POWER CONVERTERS FOR INDUSTRIAL INDUCTION HEATING APPLICATIONS

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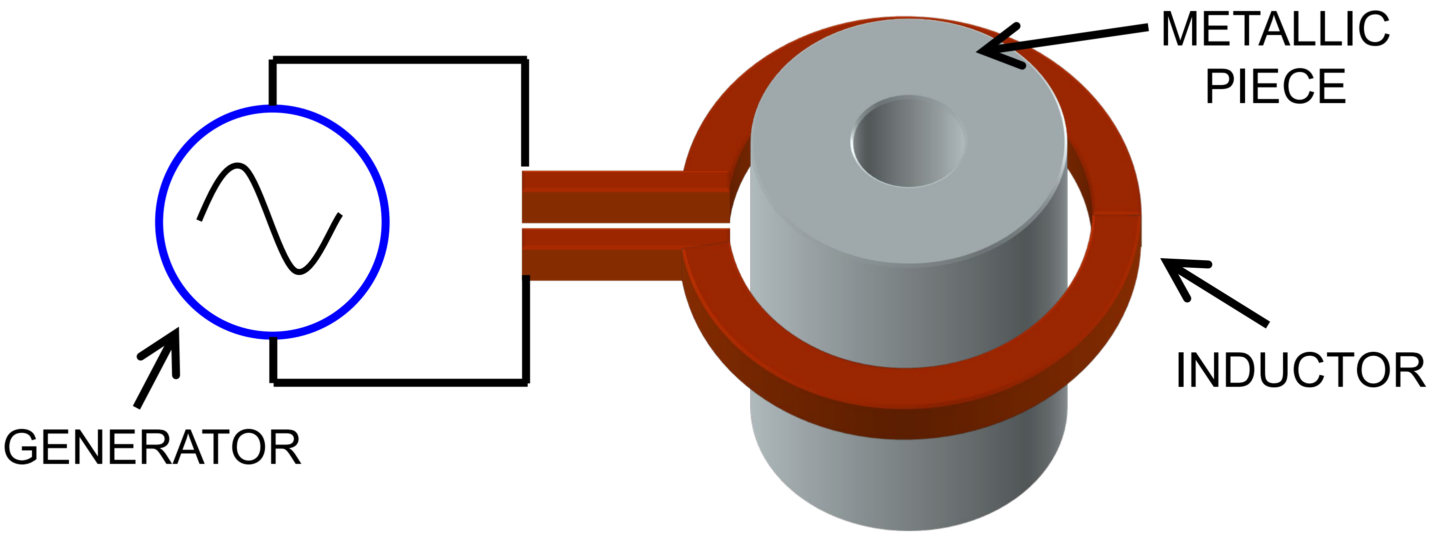
Seminario: Aplicaciones industriales del calentamiento por inducción

Outline

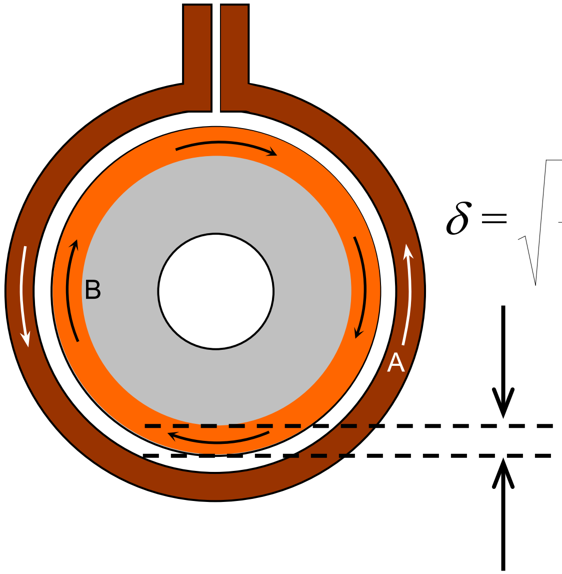
- ✓Basic Concepts in Induction Heating
- ✓ Compensation of the Load
- ✓Series Resonant Converters for IH
- ✓Parallel Resonant Converters for IH
- ✓Semiconductors used in IH
- ✓Applications
  - ✓Forging
  - ✓Hardening
  - ✓Multipurpose Generators
  - ✓Bonding
  - ✓Welders
- ✓Controllers
- ✓Roadmap

Basic Concepts in IH

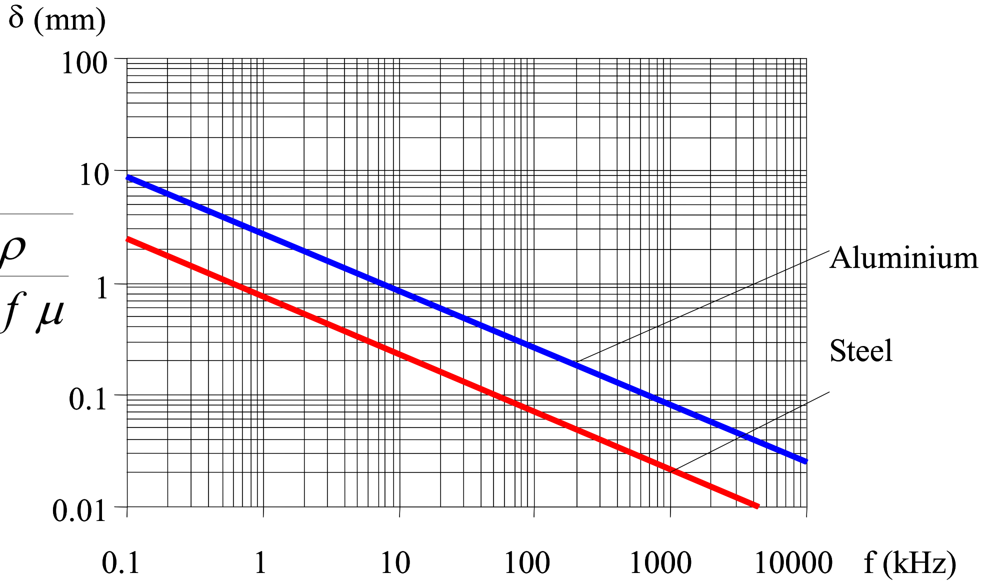


A: Inductor current

B: Induced current



$$\delta = \sqrt{\frac{\rho}{\pi\ f\ \mu}}$$



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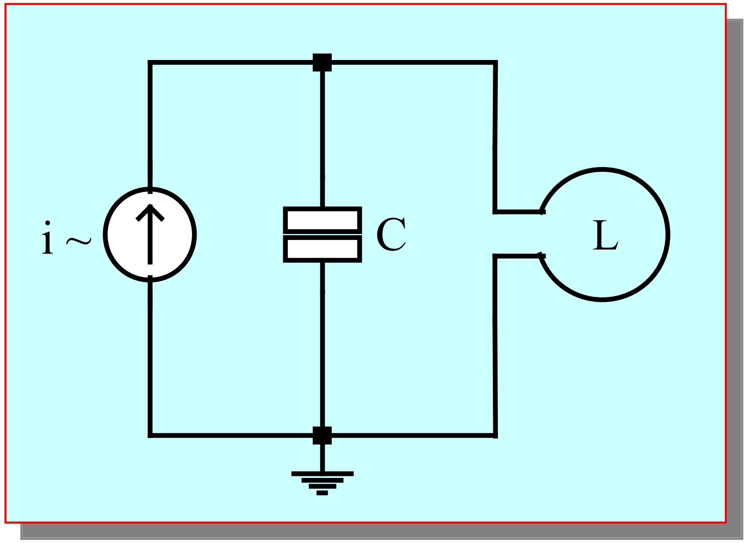
Compensation of the Load

