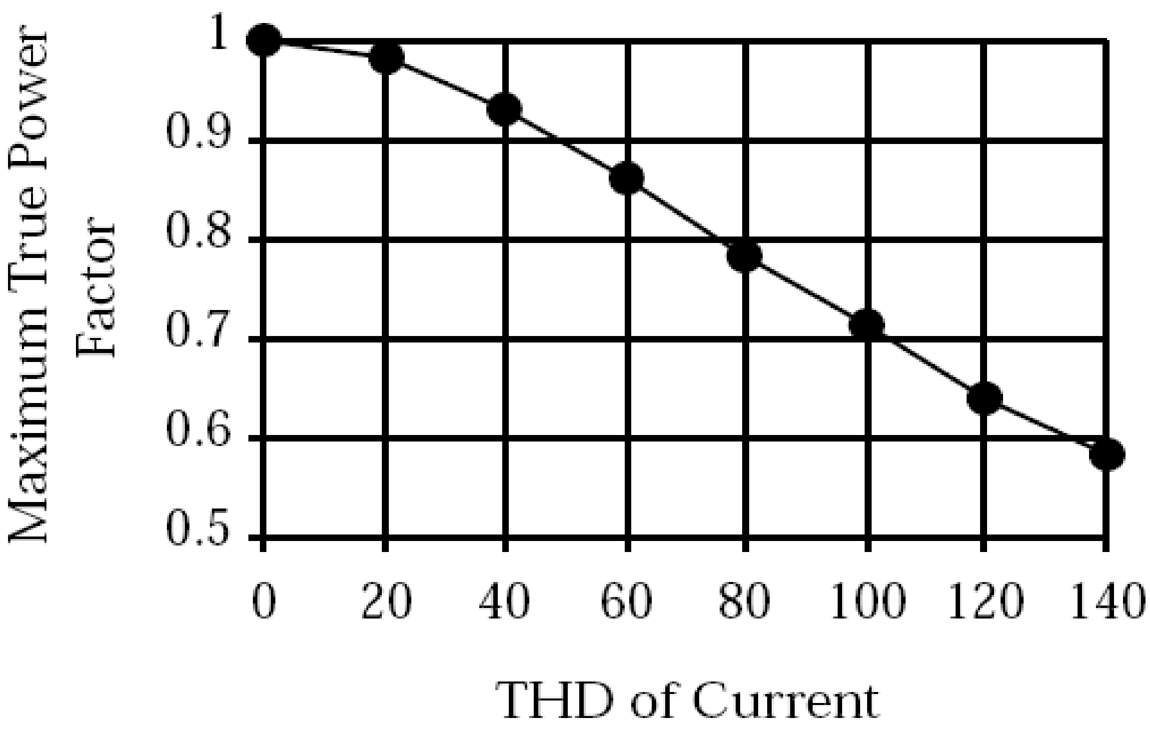
$$I_{rms}(Distorted) = \sqrt{I_{rms}^2 - I_{rms1}^2}$$

$$THD_I = \sqrt{\left(\frac{I_{rms}}{I_{rms1}}\right)^2 - 1} \times 100$$

$$PF = \frac{1}{\sqrt{1 + \frac{THD_I}{100}}}$$

Total Harmonic Distortion

- Incorporating these two assumptions
  (*Pavg ≈ P1avg* and *Vrms ≈ V1rms*)
  the following approximate form for Power Factor:



For internal use only

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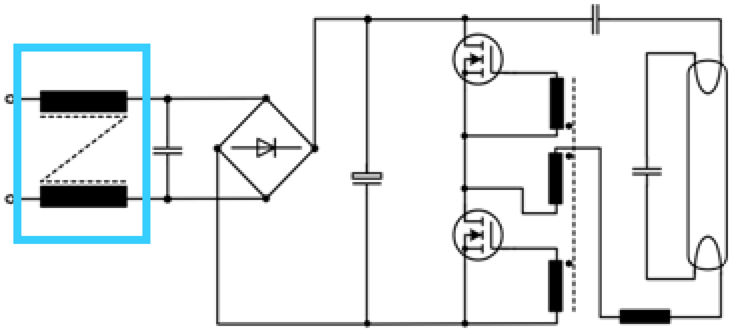
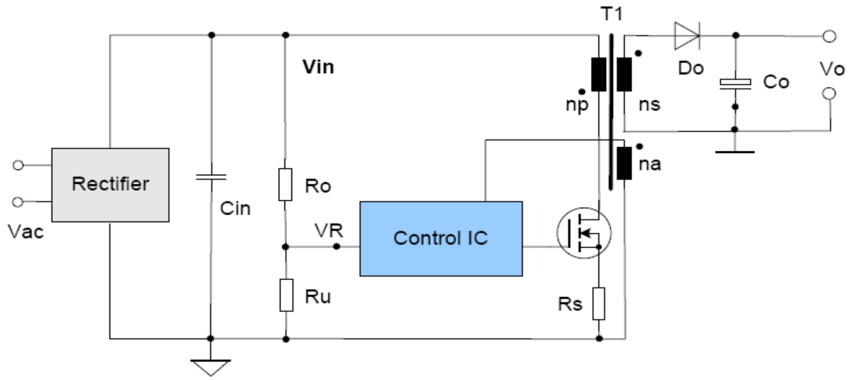
Methods of Power Factor Correction

Passive Solution
by iron core choke
Characteristics:
Pros: rugged, supports EMI, cheap
Contras: heavy, big, tends to humming
output voltage dependent on load

