Reinhold Environmental Ltd.

2008 APC Round Table
& Expo Presentation

July 13-15, 2008, in Savannah, GA

Theory of high frequency power supplies

2008 APC/PCUG Conference, Savannah

Per Ranstad

PSP Environmental R&D

14/7/08

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Outline

1.	Introduction	10min
1.	Theory of operation	25min
2.	Aspects on ESP operation and efficiency	15min
3.	Discussion	10min

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1 Introduction

1. Introduction
    1. Why 'High frequency power conversion' ?
    2. History

2. Theory of operation

3. Aspects on ESP operation and efficiency

4. Discussion

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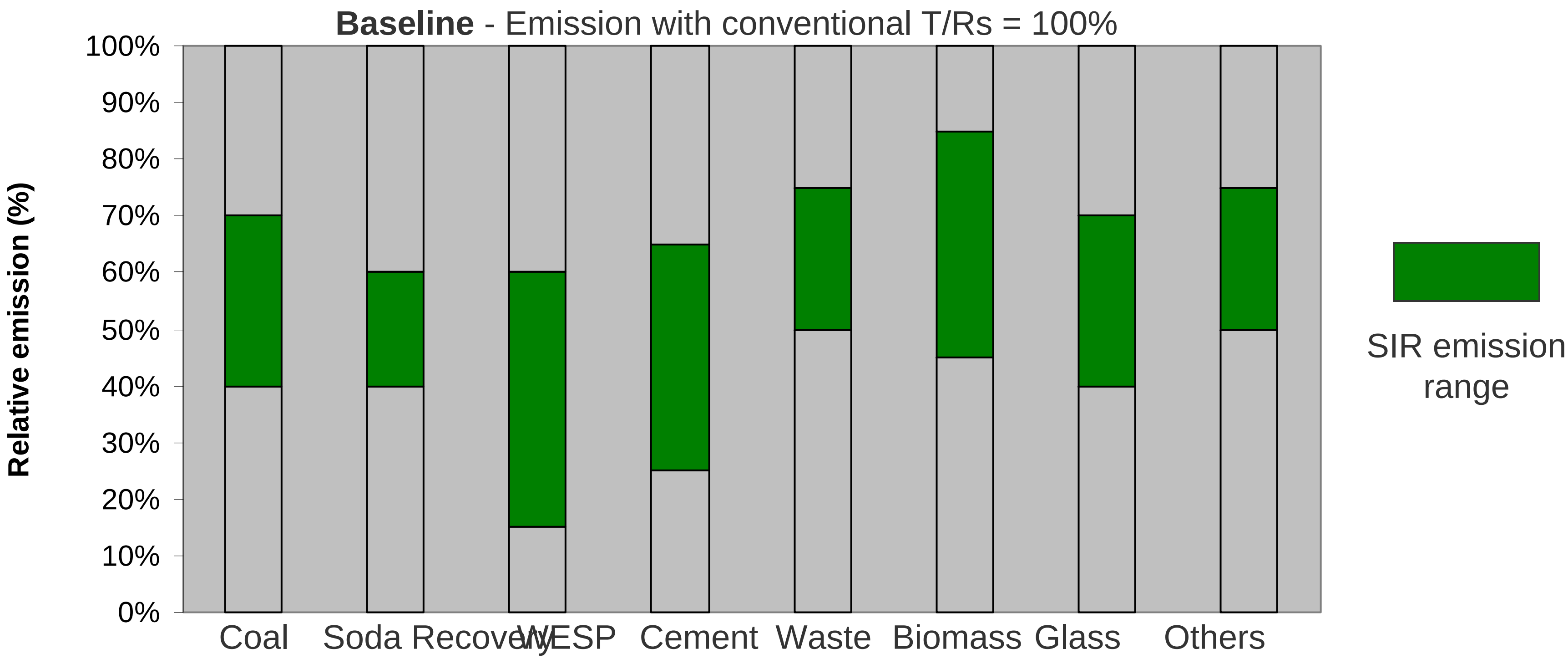
Why High frequency power supplies ?

No. of SIRs by Application & corresponding SIR emissions



	Coal	Soda Recovery	WESP	Cement	Waste	Biomass	Glass	Others	
No. SIRs	360	155	108	99	57	130	52	59	Total: 1020 SIR
No. ESPs	38	59	43	37	25	77	18	21	at 318 plants
	(15.000 MWe)								

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History, Early High frequency ESP power supplies, Prototypes

60kV, 200mA, (80kHz) -89

(smps, mosfet)

Field tested on: Coal fired boilers,

Bio mass

80kV, 250mA, (25kHz) -91

(resonant, IGBT)

Field tested on: Coal fired boilers,

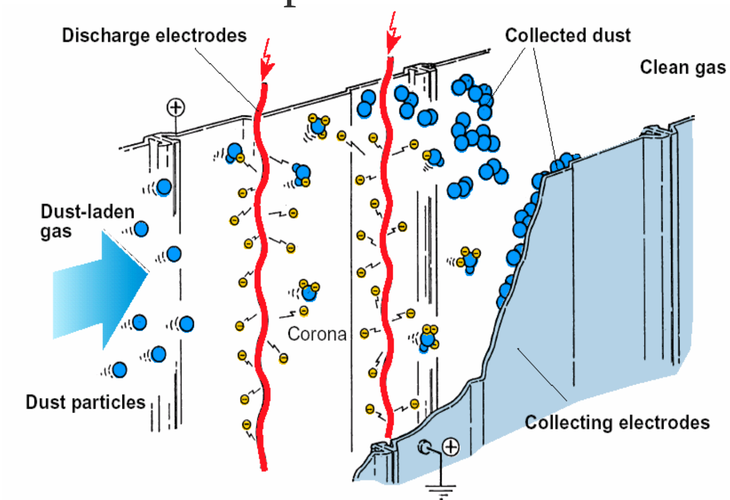
Bio mass

Soda recovery

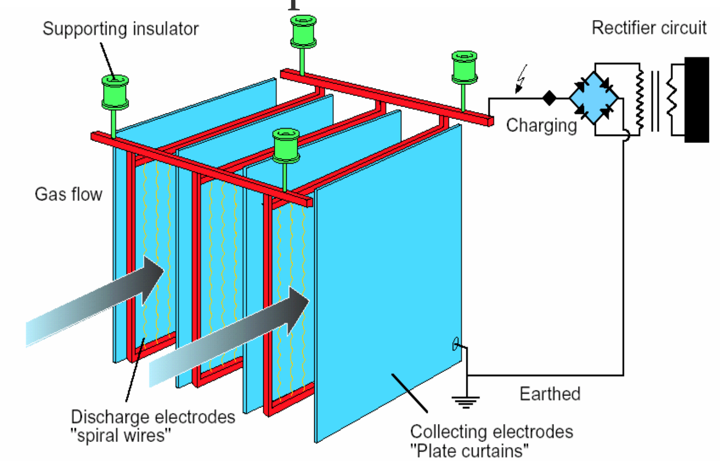
Electrostatic precipitation

Power plant

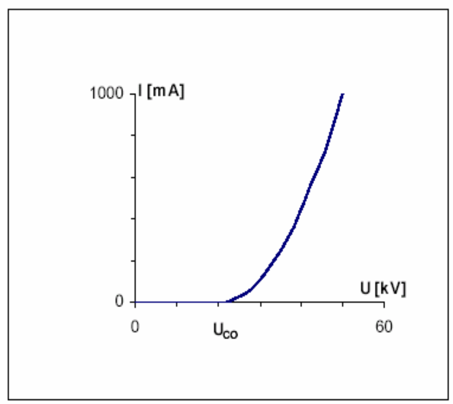
Operation



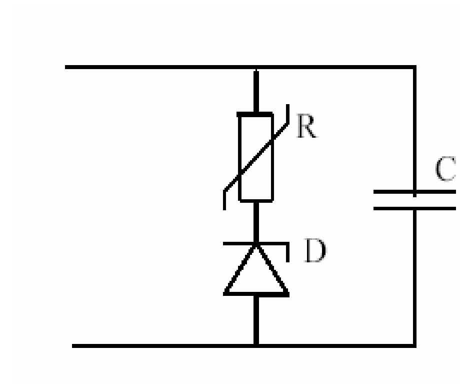
Implementation



Load characteristic



Model



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An ESP power supply comparison