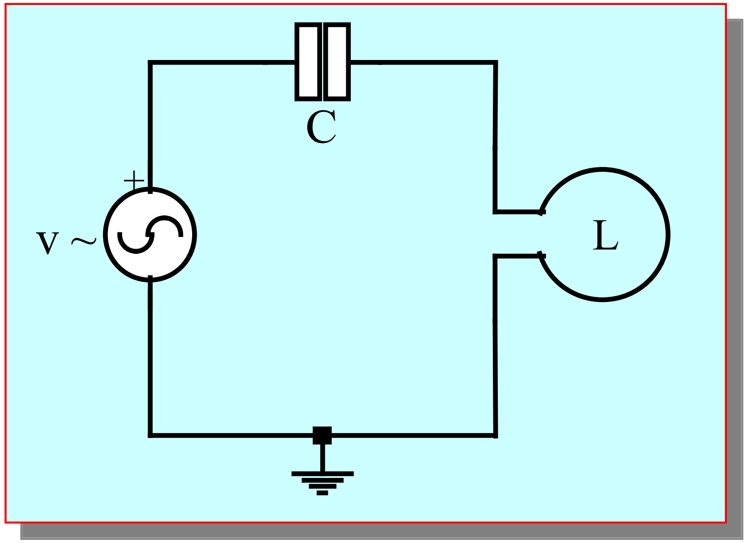
- **PARALLEL COMPENSATION:**



CURRENT-FED

$$P = \frac{i^2}{2}\mathrm{Re}(Z)$$

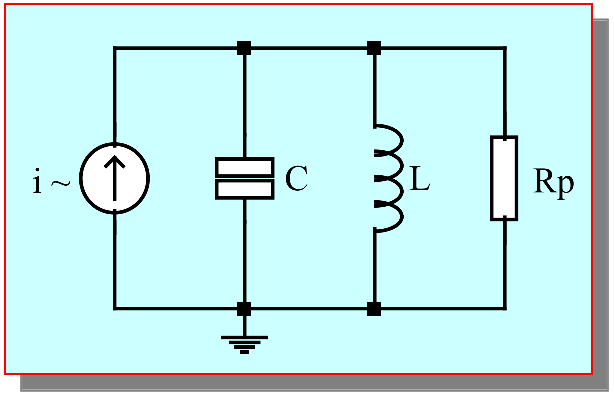
- **SERIES COMPENSATION:**



VOLTAGE-FED

$$P = \frac{v^2}{2}\mathrm{Re}(Y)$$

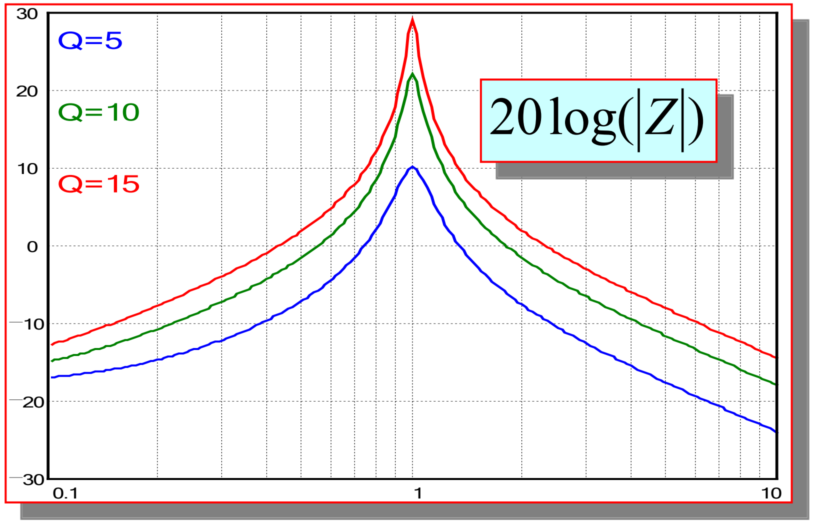
Parallel Compensation of the Load



$$Z(j\omega) = \frac{R_p}{1 + jQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)} = \mathrm{Re}\{Z(j\omega)\} + j\,\mathrm{Im}\{Z(j\omega)\}$$

$$\varphi = \arg\{Z\} = -\arg\{Z^{-1}\} = -\mathrm{atan}\,Q\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \Rightarrow \tan\varphi = -Q\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$$

$$Z = \frac{R_p}{1 - j\tan\varphi} \begin{cases} |Z| = \dfrac{R_p}{\sqrt{1+\tan^2\varphi}} = R_p\cos\varphi \\ \mathrm{Re}\{Z\} = \dfrac{R_p}{1+\tan^2\varphi} = R_p\cos^2\varphi \\ \mathrm{Im}\{Z\} = \dfrac{R_p\tan\varphi}{1+\tan^2\varphi} = R_p\cos\varphi\sin\varphi \end{cases}$$



Parallel Compensation of the Load

$\omega \leq \omega_0$ → $\varphi \geq 0$

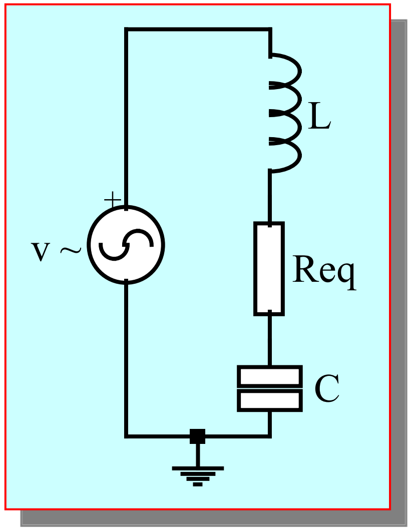
PHASE LEADING
VOLTAGE LEADS OVER THE CURRENT
INDUCTIVE MODE

$\omega \geq \omega_0$ → $\varphi \leq 0$

PHASE LAGGING
VOLTAGE LAGS OVER THE CURRENT
CAPACITIVE MODE

PARALLEL RESONANT LOAD HAS TO BE DRIVEN IN RESONANCE. POWER REGULATION IS ONLY POSSIBLE WITH A VARIABLE INPUT POWER SUPPLY

Series Compensation of the Load

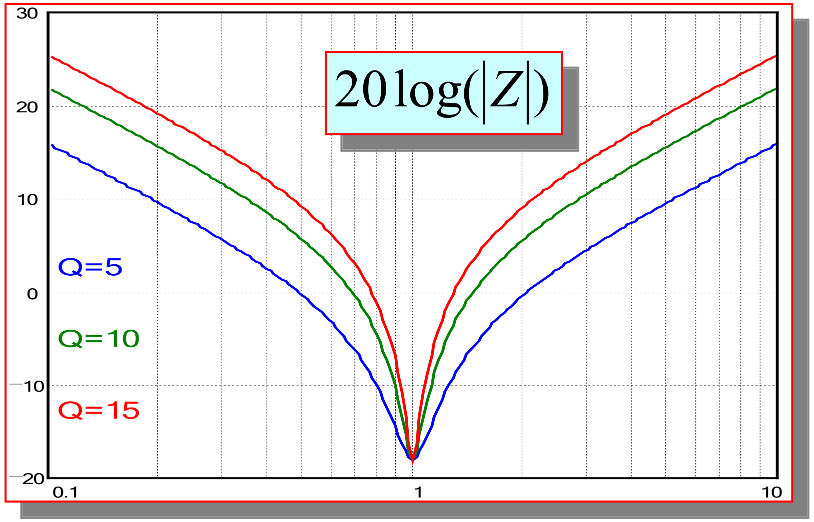


$$Y(j\omega) = \frac{G_{eq}}{1 + jQ\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)} = \mathrm{Re}\{Y(j\omega)\} + j\,\mathrm{Im}\{Y(j\omega)\}$$

$$G_{eq} = \frac{1}{R_{eq}}$$

$$\varphi = \arg\{Z\} = \arg\{Y^{-1}\} = \mathrm{atan}\, Q\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right) \Rightarrow \tan\varphi = Q\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$$

$$Z = \frac{G_{eq}}{1 + j\tan\varphi} \quad \left\{ \begin{array}{l} |Y| = \dfrac{G_{eq}}{\sqrt{1+\tan^2\varphi}} = G_{eq}\cos\varphi \\ \mathrm{Re}\{Y\} = \dfrac{G_{eq}}{1+\tan^2\varphi} = G_{eq}\cos^2\varphi \\ \mathrm{Im}\{Y\} = \dfrac{-G_{eq}\tan\varphi}{1+\tan^2\varphi} = -G_{eq}\cos\varphi\sin\varphi \end{array} \right.$$



Series Compensation of the Load

$\omega \leq \omega_0$ → $\varphi \leq 0$

PHASE LAGGING
VOLTAGE LAGS OVER THE CURRENT
CAPACITIVE MODE

$\omega \geq \omega_0$ → $\varphi \geq 0$

PHASE LEADING
VOLTAGE LEADS OVER THE CURRENT
INDUCTIVE MODE

A SERIES RESONANT LOAD CAN BE DRIVEN IN RESONANCE OR ABOVE OR BELOW RESONANCE. POWER REGULATION IS POSSIBLE WITH A VARIABLE INPUT POWER SUPPLY OR BY THE INVERTER ITSELF