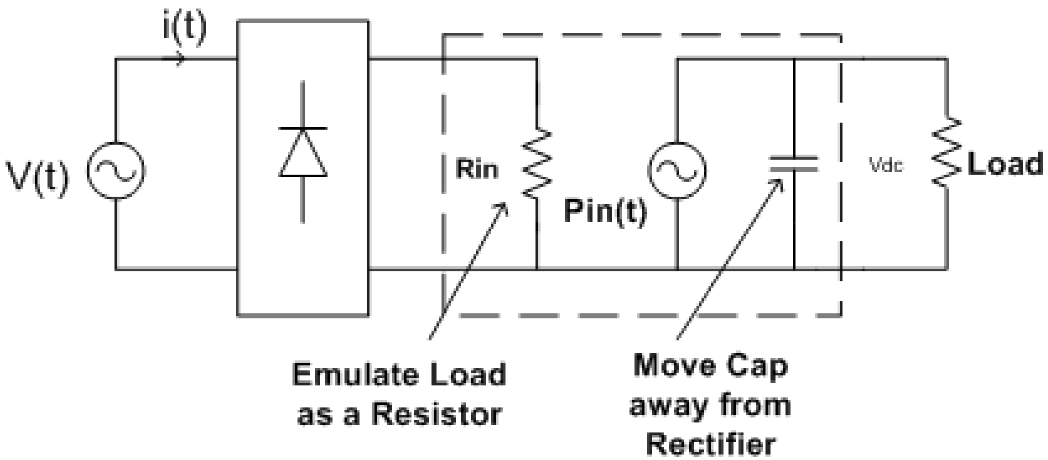


Active Solution
by ferrite/powder core choke, diode, MOSFET, control IC
Characteristics:
Pros: light, effective, output voltage stable
allows wide input voltage range
Contras: additional components but costs partially
compensated in remaining system



Active Power Factor Correction Concept

- Emulate Load after bridge rectifier as a lossless resistor.



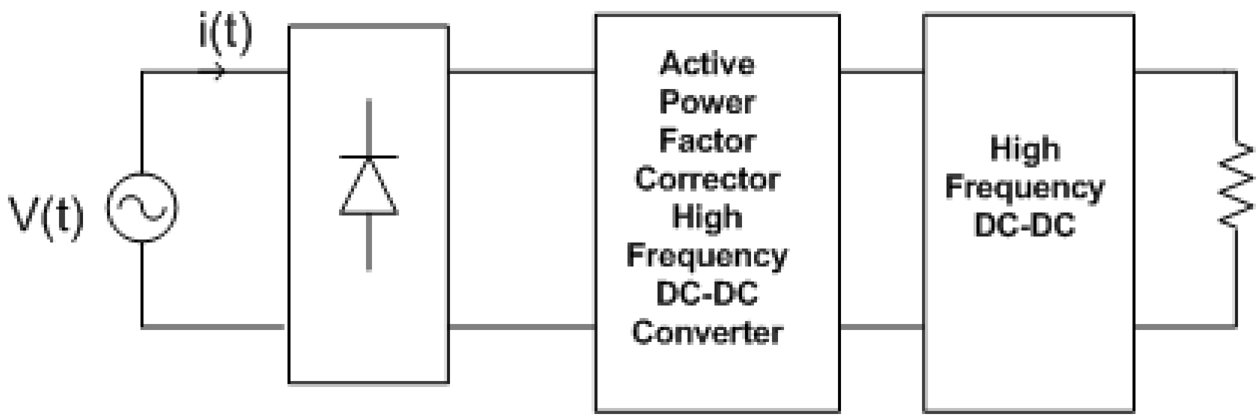
- Output ripple is twice the line frequency.
- Conversion ratio= $\dfrac{V_{dc}}{V_{in} \cdot |\sin wt|}$
- Control is needed for $R_{in} = V^2_{in} / P_{in}$ to provide required output power.

Active Power Factor Correction Concept

- Slow control loop. Cross-over frequency should be about 20Hz at high line input voltage.
- Input Voltage Feed-forward is required to provide constant output Regulation. The input voltage feed-forward must be constant during each half cycle.

Active Power Factor: Two Stage Method

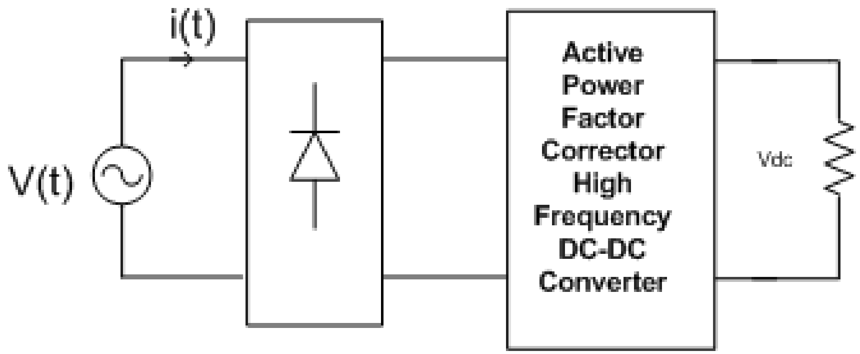
- Two Stage Method
  - Tight Output Voltage Regulation at load is provided by second stage.



  - Boost most commonly used. CRM for Po<250watts; CCM Average current mode control for Po>250watts

Active Power Factor Correction: Single Stage Method

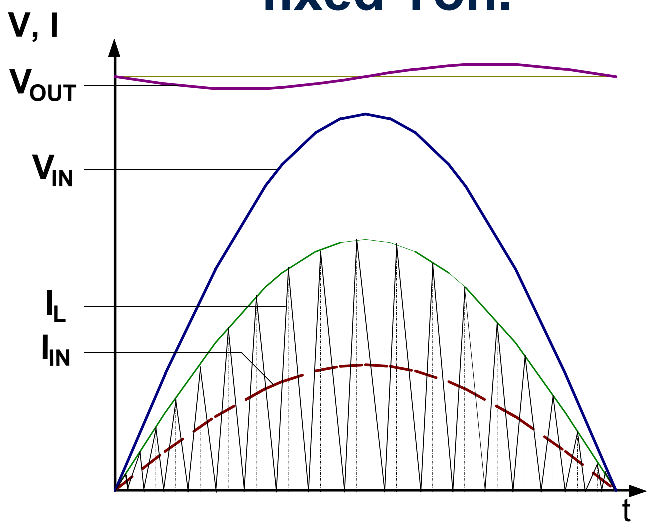
- Single Stage Method



- Output Voltage Regulation at load is not tight.
- High output ripple (second harmonic) at load. Used in applications such as LED lighting in which high output ripple voltage is inconsequential.
- CRM Flyback (Buck-Boost) most commonly used.
- Coupled inductor provides galvanic Isolation for safety is provided.