SIR

High frequency power supply

Mains frequency power supply

160 kg

200 kg + 800 kg

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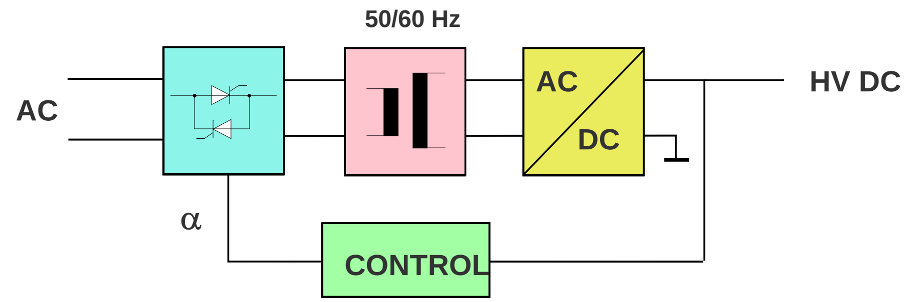
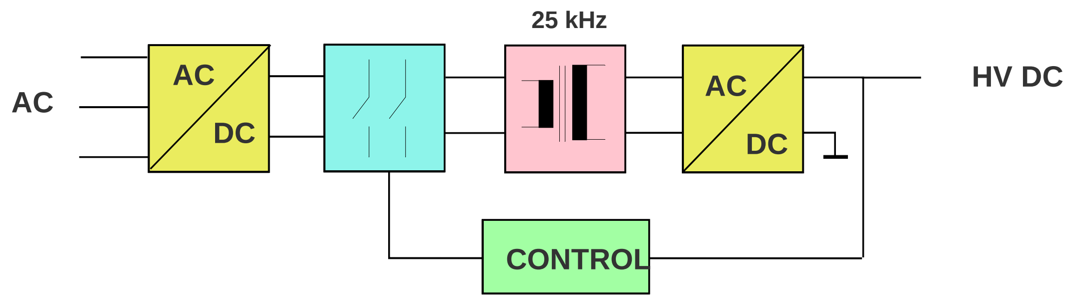
Power processing

Mains frequency power processing



High frequency power processing



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2 Theory of operation

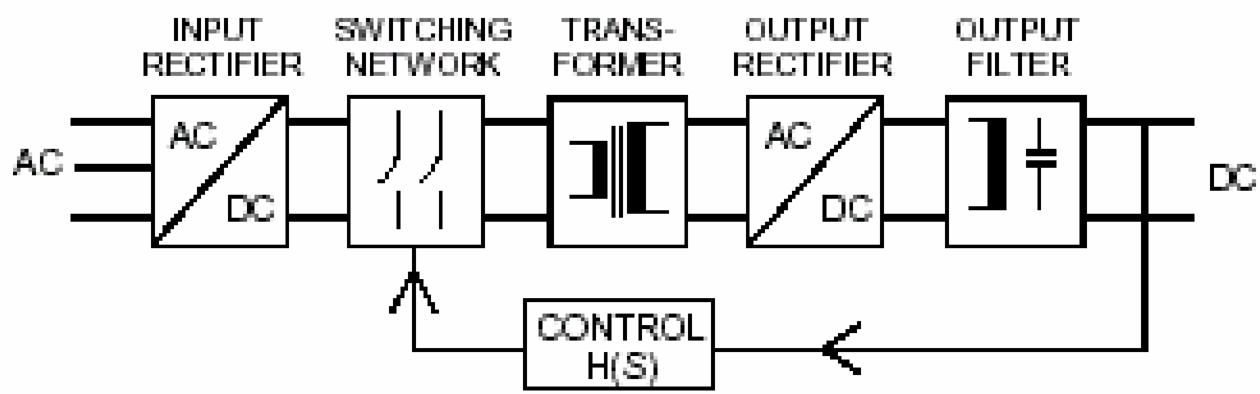
1. Introduction

2. Theory of operation
    1. Basic circuits
    2. The ESP as an electric load
    3. Key components
    4. System properties

- Aspects on ESP operation and efficiency

1. Discussion

High frequency power converter



- Switch mode power converters, SPC
- Resonant mode power converters, RPC
- Quasi resonant power converters

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High frequency power conversion, general

Pro

- Energy per cycle
  - Size
  - Control
- Induction
  - Transformer

$$P = f \cdot W \Rightarrow W = \frac{P}{f}$$

$$e = -\frac{d\phi}{dt} = -\frac{A \cdot dB}{dt}$$

Con

- Switching losses
- High frequency conduction losses
  - Skin effect

$$P_{sw} = f \cdot W_{sw} \ , \ W_{sw} = \int_{Tsw} u \cdot i \, dt$$

$$\lambda = \frac{K}{\sqrt{f}}$$

0.1mm at 100kHz

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Load characteristics, ESP

- Capacitve load
  - 20-200nF, T>1ms
- Voltage source characteristic, voltage stiff
- Sparkover
  - T_f=1us
- Wide operating range
  - $0<I<I_N$
  - $0<U<U_N$

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Power supply for ESP

Demands

- Current source characteristics (voltage stiff load)
- Short-circuit proof (spark overs)
- High efficiency
- Wide load range (0-100%)
- Voltage-source driven (Mains)
- Capacitive output filter (ESP capacitance)
- Handle transformer parasitic components
- Minimize the number of components on the high-voltage side

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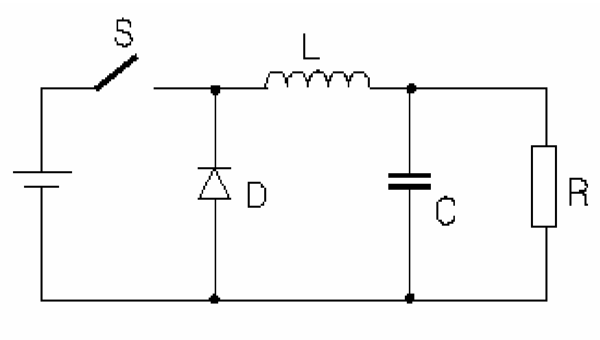
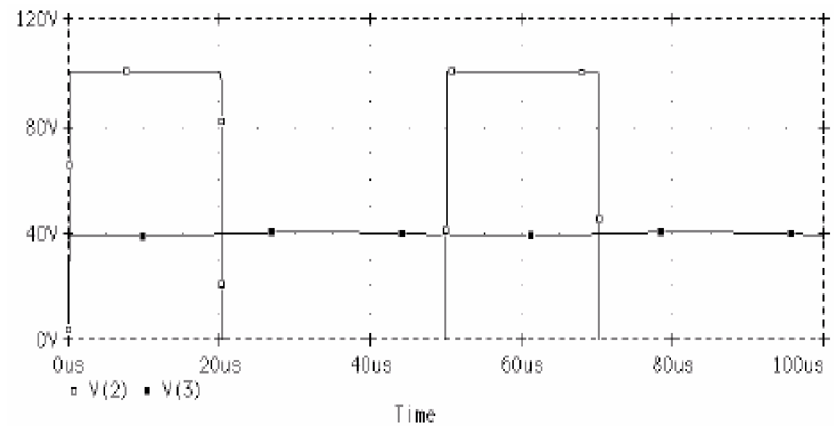
Basic SPC-circuits

Buck (Step down)

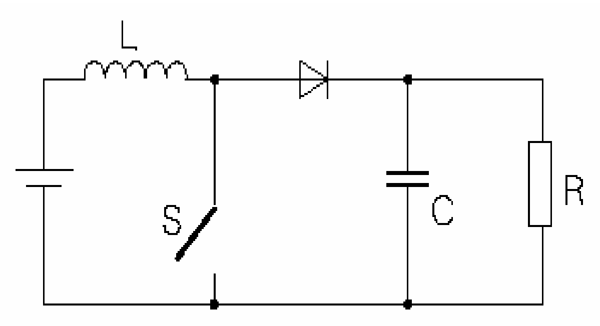
M=d

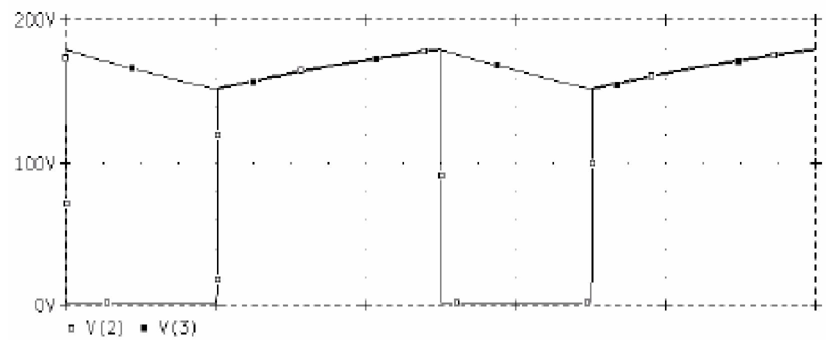




Boost (Step up)

M=1/(1-d)