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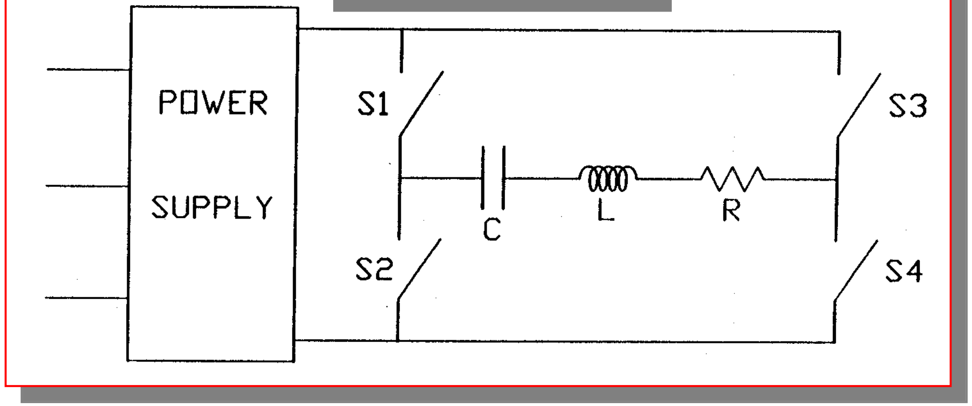
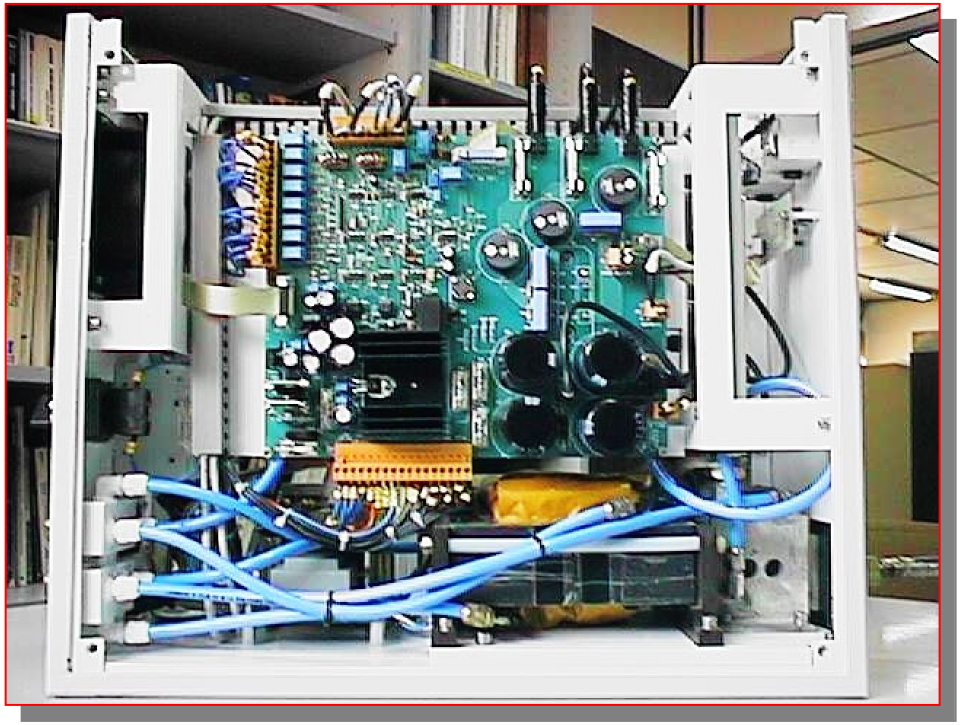
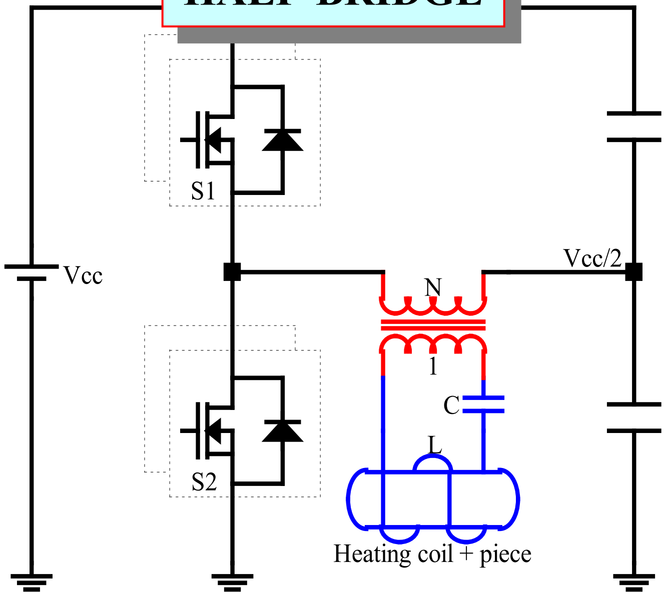
Basic Topologies Used

FULL-BRIDGE





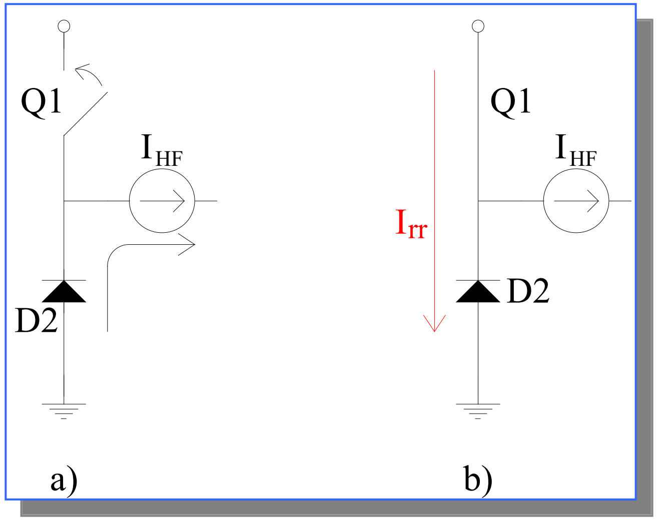
HALF-BRIDGE

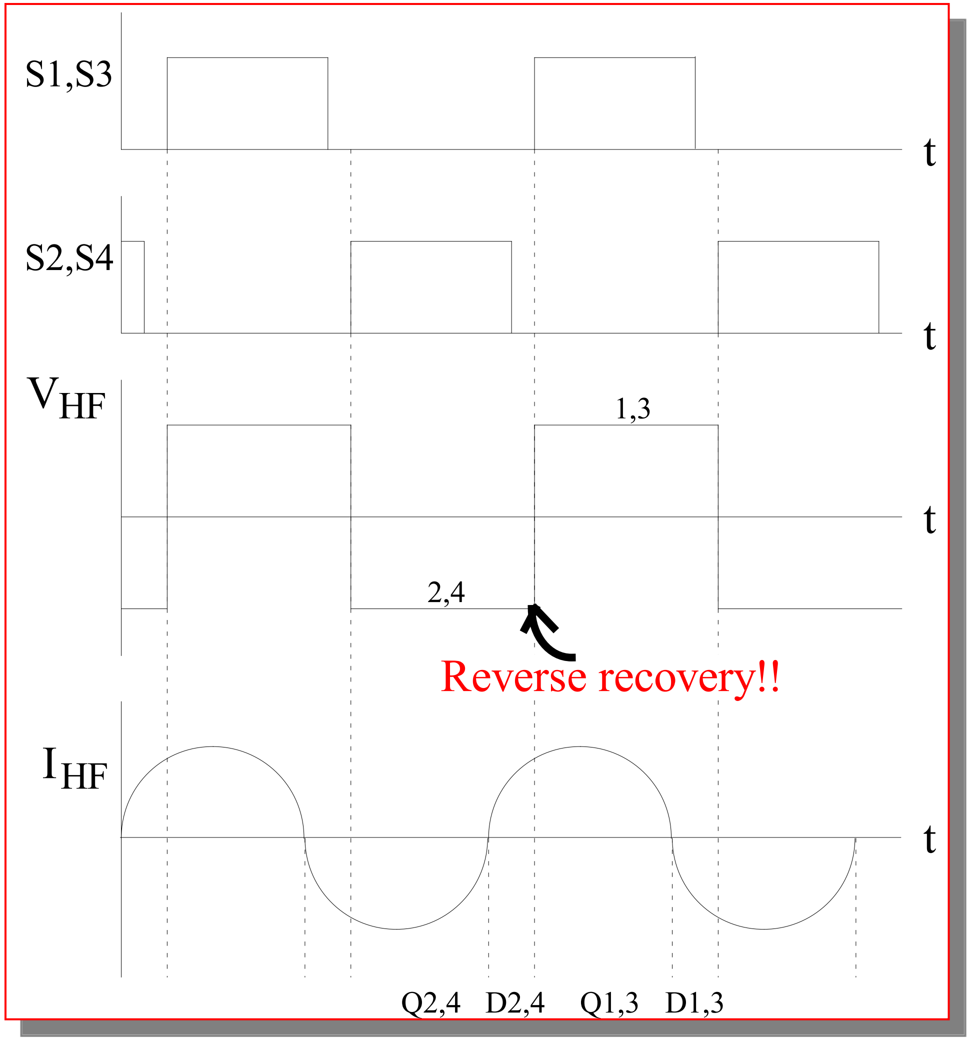


SWITCHES ARE UNIDIRECTIONAL IN VOLTAGE AND BIDIRECTIONAL IN CURRENT.