Control Methods for Boost-Converter

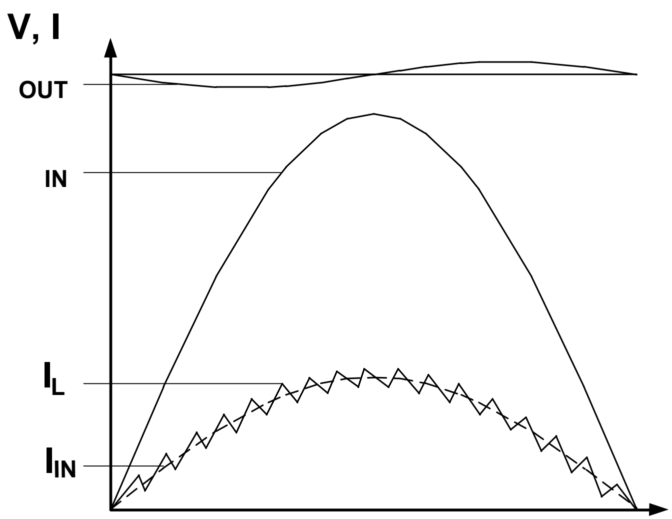
Critical Conduction Mode CRM Variable frequency fixed Ton.



Characteristics:

Pro
no reverse recovery losses of diode
simple control method
Contra
difficult smoothing of peak currents
at light load

Continuous Current Mode CCM usually constant frequency

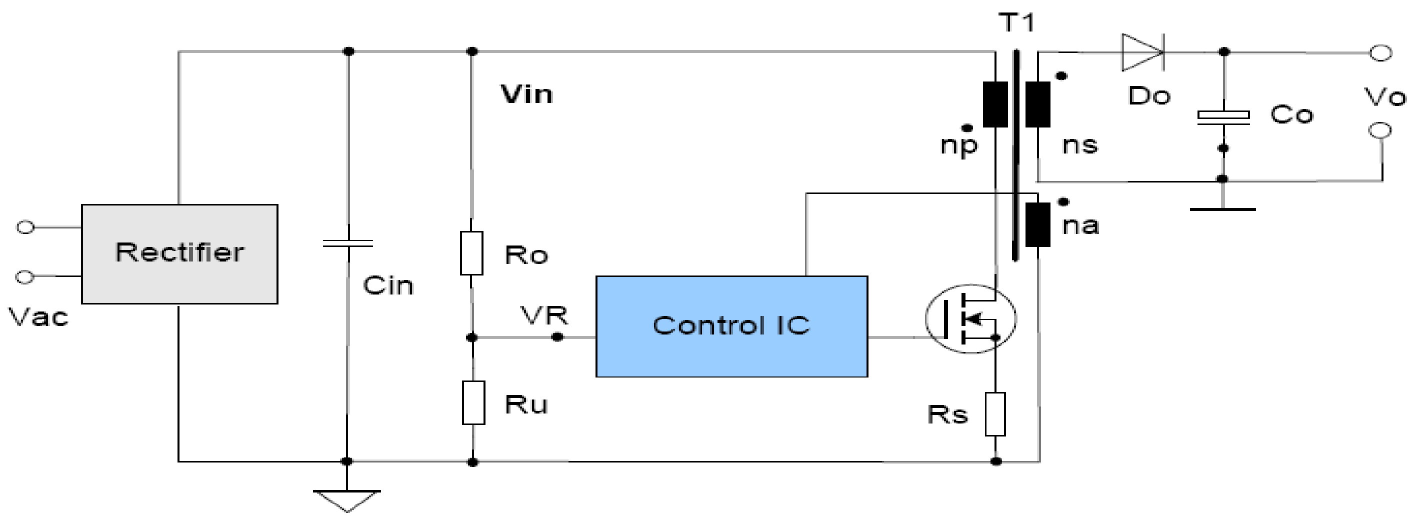


Characteristics:

Pro
easy smoothing of peak currents
stable operation at light load
Contra
reverse recovery losses of diode
complex control method

Active Power Factor Correction: PFC Flyback Converter features

Advanatges	Disadvantages
- Is inherently a Power Factor Corrector when operated in DCM. Simple hysteretic fixed ton control.	- High Voltage Stress on MOSFET and diode.
- Coupled Inductor provides galvanic isolation for safety.	- Filtering for EMI due to switching input current. However, this problem is reduced by QR operation.
- Inherent Current limiting.	
- Low Cost: Few Components, single stage . Can Buck & Boost.	