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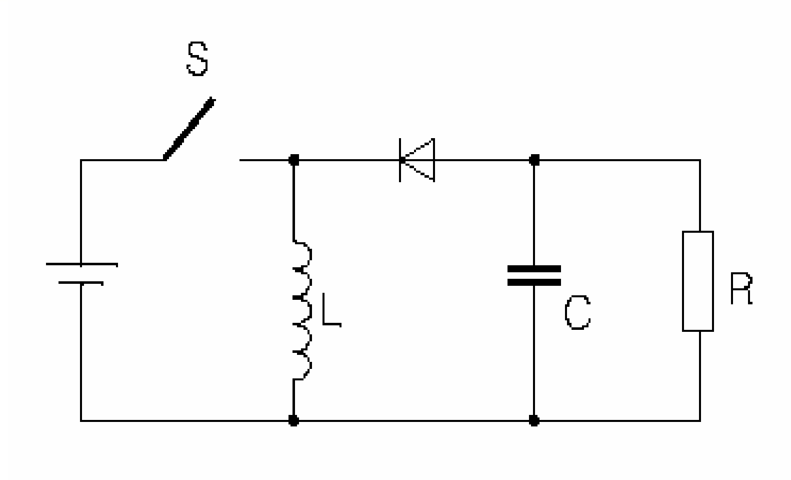
Cascaded SPC circuits

Buck-boost
(Flyback)

M=d/(1-d)

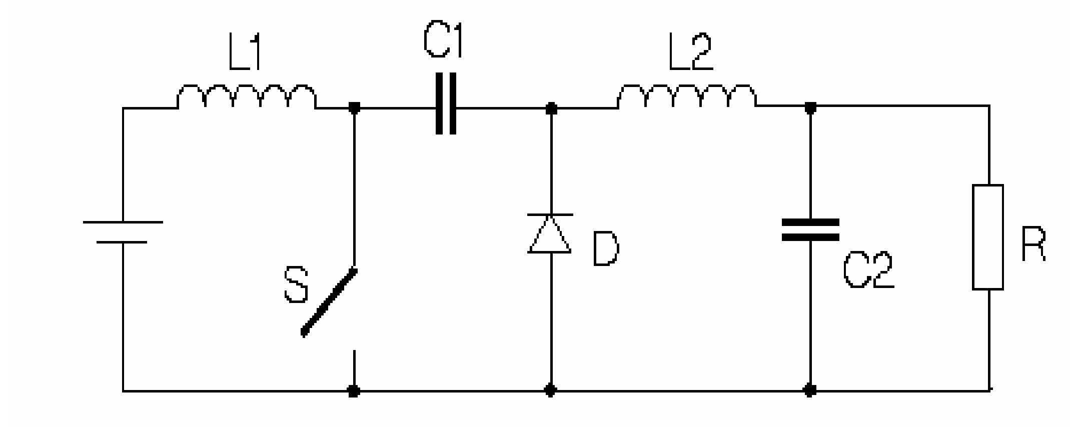


4.6

Boost-buck

(Cuk)

M=d/(1-d)



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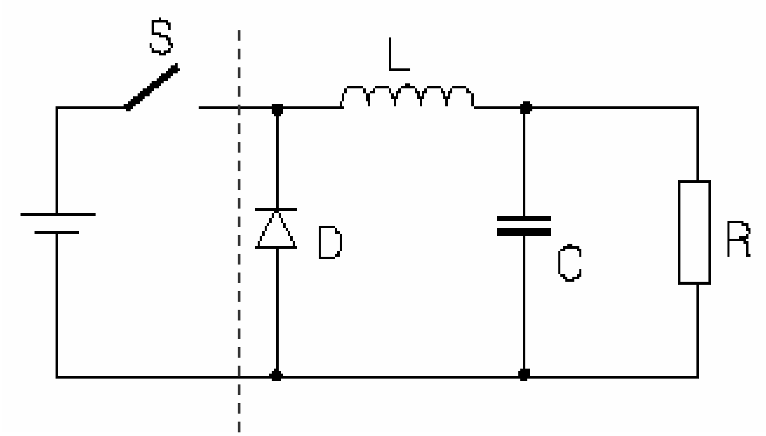
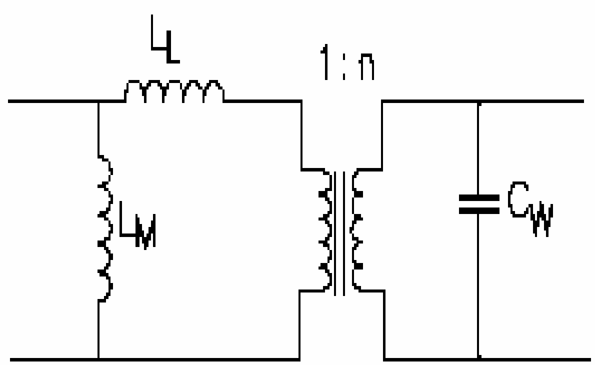
Prototype 1, comments

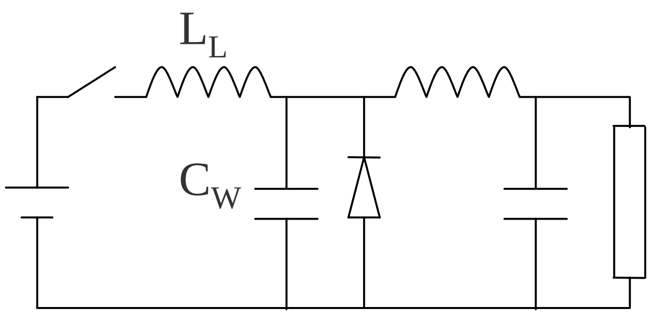
Buck-converter



Non-ideal transformer



Resonant-switch converter



PCL

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SPC circuits, evaluation

Pro

- Simple circuitry
- Few components
- Easy to analyze

Con

- Hard switching
- Not tolerant to parasitic elements
- High losses

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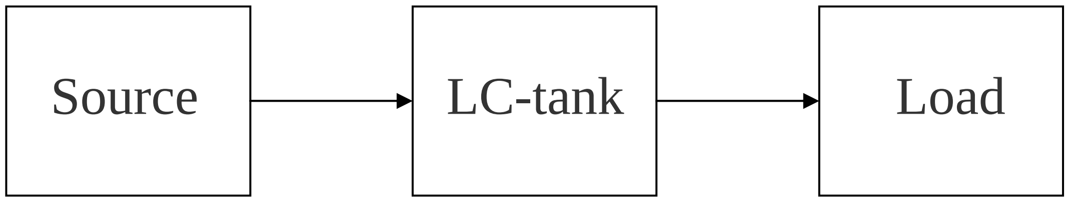
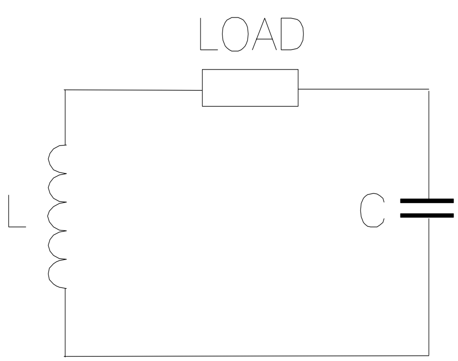
RPC, Load-resonant converters