CAPACITIVE OR ZCS SWITCHING

$$\omega < \omega_0$$

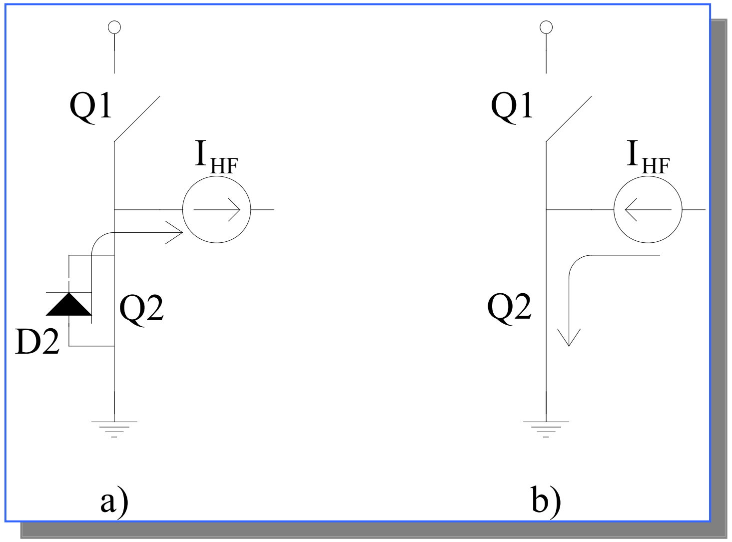


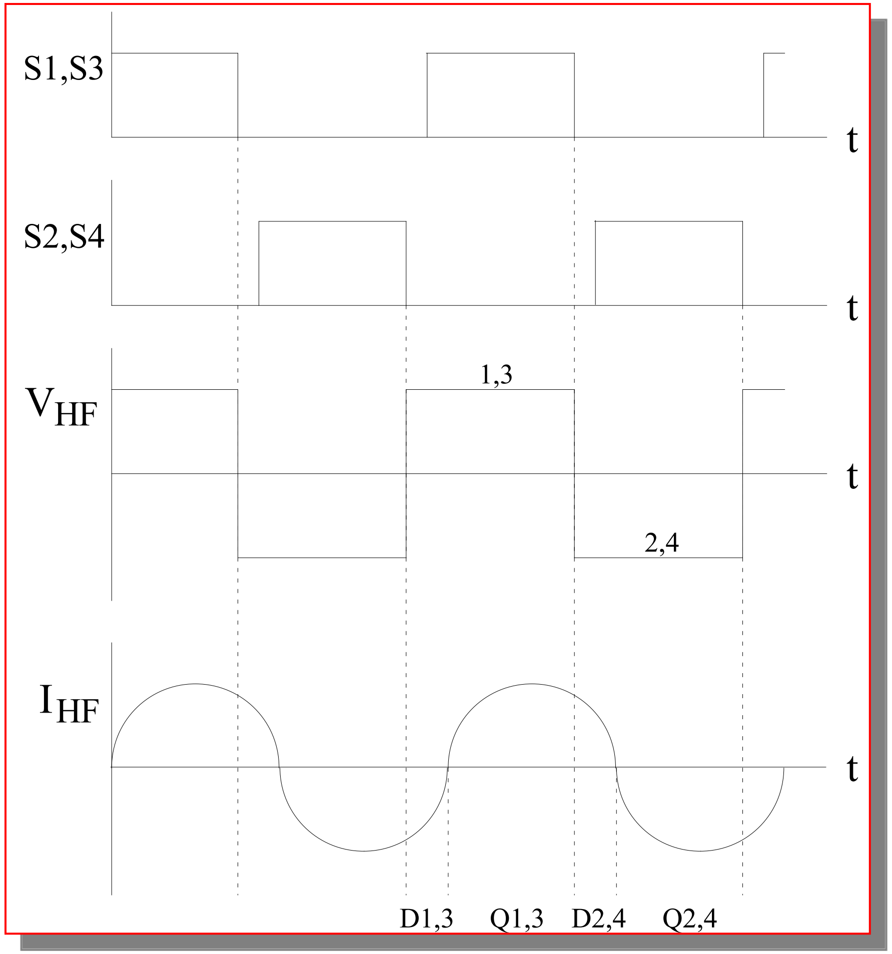


- **FOR CURRENT LEADING, THE SWITCHING PROCESS IS FIXED BY THE TURN-ON OF THE TRANSISTORS.**
- **NO TURN-OFF LOSSES.**
- **TURN-ON LOSSES (TURN-ON SNUBBER).**
- **REVERSE RECOVERY PROBLEMS WITH THE ANTI-PARALLEL DIODES.**
- **ADDITIONAL LOSSES DUE TO THE DISCHARGE OF THE PARASITIC CAPACITOR Coss.**

INDUCTIVE OR ZVS SWITCHING

$$\omega > \omega_0$$





- **FOR CURRENT LAGGING, THE SWITCHING PROCESS IS FIXED BY THE TURN-OFF OF THE TRANSISTORS.**
- **NO TURN-ON LOSSES.**
- **TURN-OFF LOSSES (TURN-OFF SNUBBER).**
- **NO REVERSE RECOVERY PROBLEMS WITH THE ANTI-PARALLEL DIODES.**
- **PARASITIC CAPACITOR Coss ACTS LIKE A LOSSLESS TURN-OFF SNUBBER.**

Switching Modes in Series Inverters

INDUCTIVE PHASE
ZVS OR TURN-OFF CONTROLLED

	ON	OFF
S	*ZVS*	*HARD*
D	*HARD*	*ZCS*

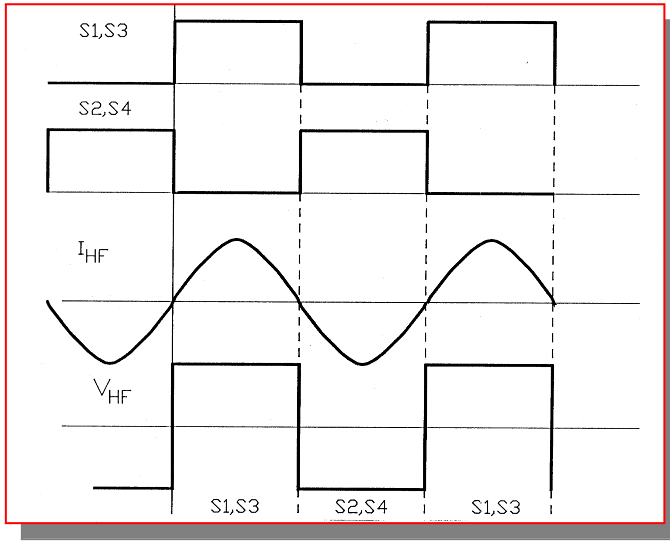
- HIGH TURN-OFF LOSSES FOR S
- REDUCED TURN-ON LOSSES FOR D
- HIGH OVERVOLTAGE DUE TO TRANSISTOR TURN-OFF

CAPACITIVE PHASE
ZCS OR TURN-ON CONTROLLED

	ON	OFF
S	*HARD*	*ZCS*
D	*ZVS*	*HARD*

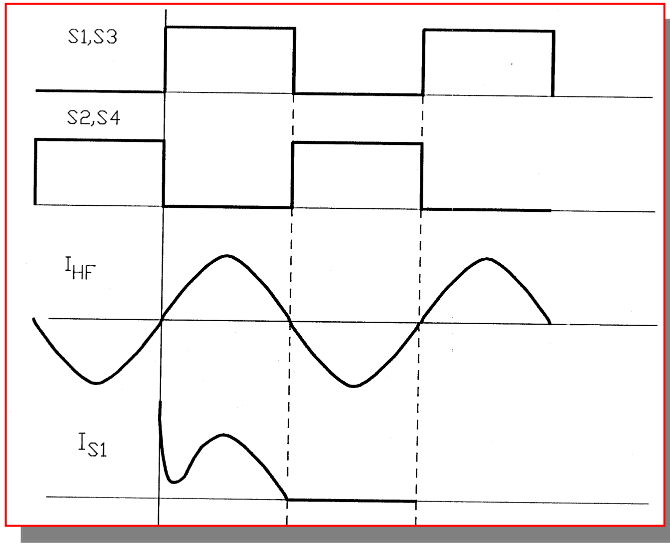
- L ACTS LIKE A LOSSLESS TURN-ON SNUBBER
- REDUCED TURN-ON LOSSES FOR S
- HIGH TURN-OFF LOSSES FOR D
- HIGH OVERVOLTAGE DUE TO REVERSE RECOVERY DIODE CURRENT

IN-PHASE SWITCHING



IDEAL

- OUTPUT VOLTAGE AND CURRENT IN PHASE.
- MINIMAL SWITCHING LOSSES.
- NO REVERSE RECOVERY PROBLEMS WITH ANTI-PARALLEL DIODES.