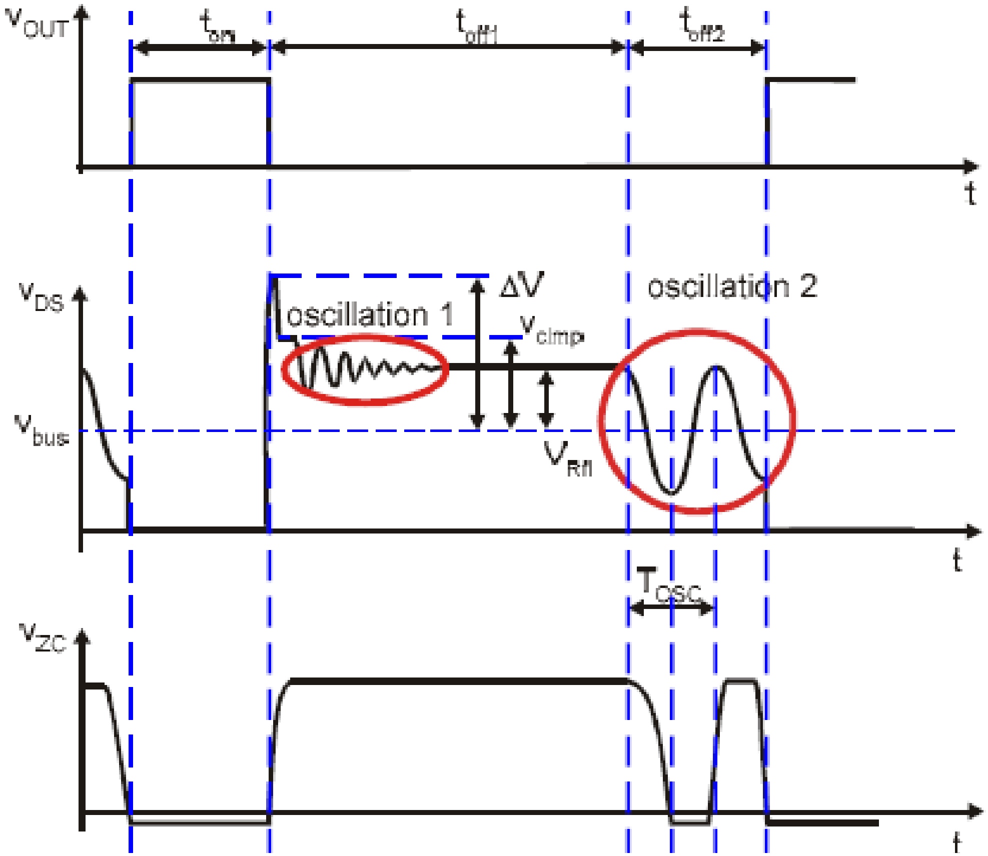


Flyback with QR operation

- Flyback can be implemented with FF or QR. QR offers the following advantages:

- High efficiency due to zero voltage switching.

- Reduced EMI noise.



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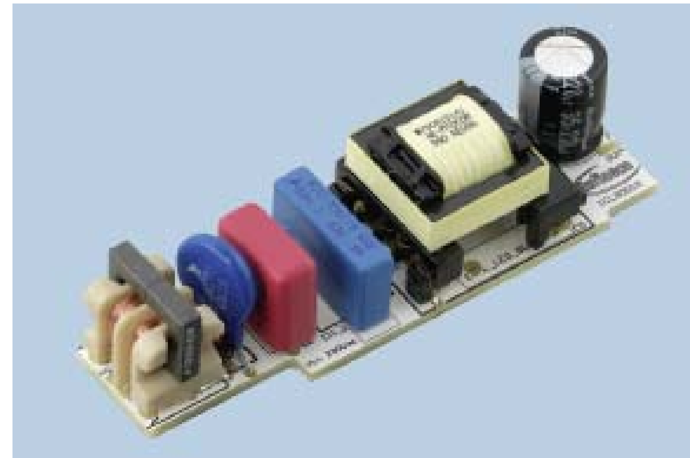
LEDs AND POWER FACTOR CORRECTION.

- Requirements for LED solutions:
  - Appears to the source as a resistive load
  - Meets regulatory, market and safety requirements
  - Control to provide required output power.
  - LOW COST (Let us not Forget):
    - Solution: Single Stage Flyback.
      - Very few components --primary side control results in as few as 20 components.
      - Has inherent current limiting. No added circuitry for protection.
      - Simple low cost hysteretic control can be used.
      - Inherent very high PF.
      - Full galvanic isolation

ICL8001G: Single Stage LED Driver

ICL 8001G Performance
- vs standard PFC controller -

- **Precise PWM generation**
- **Propagation delay correction**
- **Fold back correction**
- **Start Up Cell**
- **Programmable Protection**