General

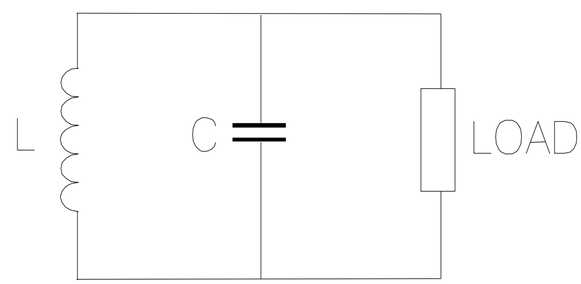


4.8

Series-loaded, SLR



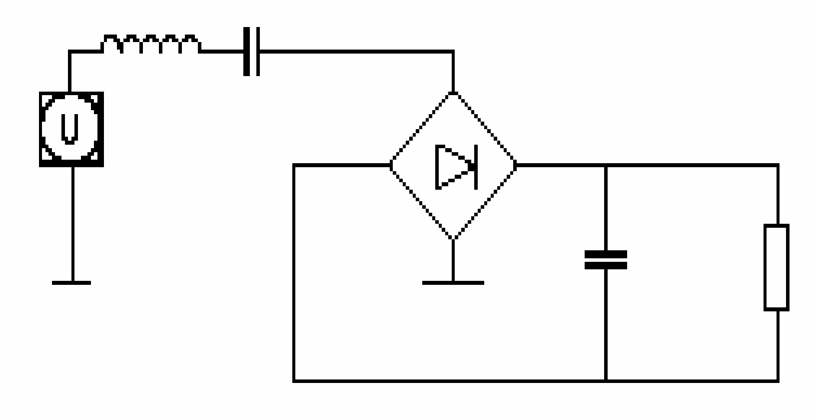
Parallel-loaded, PLR



4.9

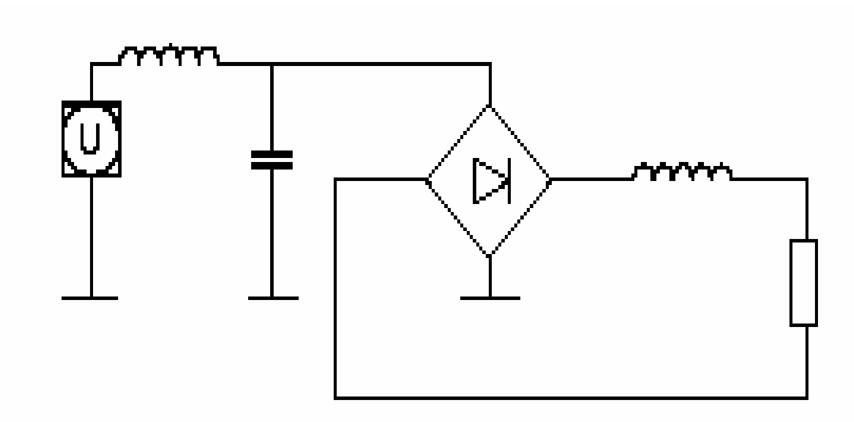
Load-resonant converters

SLR



$$f_0 = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

PLR



$$Z_0 = \sqrt{\frac{L}{C}}$$

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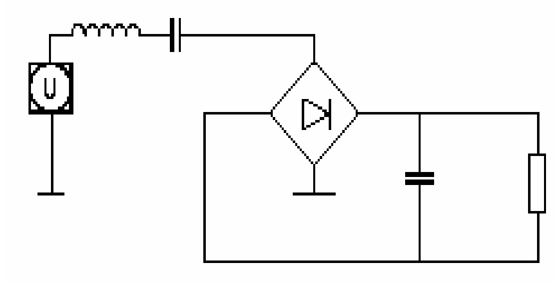
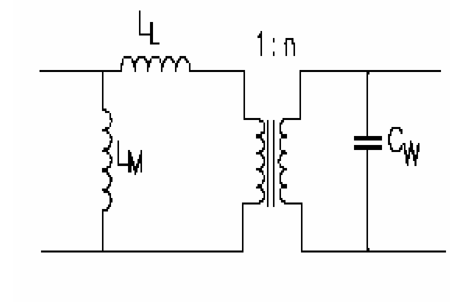
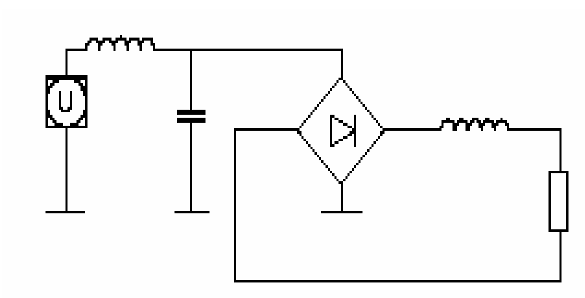
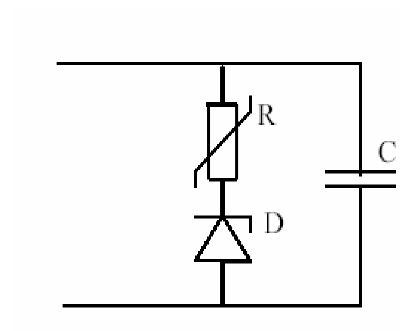
Load resonant converters









- SLR and PLR can utilise transformer parasitics in the operation
- SLR can utilise the load capacitance in the output filter

SLR is the preferred topology

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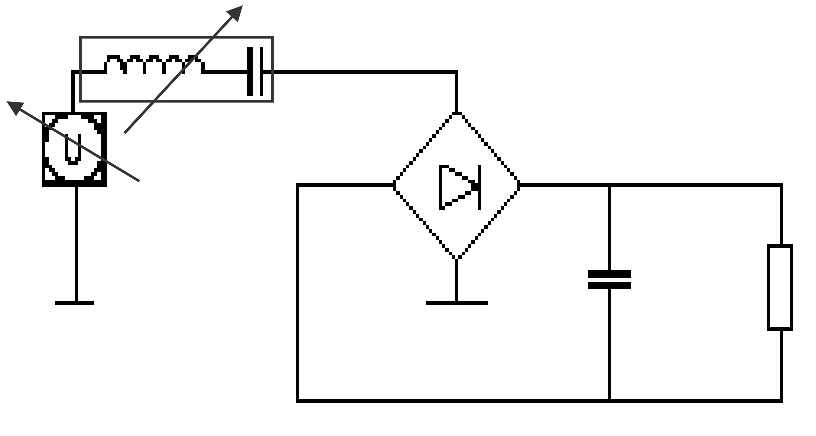
SLR, Control