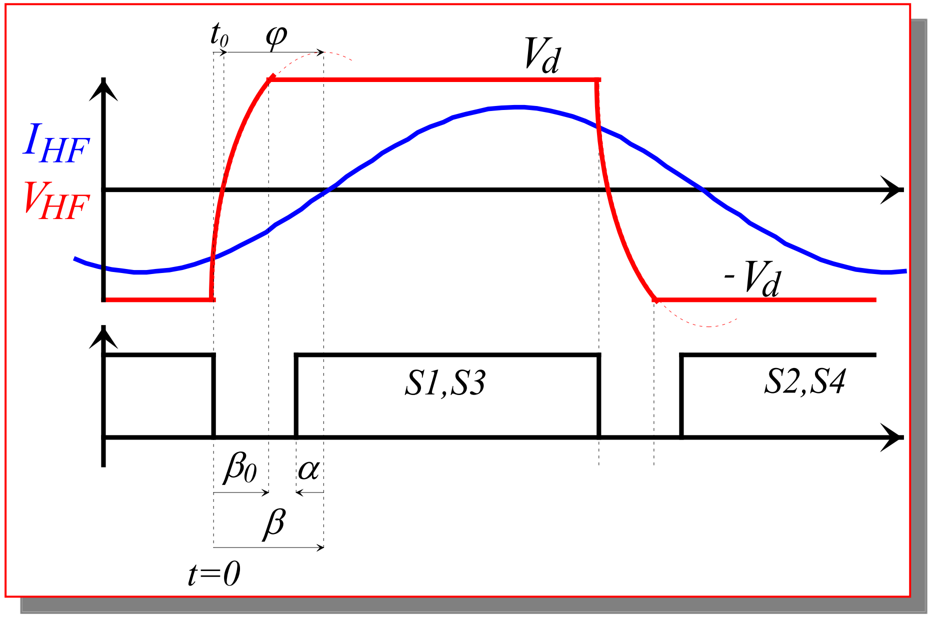
REAL

- DUE TO THE PARASITIC CAPACITOR OF THE SWITCHES (Coss), AN OVERCURRENT IS GENERATED AT TURN ON, CAUSING ADDITIONAL LOSSES THAT LIMIT THE MAXIMUM OPERATING FREQUENCY OF THE INVERTER (TURN-ON LOSSES).

SOFT-SWITCHING CONDITIONS

TO HAVE SOFT SWITCHING IT IS NECESSARY TO ACCOMPLISH:

$$\left\{ \begin{array}{ll} \boxed{\beta_0 \le \beta} & \text{FOR CLAMPED MODE.} \\ \boxed{0 \le |\alpha| \le \beta - \beta_0} & \text{FOR ZVS TURN-ON.} \end{array} \right.$$



THIS TWO CONDITIONS ENSURE THE DIODES POLARISATION (CLAMP), AND THE TRANSISTOR TURN-ON WHEN THE DIODES ARE STILL DRIVING (ZVS).

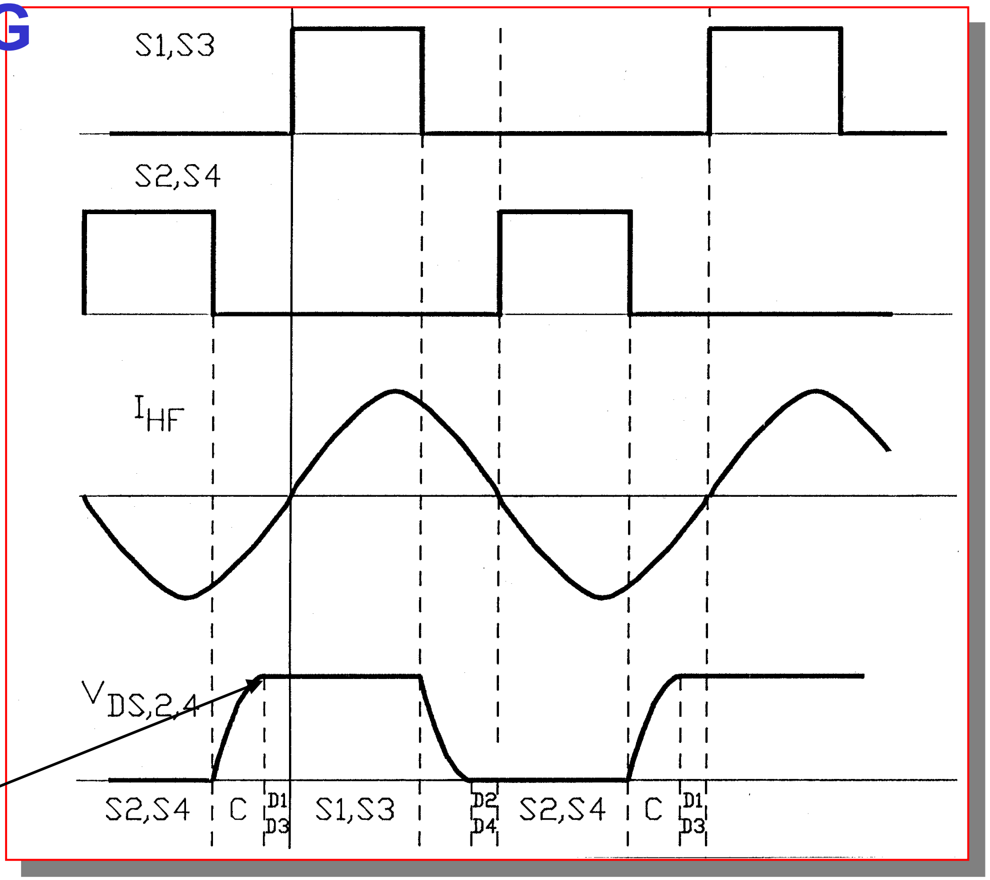
CONSEQUENTLY

$$\beta \ge \arccos\left(\cos\alpha - \frac{2C\omega V_d}{I_0}\right)$$

Switching Modes in Series Inverters

SOFT-SWITCHING ZVS DRIVING

- **TURN-OFF BEFORE TURN-ON TO AVOID OVERLAPPING (DEAD TIMES NEEDED).**
- **CURRENT LAGGING TO AVOID REVERSE RECOVERY PROBLEMS WITH THE ANTIPARALLEL DIODES.**
- **Coss (OR SNUBBERS) HAVE TO BE FULLY CHARGED BEFORE TURN-ON (TO AVOID LOSSES).**
- **NO TURN-ON LOSSES**