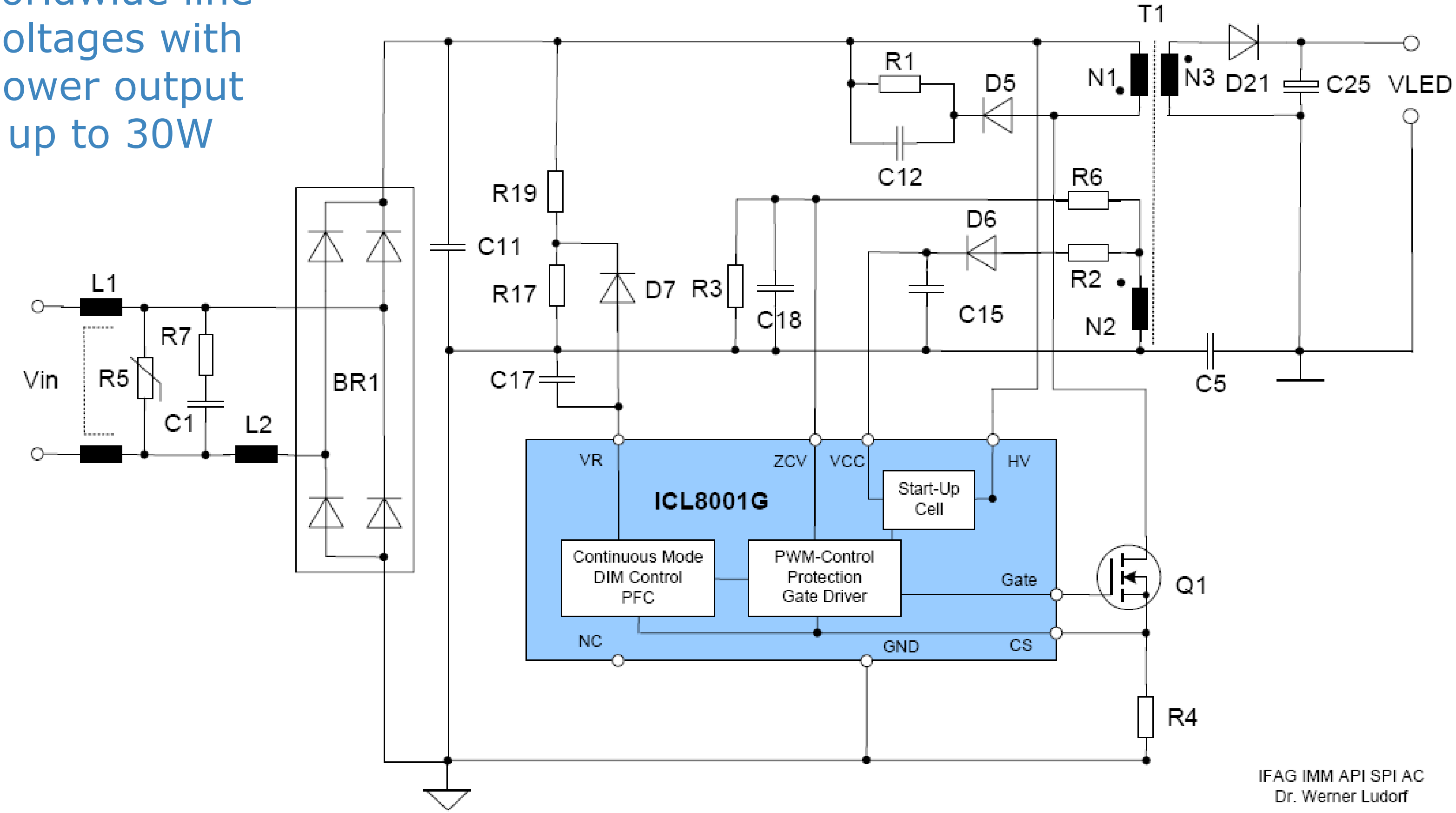


ICL8001G: Single Stage LED Driver

Supports worldwide line voltages with power output up to 30W

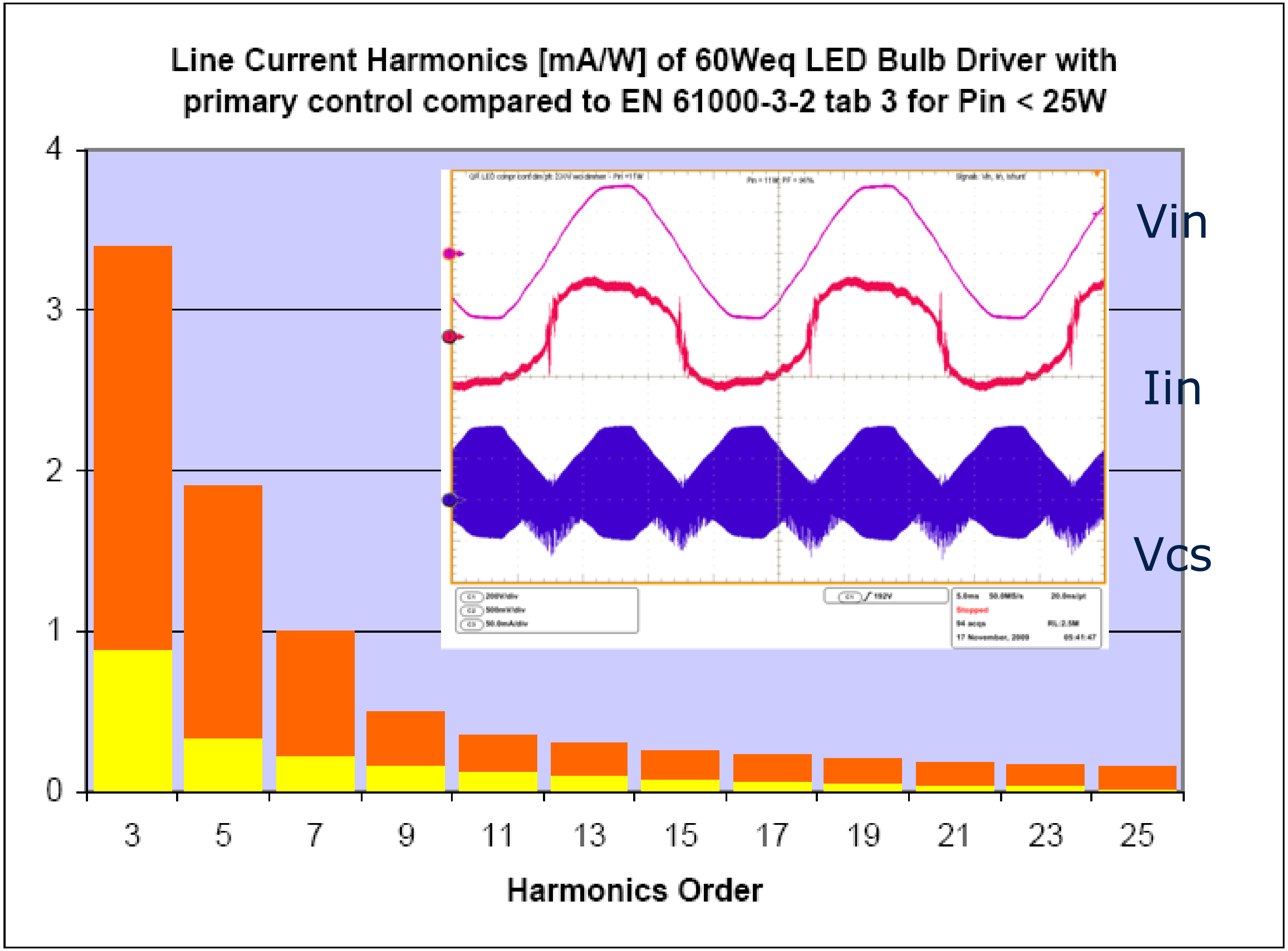
LED Bulb QR Flyback Driver with ICL8001G for