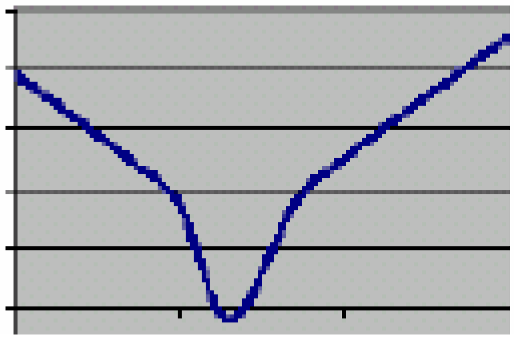
•Control of LC-tank impedance

  •Frequency modulation

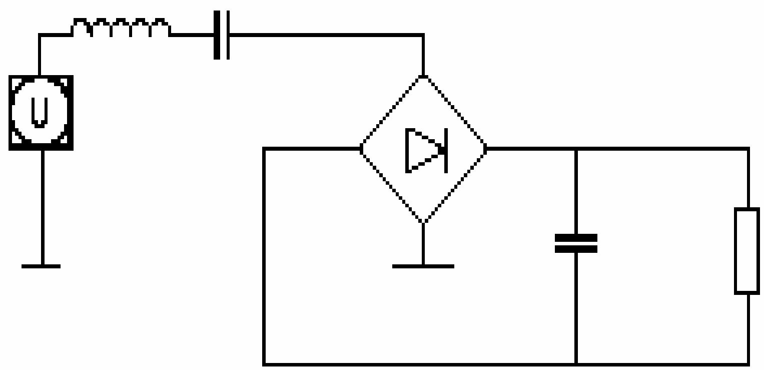
•Control of voltage-source amplitude

  •Phase-shift modulation

Tank impedance vs frequency



SLR, frequency modulation



Mode1 $0 < d < 1/2$

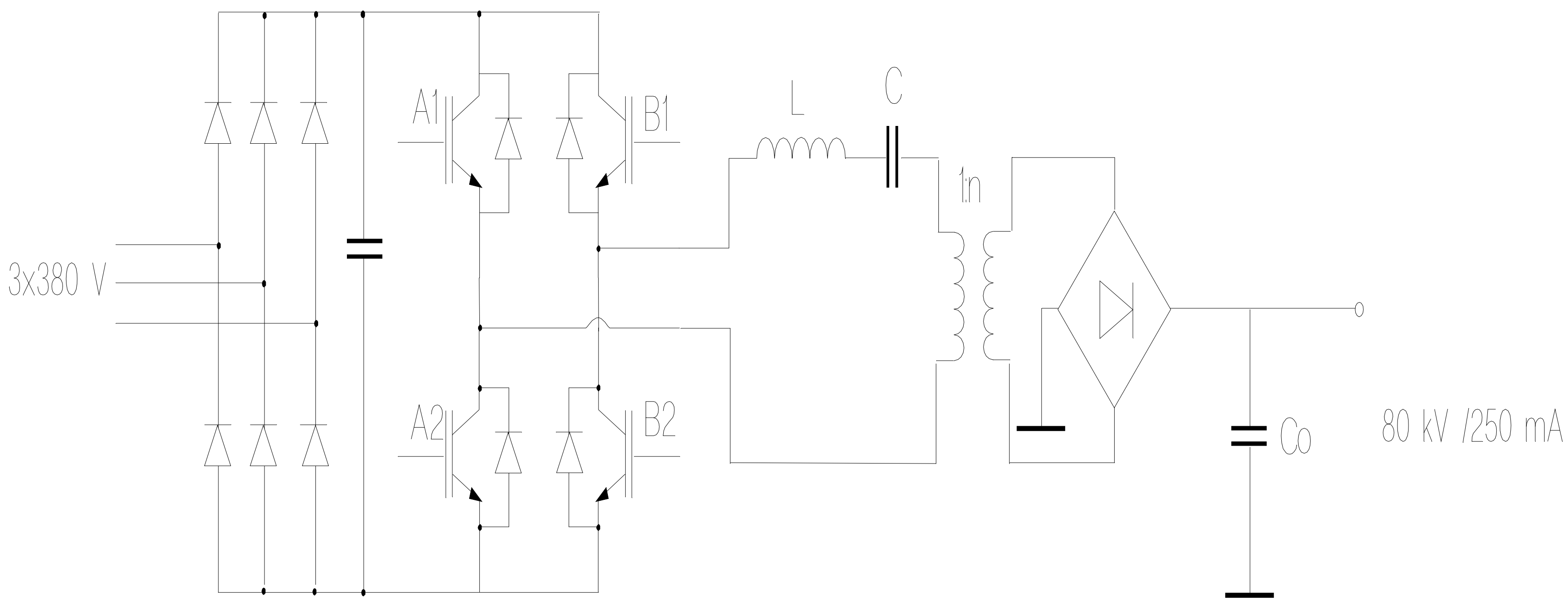
Mode2 $1/2 < d < 1$

Mode3 $d > 1$

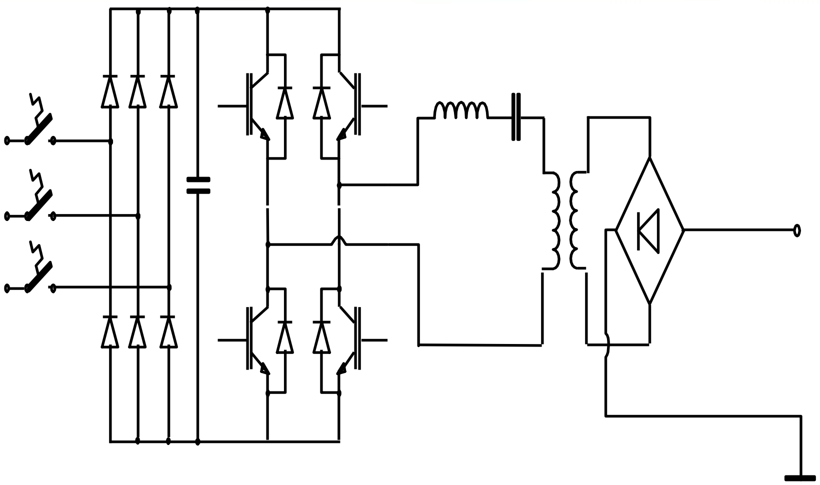
normalized frequency

$d = fs / fo$

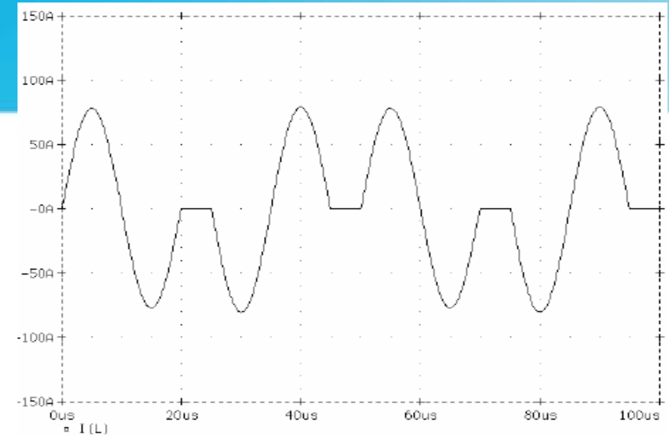
SLR, Circuit diagram



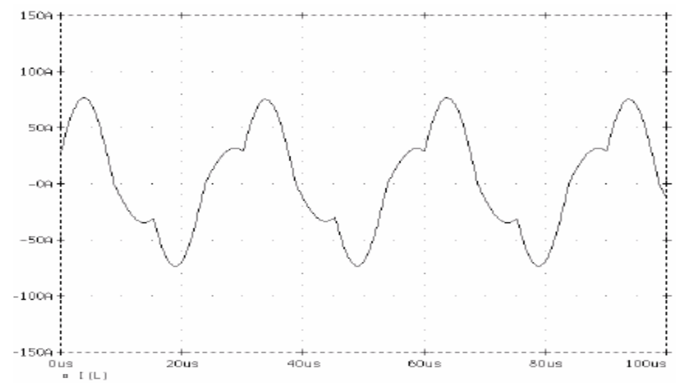
SLR, frequency modulation



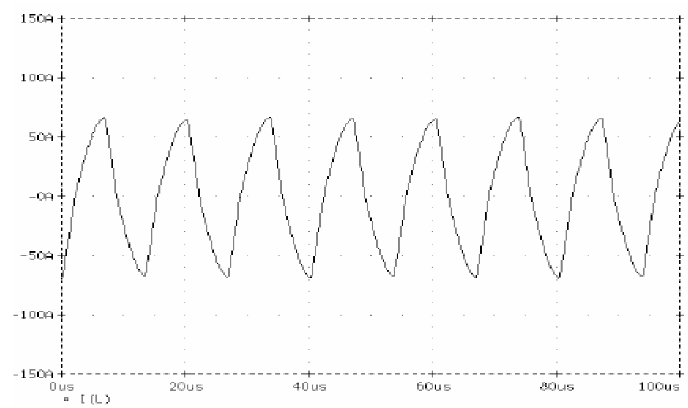
Mode1



Mode2



Mode3



Mode1 $0 < d < 1/2$

Mode2 $1/2 < d < 1$

Mode3 $d > 1$

SLR modes of operation, FM

Mode 1

- PRO
  - Easy to control
    - I ~ f
  - Soft turn-off
    - ZVS, ZCS
- CON
  - Discontinuous conduction
    - High RMS current (k > 1,57)
    - High component stress
    - High losses

Mode 2

- PRO
  - Continuous conduction
  - Soft turn-off
    - ZVS, ZCS
- CON
  - Hard turn-on
    - Diode reverse recovery
    - High losses

Mode 3

- PRO
  - Continuous conduction
    - Lowest RMS current (1.11< k < 1,15)
  - Soft turn-on
    - ZVS, ZCS
- CON
  - Hard turn-off
    - Capacitive snubber

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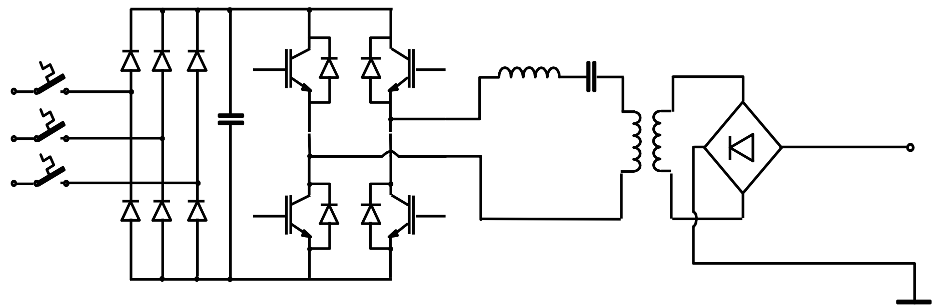
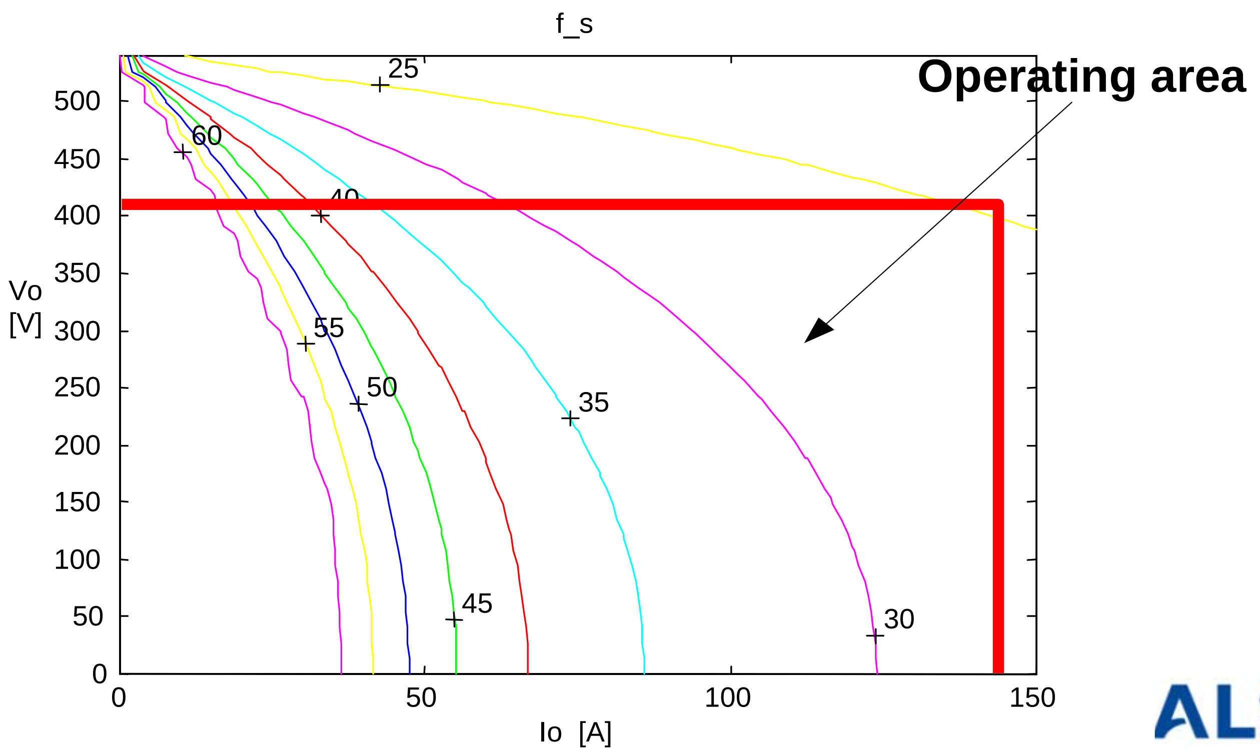
Control loop, FM-control