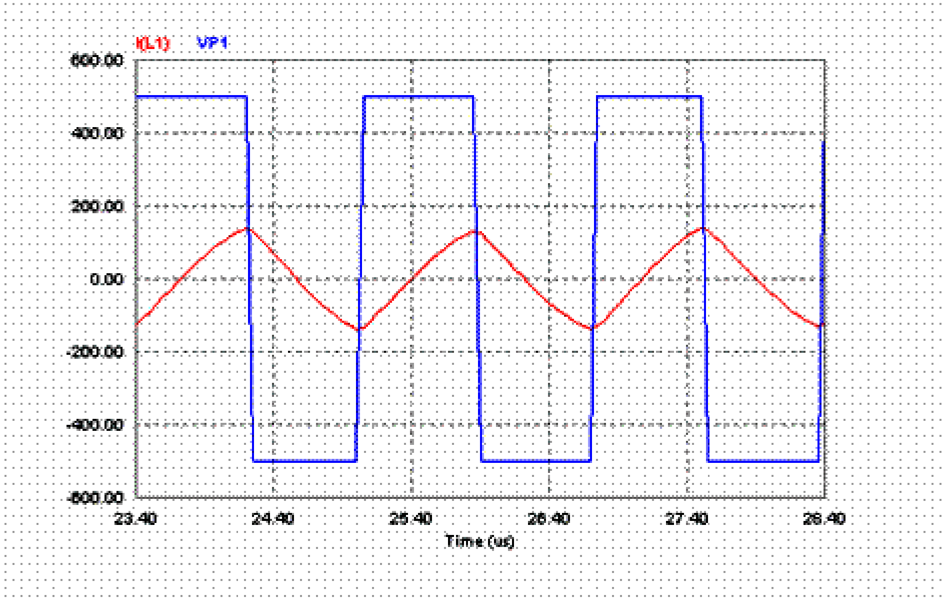


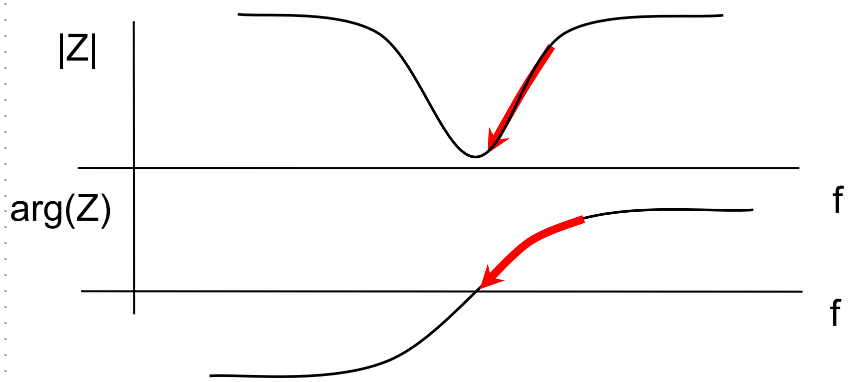
SOFT-SWITCHING

OPTIMUM SWITCHING

- **$\beta=\beta_0$: THE TURN OFF IS ADVANCED TO ENSURE CLAMPED MODE.**
- **$\alpha=0$: THE TURN ON IS JUST AT THE ZERO CROSSING OF THE CURRENT.**