Phase Cut Dimming & PFC using Primary Control

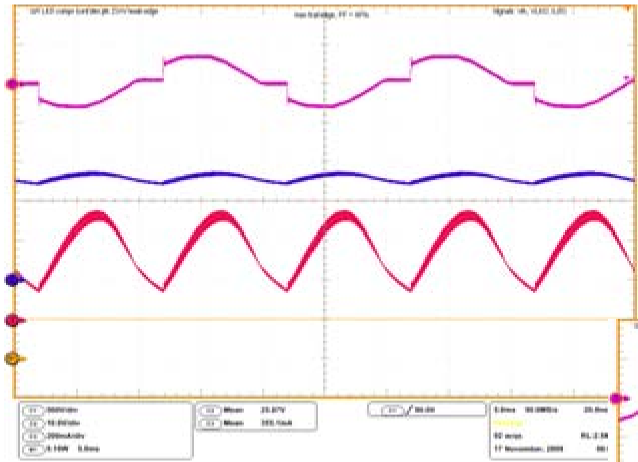


IFAG IMM API SPI AC
Dr. Werner Ludorf

PFC performance

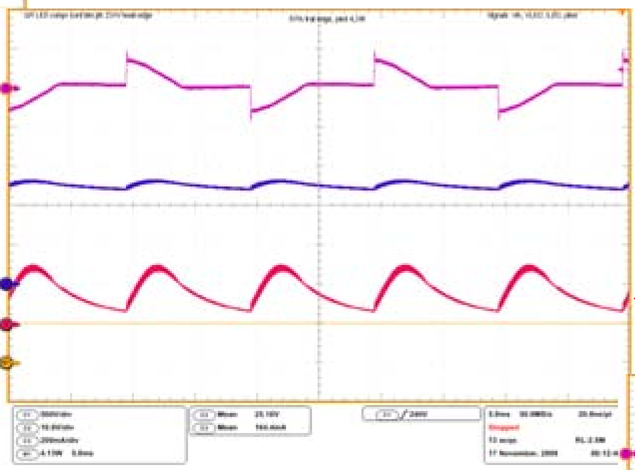


Phase Cut Dimming – Leading Edge



Maximum Dimming-Level

- **PFC function as ideal precondition for stable leading edge dimmer operation**
- **Oscillations caused by interaction of EMI filter with leading edge dimmer are depending on EMI filter design applied**