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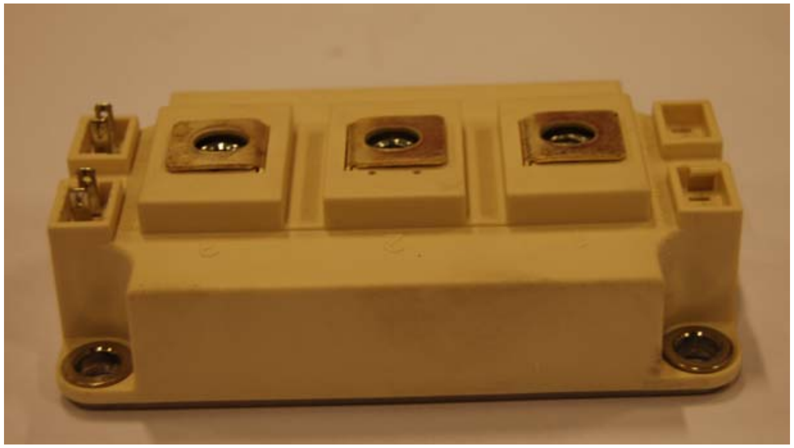
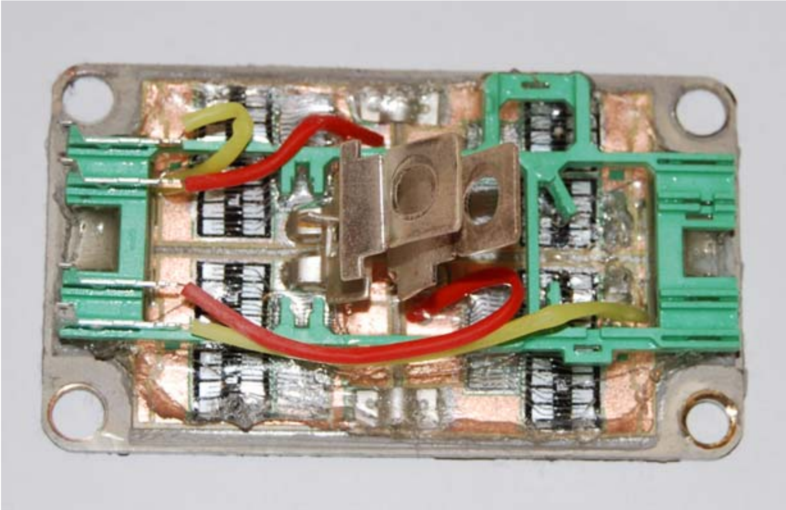
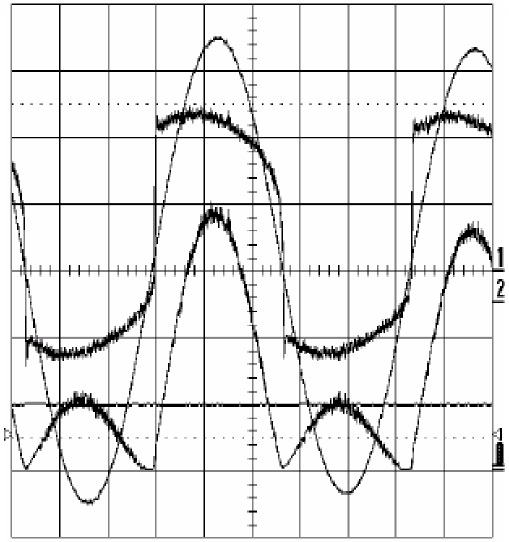
IGBT, On-state voltage vs di/dt

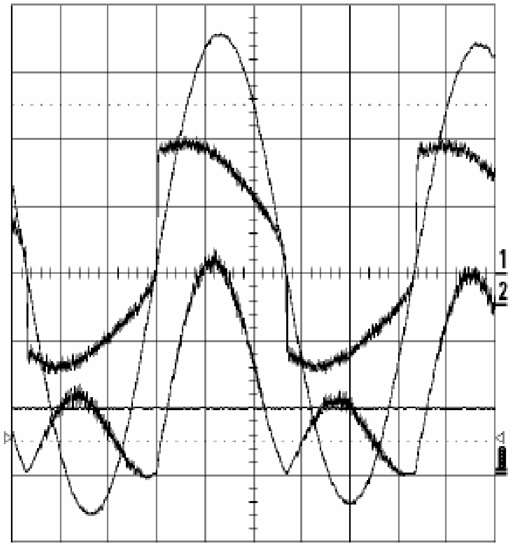




IGBT1



IGBT2



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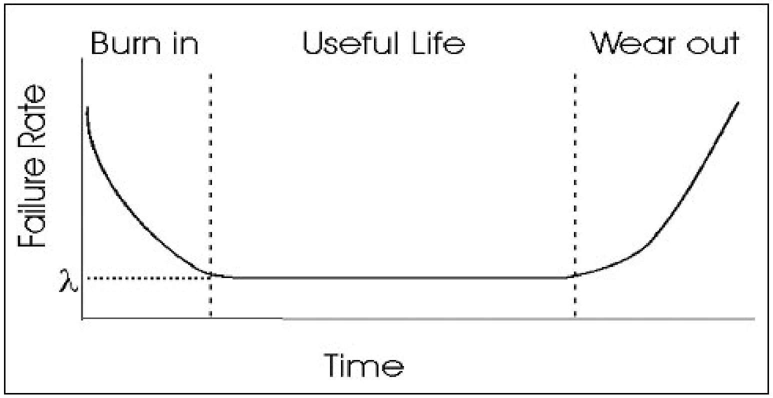
Reliability

<u>General</u>

- Integrated system
- Less material
- Bridge-leg conf
- Environment
- Availability



<u>Measured</u>

- Fleet MTBF 30 years
- Failures concentrated to specific plants

$$MTBF = \frac{Operating}{No\ of\ \ failures} = \frac{1}{\lambda}$$

<u>Comments</u>

- Installation
- Trained technicians
- Components
- Maintenance

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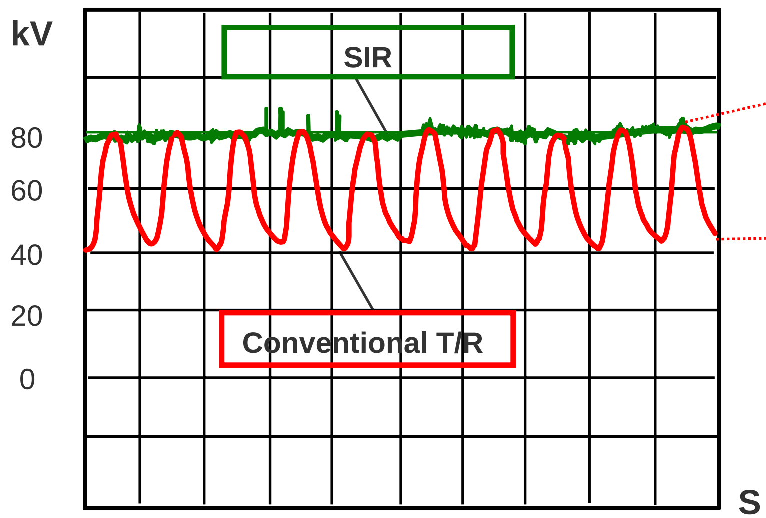
3 Aspects on ESP operation and efficiency