FM: **FREQUENCY MODULATION**



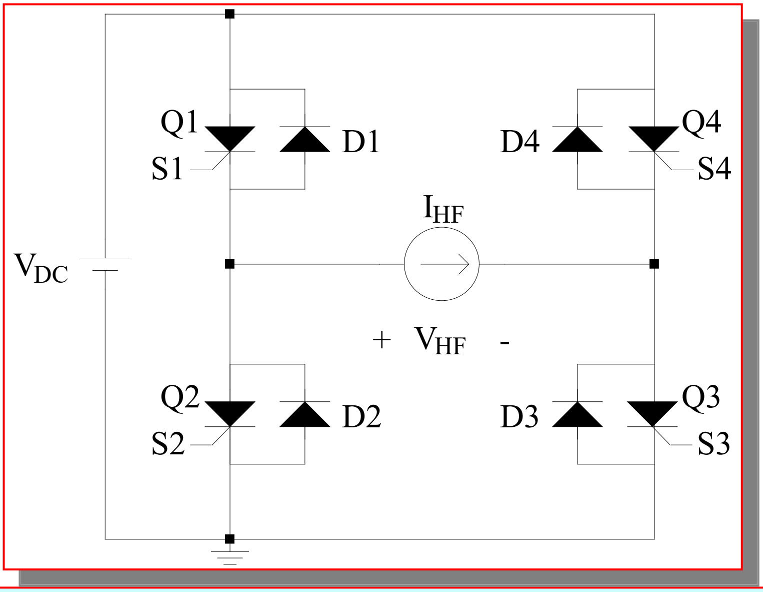


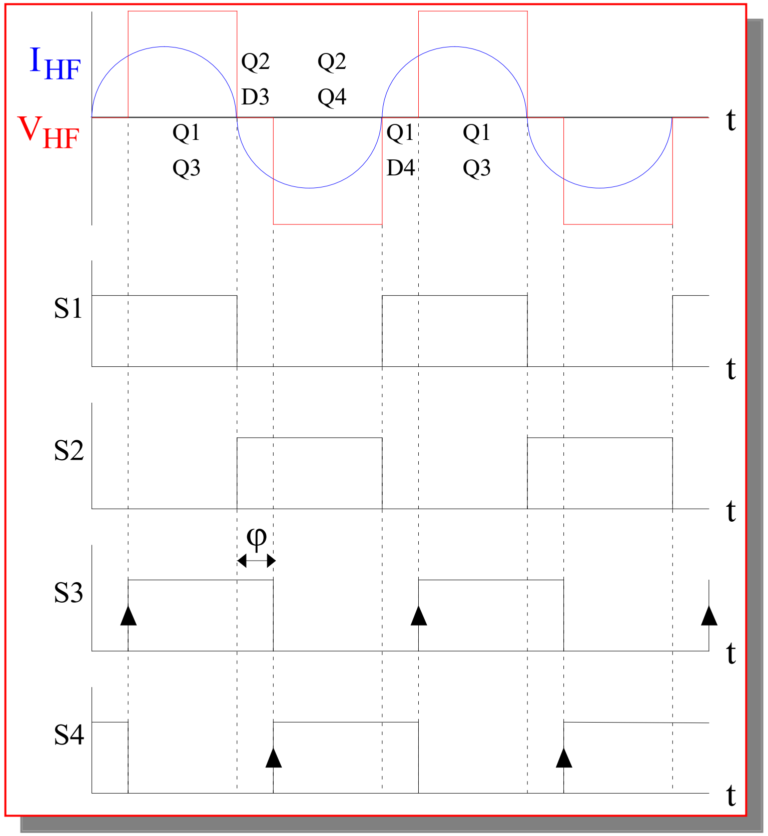
INDUCTIVE MODE PREFERED:
WORKING FREQUENCY HIGHER THAN RESONANT FREQUENCY

f ↓ ⇒ |Z| ↓ ⇒ arg(Z) ↓ ⇒ Power ↑

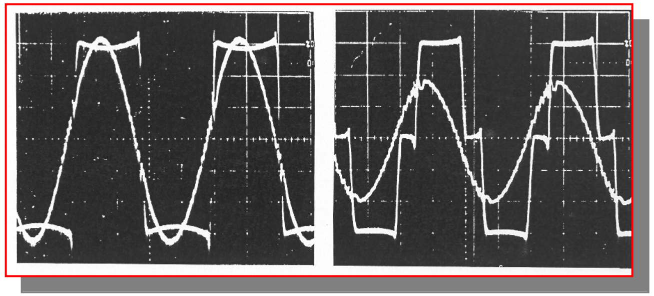
f ↑ ⇒ arg(Z) ↑ ⇒ Power losses ↑

PS: **Phase Shift-turn-on Controlled**

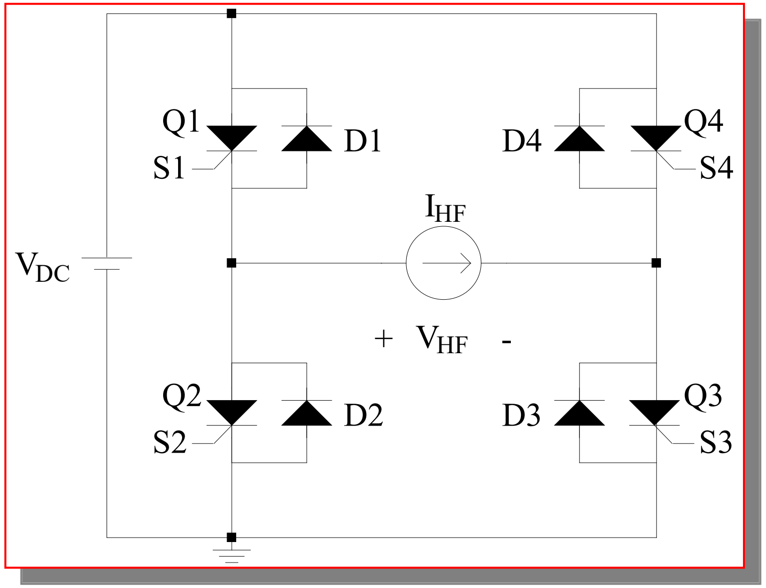


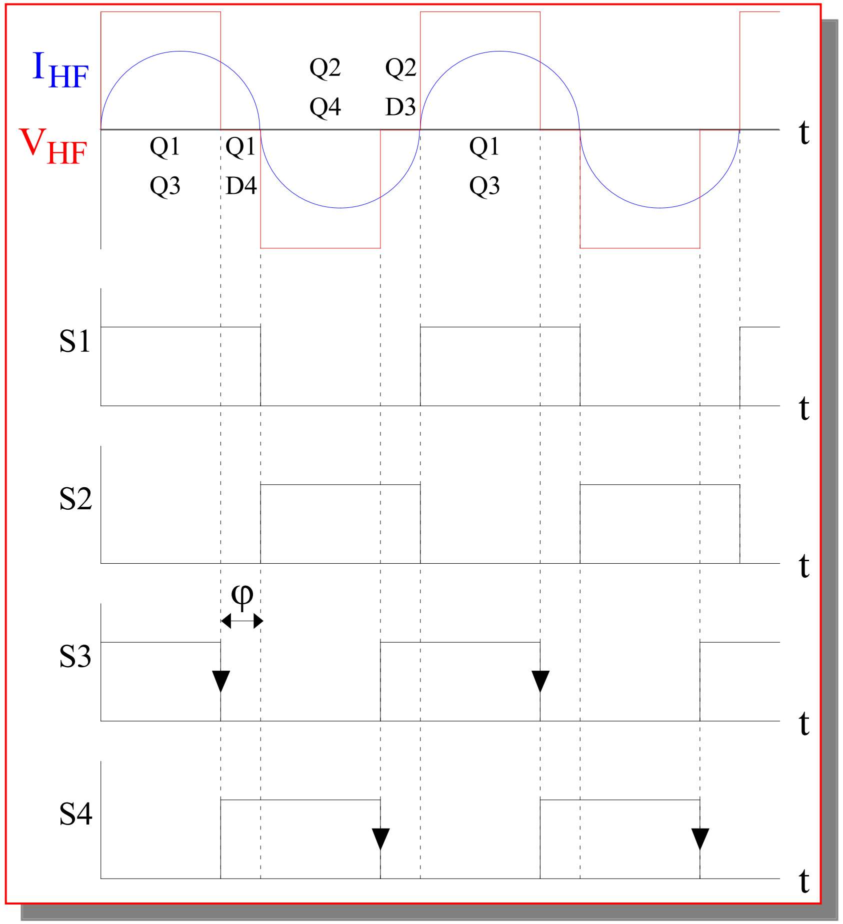


- **LEFT SWITCHES COMMUTATE AT THE ZERO CROSSING OF THE OUTPUT CURRENT.**
- **RIGHT SWITCHES ARE DELAYED A PHASE-SHIFT φ.**
- **RIGHT SWITCHES ARE TURN-ON CONTROLLED.**
- **OPTIMUM FOR IGBT SWITCHES.**



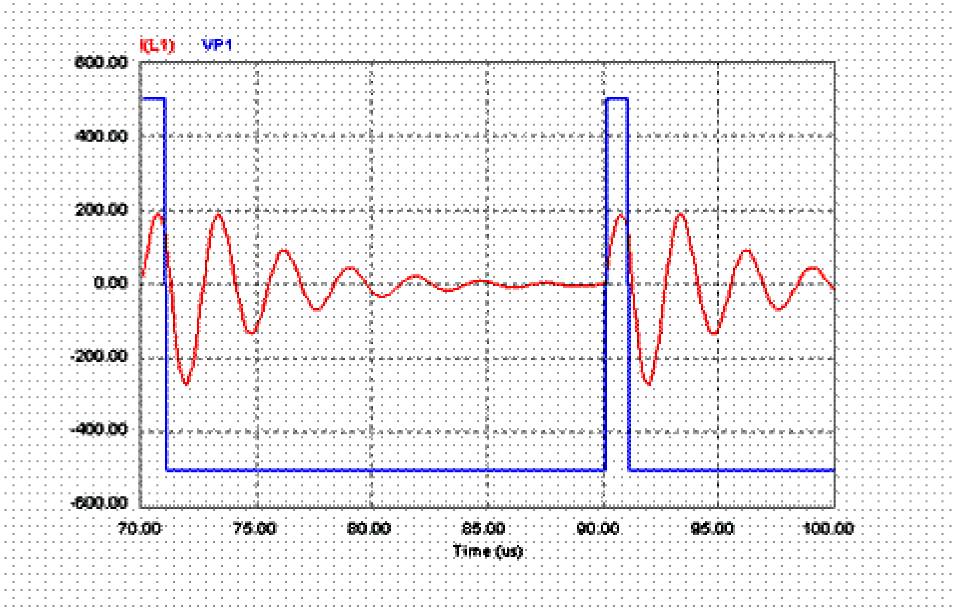
PS: **Phase Shift-turn-off Controlled**

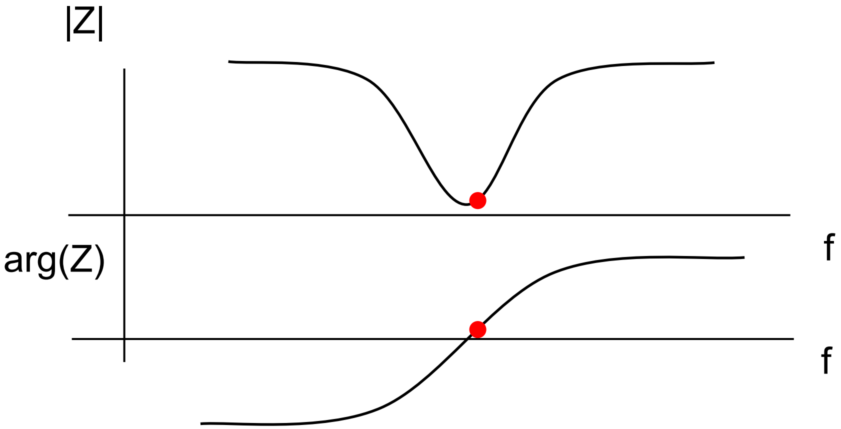




- **LEFT SWITCHES COMMUTATE AT THE ZERO CROSSING OF THE OUTPUT CURRENT.**
- **RIGHT SWITCHES ARE ADVANCED A PHASE-SHIFT φ.**
- **RIGHT SWITCHES ARE TURN-OFF CONTROLLED.**
- **OPTIMUM FOR MOS SWITCHES.**

PDM: PULSE DENSITY MODULATION-IN PHASE SWITCHING

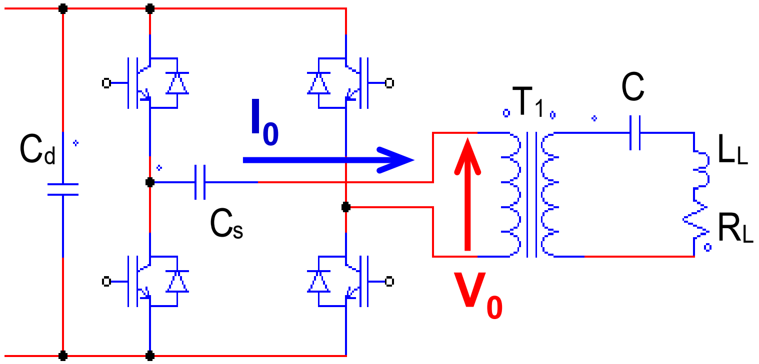


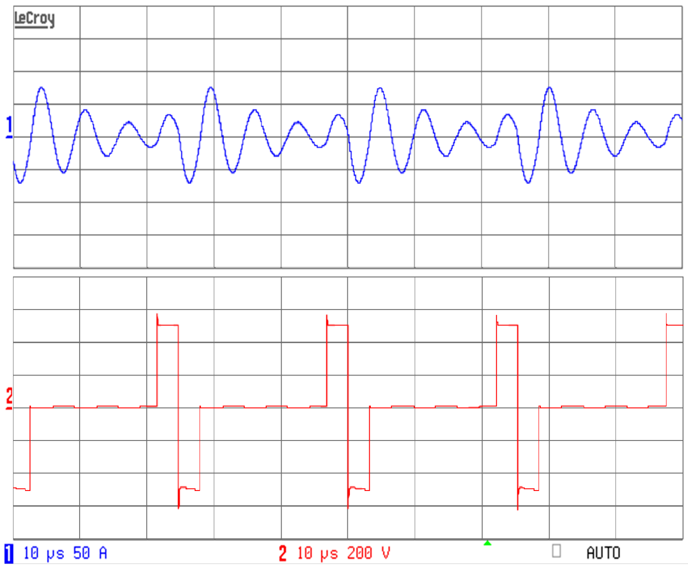


Number of pulses per cycle ↑ ⇒ Power ↑

arg(Z) minimum ⇒ Power losses minimum

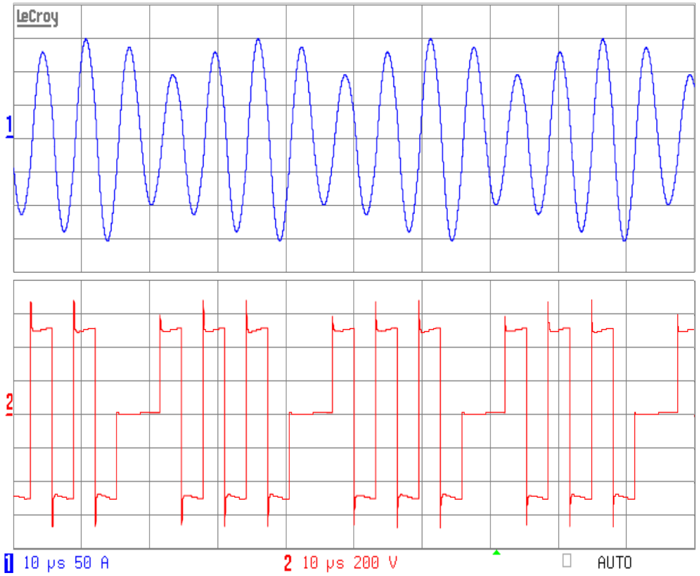
PDM: INVERTER WAVEFORMS





I_0 (50 A/div)