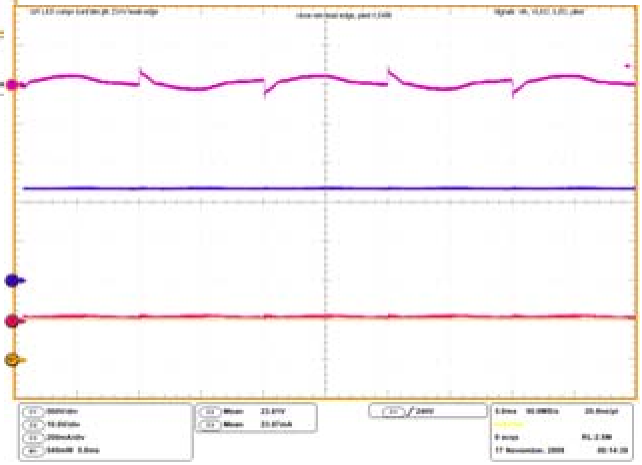


Vin

Vout

Iout

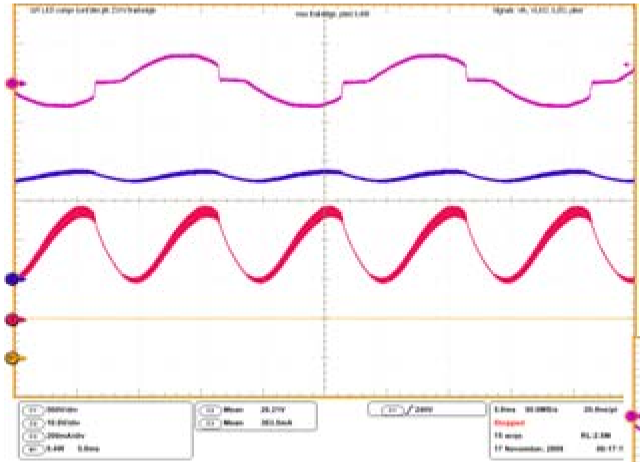
Medium Dimming-Level



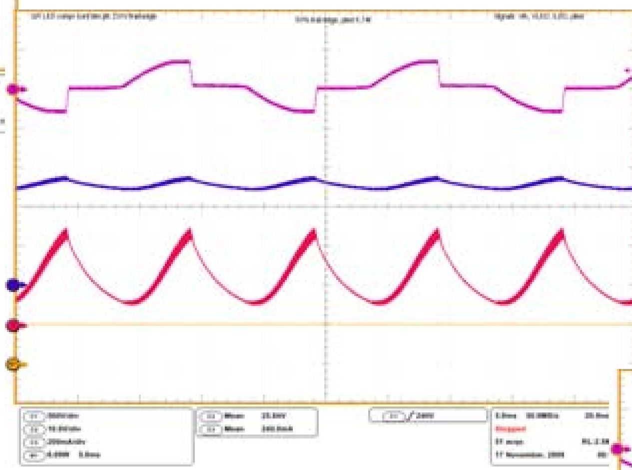
Minimum Dimming-Level

Reference Dimmer : Ehmann Lumeo Domus 1060 60-300W

Phase Cut Dimming – Trailing Edge



Maximum Dimming-Level

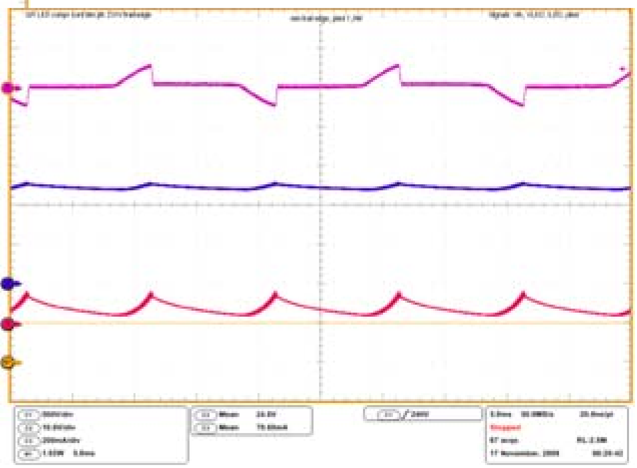


Medium Dimming-Level

Vin

Vout

Iout



Minimum Dimming-Level

Reference Dimmer : Ehmann Lumeo Domus 4660 20-315W

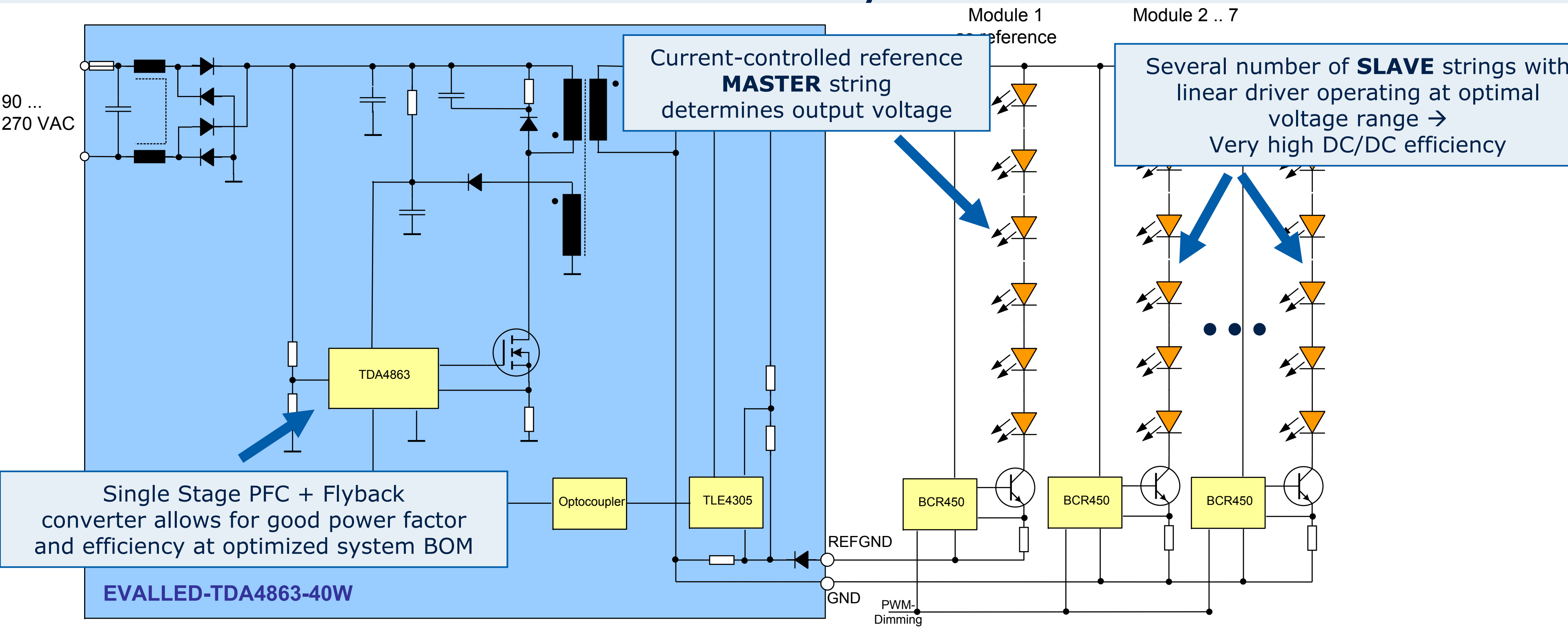
LED Bulb Driver with ICL8001G Feature Summary

- Best in class BOM cost with 30% material cost reduction
- Isolated Driver output for efficient thermal management
- High quasiresonant (QR) flyback driver efficiency up to 90%
- High power factor PF > 98% adjustable
- Phase cut controlled continuous LED current dimming
- Primary side output power control
- Small formfactor fits E27 bulb
- Cycle by cycle current limitation
- Output short circuit and output over voltage protection
- Over temperature detection

Backup material

- Additional PFC corrected LED solutions from Infineon.

Single Stage PFC with Fly-back combined with linear drivers on secondary side

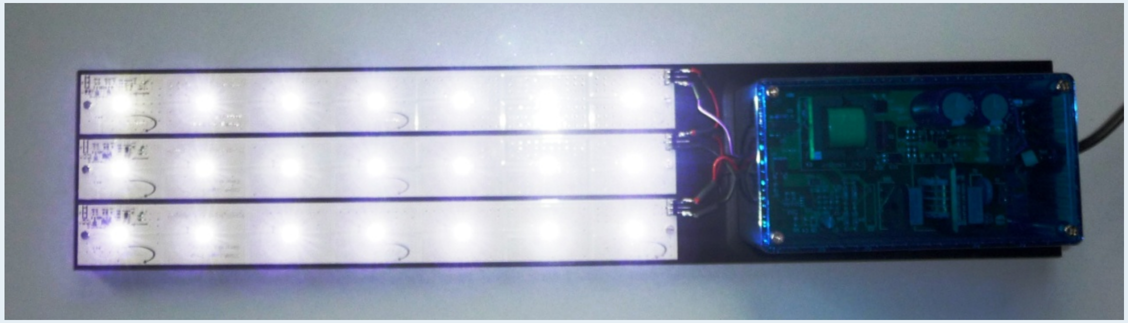


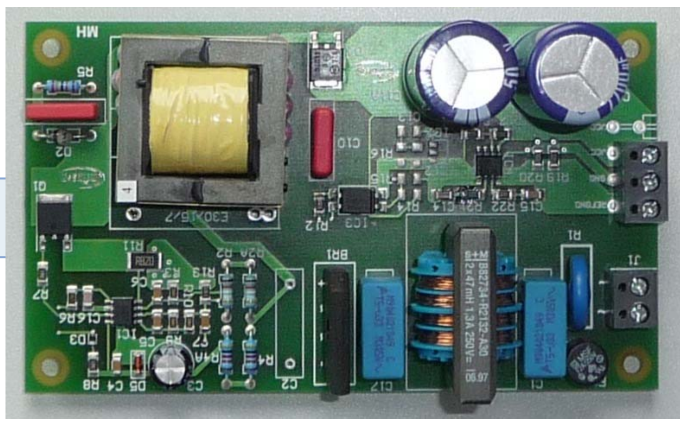
Optimized System Solution:

Combination of single-stage PFC + Flyback AC/DC converter, constant current control and linear drivers allows

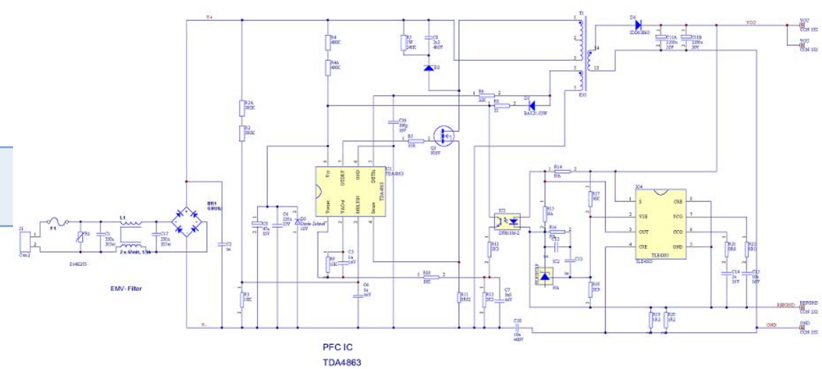
- high power factor,
- high efficiency and
- no EMI on secondary side

Off-Line LED Driver Solution
40W Single Stage Evaluation Board





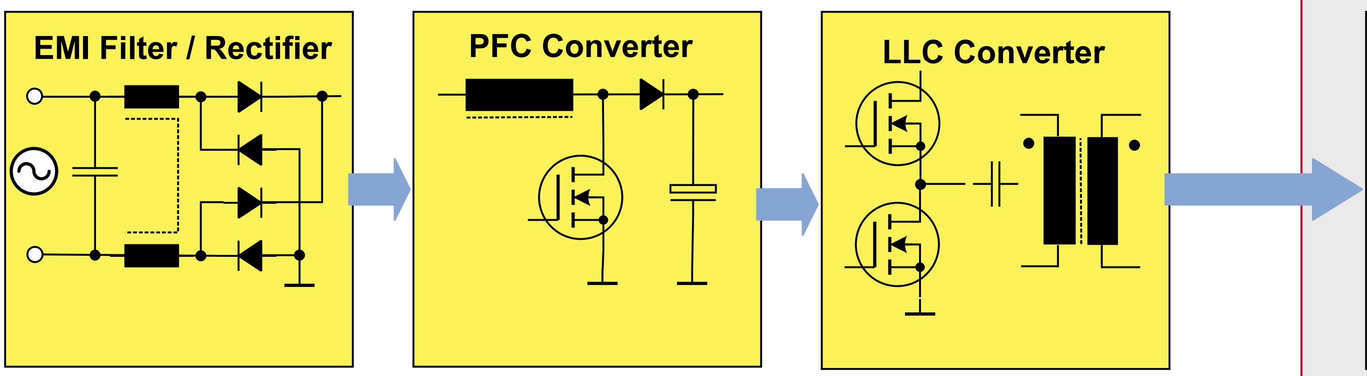
Order Code EVAL-LED-TDA4863G-40W



- TDA4863 Flyback controller & PFC in a single stage topology
- TLE4305 CV CC Feedback
- Optimised for low cost multi LED string system with BCR450 linear current regulators
- Scalable and low cost BOM

- 40W Output: Input 190-270V AC
- 20W Output: Universal Input
- Variable, Stable Output (15V-25V)
- High Efficiency ~88% (AC to LED)
- High Power Factor >0.9
- **Order Code EVAL-LED-TDA4863G-40W**

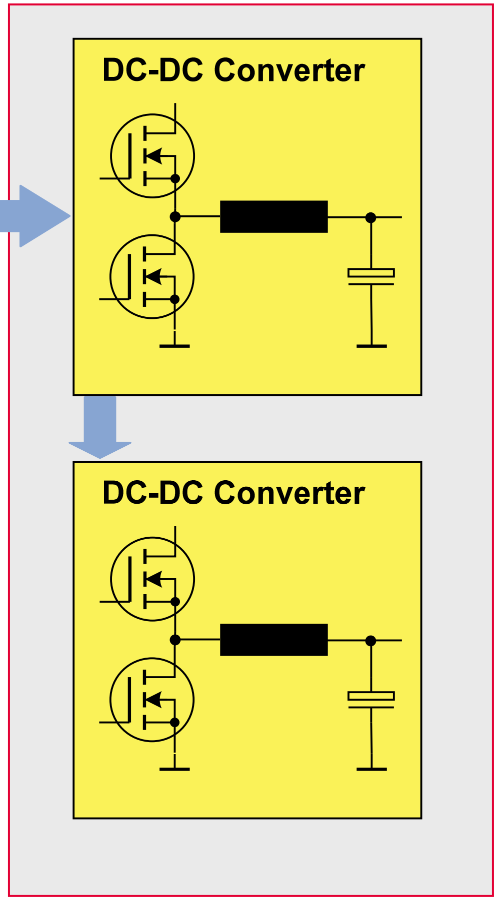
High Power Lighting Power Supply Architecture PFC+LLC [+DC-DC]



DCM PFC
TDA 4863-2
ICE2PDS01

CCM PFC
ICE2PCS0x
ICE3PCS0x

LLC
ICE1HS01G
ICE2HS01G



infineon

Never stop thinking