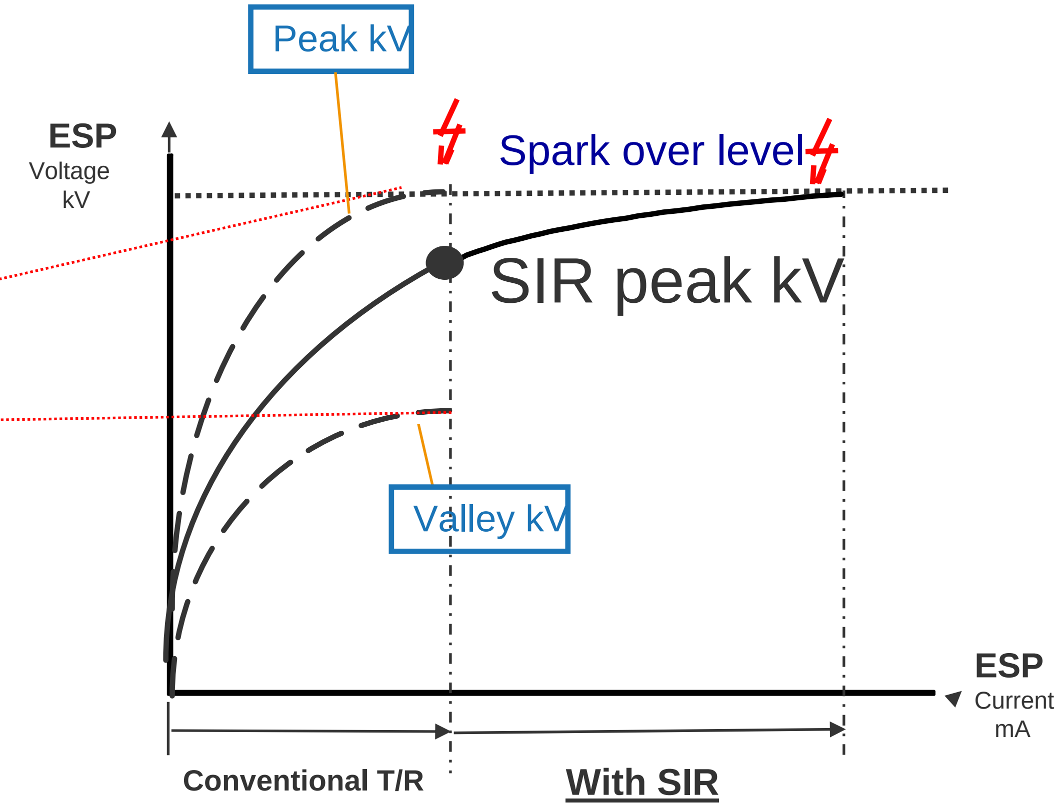
1. Introduction

2. Theory of operation
3.
4. Aspects on ESP operation and efficiency
    1. Corona current
    2. ESP voltage
    3. Holding forces /rapping /reentrainment
    4. Spark recovery
    5. Back-corona/Intermittent Enrergisation

5. Discussion

Aspects on ESP operation and efficiency
Corona current





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Aspects on ESP operation and efficiency
Voltage

Due to the non-linear current voltage dependency,

$I = I_0 (U - U_{onset})^n$, $U > U_o$, $n>1$ (2)

will the high frequency power supply give a higher average voltage compared to the mains frequency power converter for the same current.

Ex: U_{ONSET} = 20 kV, I(60kV) = 1A, n=2

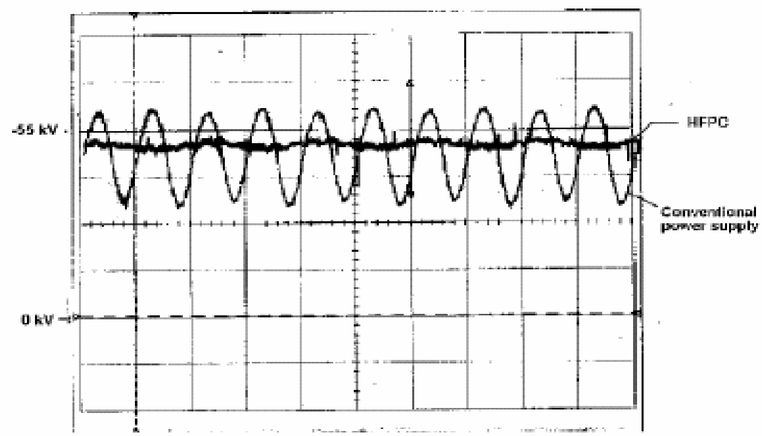
1: I= 1A (50%), 0.1A (50%)

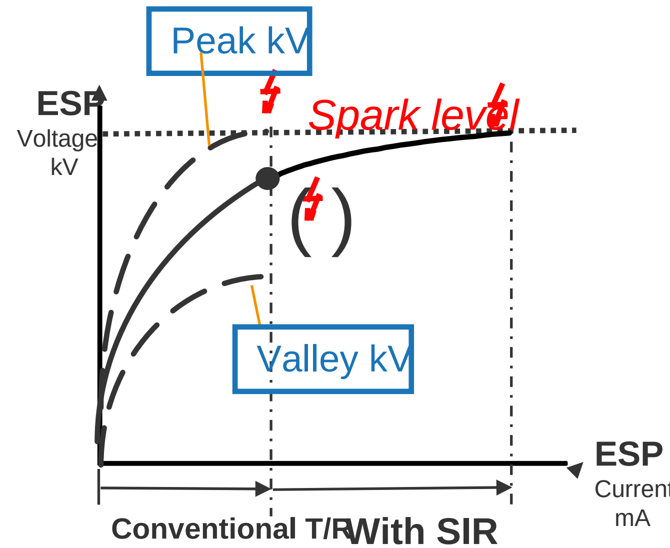
U (1A) = 60kV, U(0,1A)=32.6kV

=> ***U_{AVG}=46.3kV, I_{AVG}=0.55A***

2: I= 0.55A (100%),

U(0.55A) = 49,7kV





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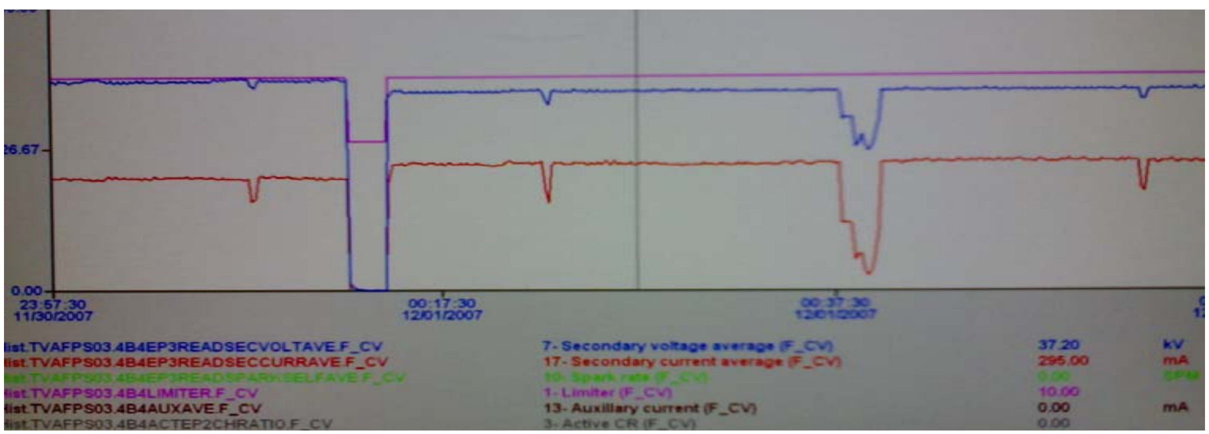
Aspects on ESP operation and efficiency
Corona current, ESP Voltage

- More mA for same peak Voltage means better particle charging
- More mA means higher holding forces, means less risk of reentrainment.
- More kV means better utilisation of the collector area

Aspects on ESP operation and efficiency
Rapping/reentrainment

- Higher holding forces, means that greater care has to be taken during rapping to really clean the electrodes.

Dust build up due to inadequate rapping in a Soda recovery recovery boiler ESP.
The corona centres can be clearly seen resulting in a reduced Voltage clearance.



Power Control rapping vs Normal rapping

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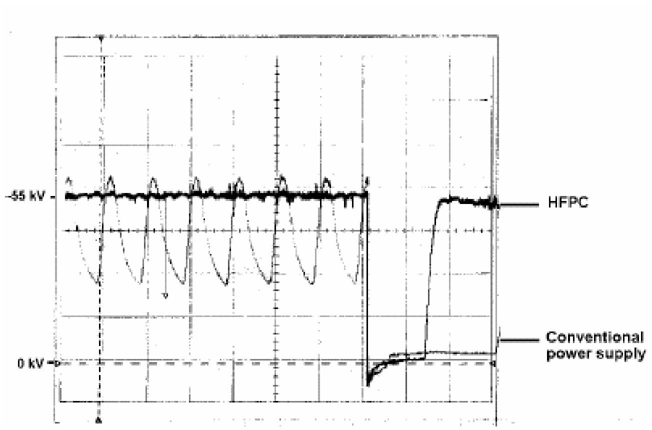
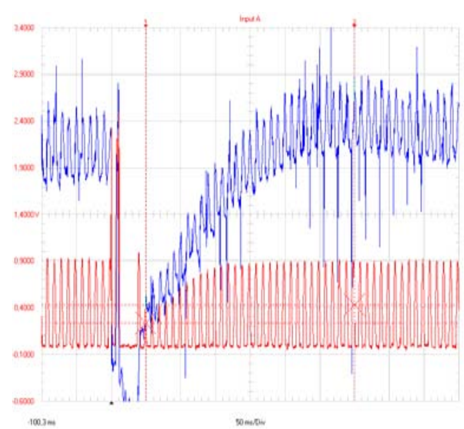
Aspects on ESP operation and efficiency
Spark recovery





- Transistor control means faster response to spark overs. Current fed to the bus section can be turned off, within micro-seconds.
- Superior bandwith of the control loop (faster) enables improved spark recovery.

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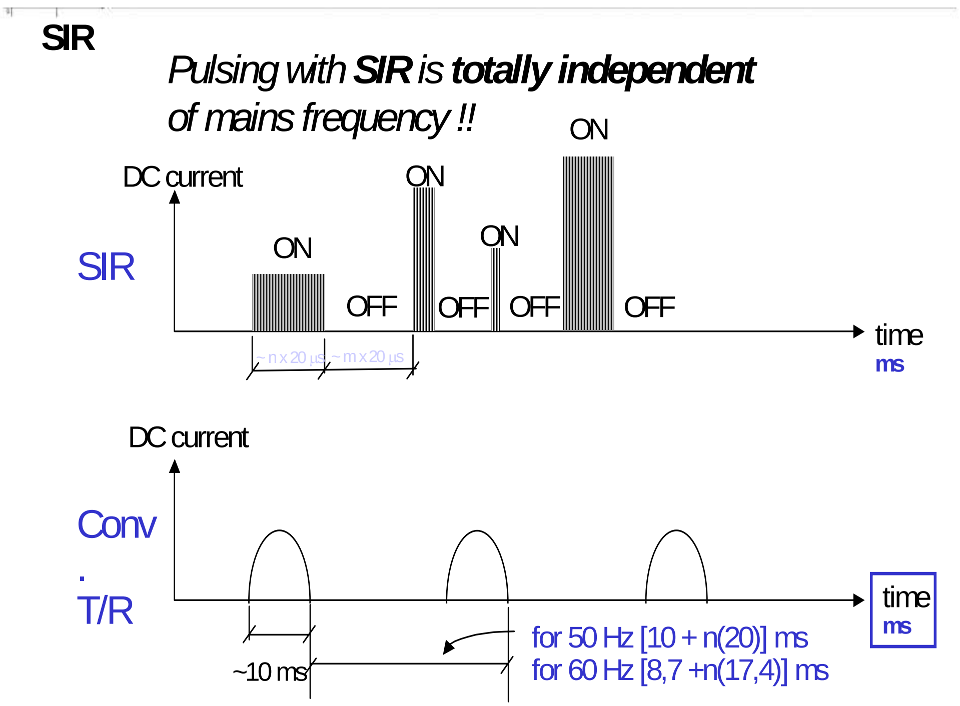
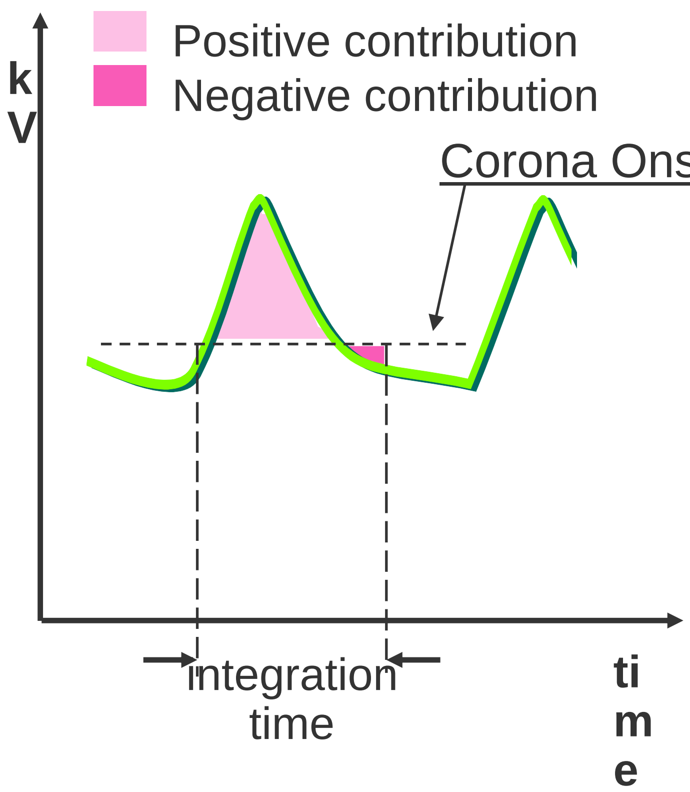
Intermittent Energisation

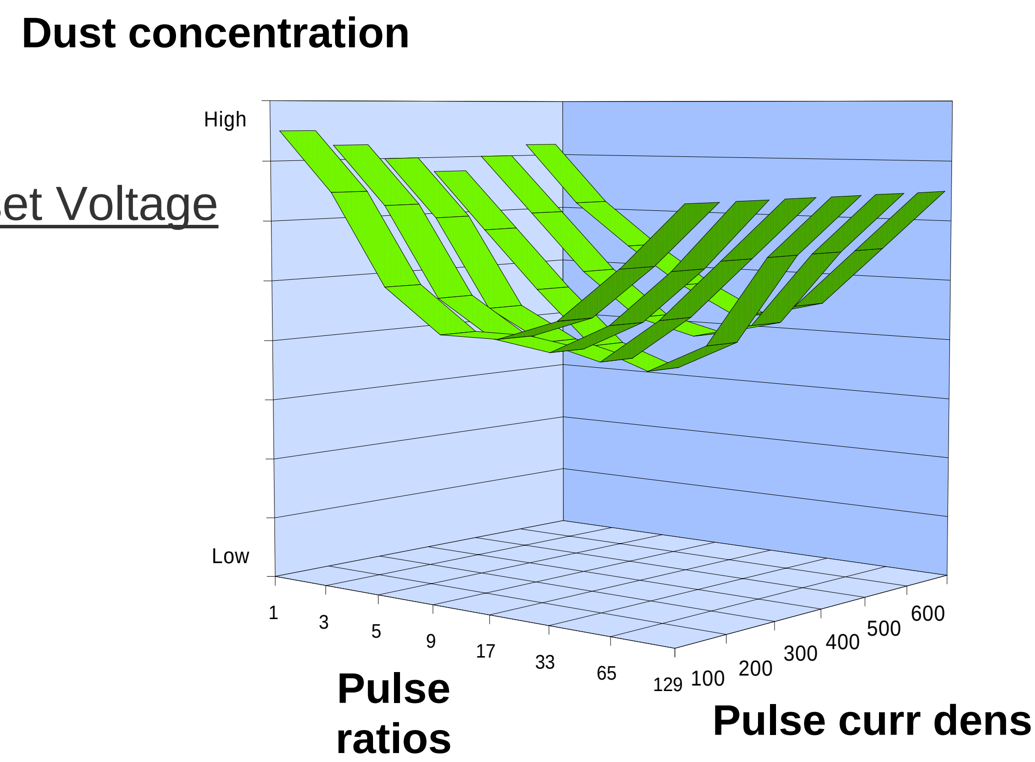


- The more exact control paired with the higher frequency offers the chance for a more detailed approach for back-corona control. The corona control can be executed faster with higher precision with exact control of pulse duration, pulse amplitude and puls cycle for full flexibility in addressing Back-Corona

Aspects on ESP operation and efficiency
Back-corona/Intermittent Energisation

EPOQ operation





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