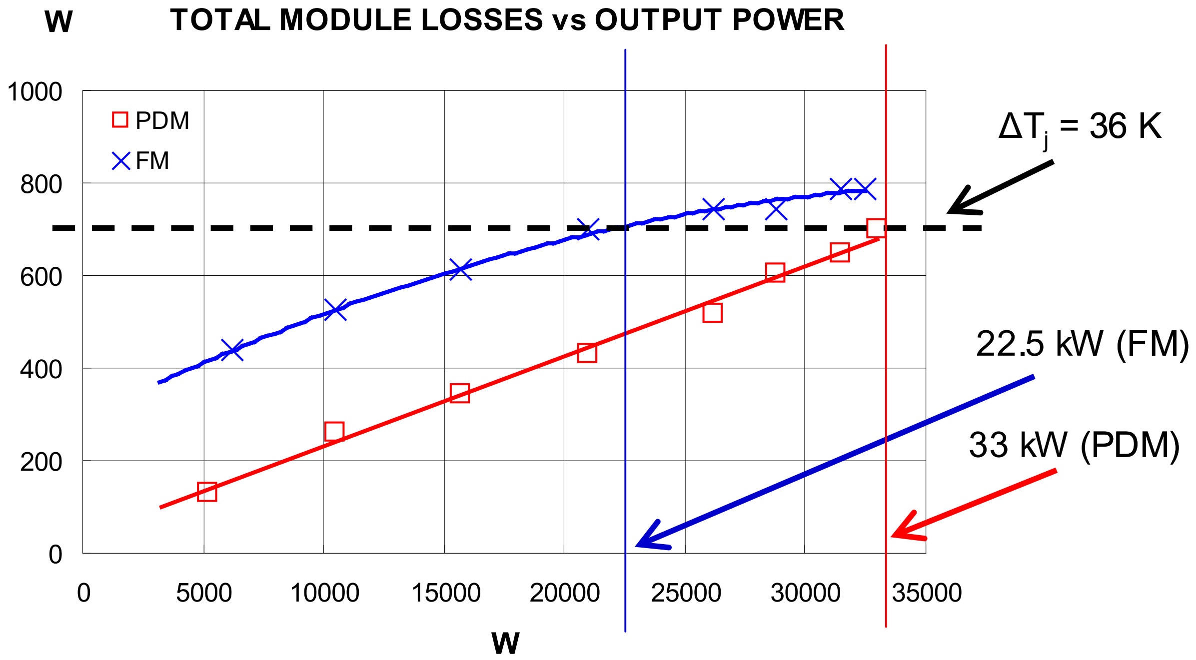
V_0 (200 V/div)



TB: 10 µs/div

EXPERIMENTAL RESULTS

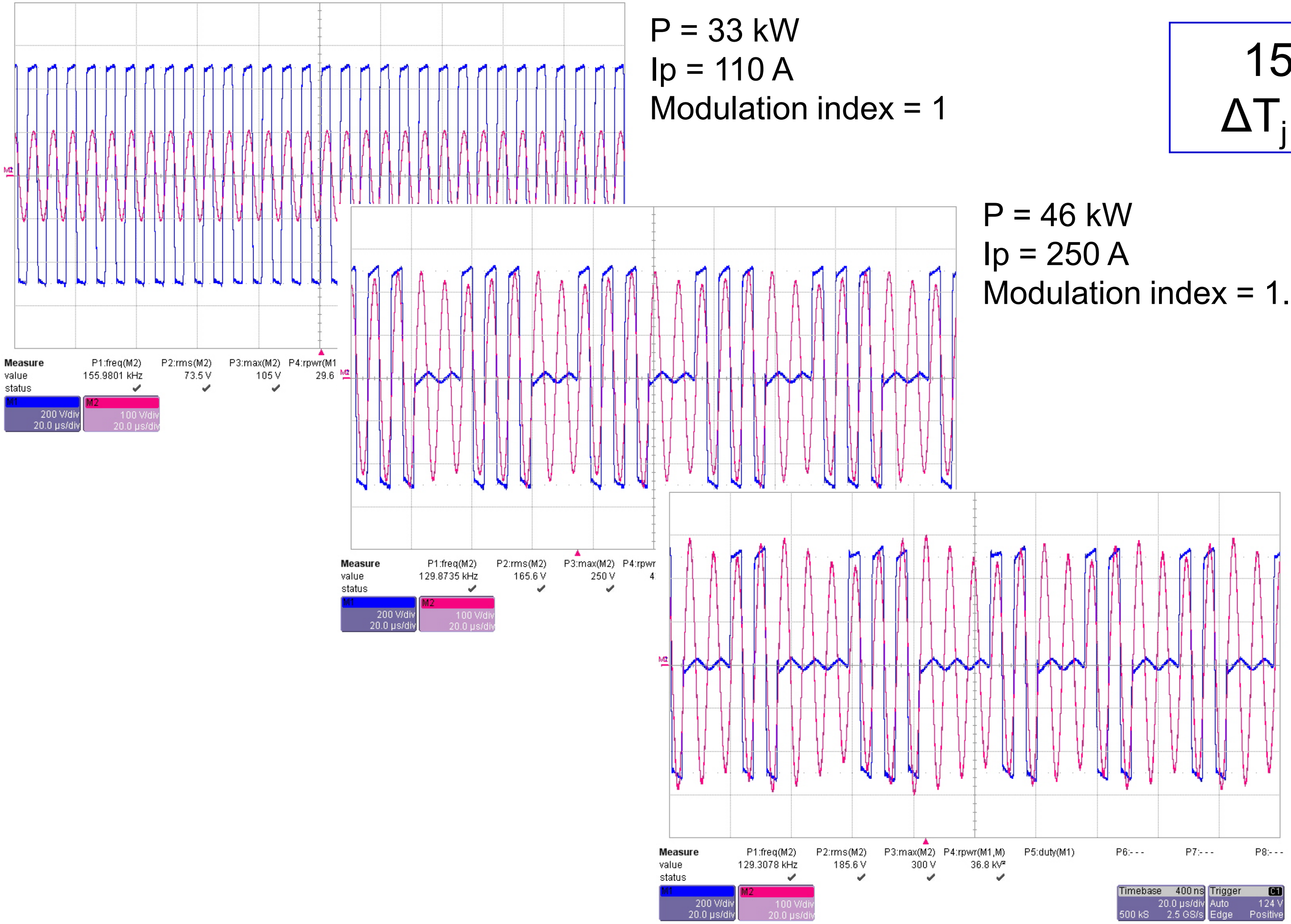
COMPARATIVE STUDY: PDM vs FM



Module power losses using Frequency Modulation (FM) and Pulse Density Modulation (PDM) control techniques

The inverter output power obtained with PDM is more than 1.4 times higher than the achieved with FM control method

SECOND POWER UPGRADING INCREASING THE MAXIMUM CURRENT PEAK



```
Measure      P1:freq(M2)    P2:rms(M2)    P3:max(M2)    P4:rpwr(M1
value        155.9801 kHz   73.5 V        105 V         29.6
status       ✓              ✓             ✓
M1 200 V/div 20.0 µs/div    M2 100 V/div 20.0 µs/div
```

```
Measure      P1:freq(M2)    P2:rms(M2)    P3:max(M2)    P4:rpwr
value        129.8735 kHz   165.6 V       250 V         4
status       ✓              ✓             ✓
M1 200 V/div 20.0 µs/div    M2 100 V/div 20.0 µs/div
```

```
Measure      P1:freq(M2)    P2:rms(M2)    P3:max(M2)    P4:rpwr(M1,M)    P5:duty(M1)    P6:- - -    P7:- - -    P8:- - -
value        129.3078 kHz   185.6 V       300 V         36.8 kV²
status       ✓              ✓             ✓             ✓
M1 200 V/div 20.0 µs/div    M2 100 V/div 20.0 µs/div    Timebase 400 ns 20.0 µs/div 500 kS 2.5 GS/s    Trigger C1 Auto 124 V Edge Positive
```

P = 33 kW
Ip = 110 A
Modulation index = 1

150 kHz
$\Delta T_j = 36$ K

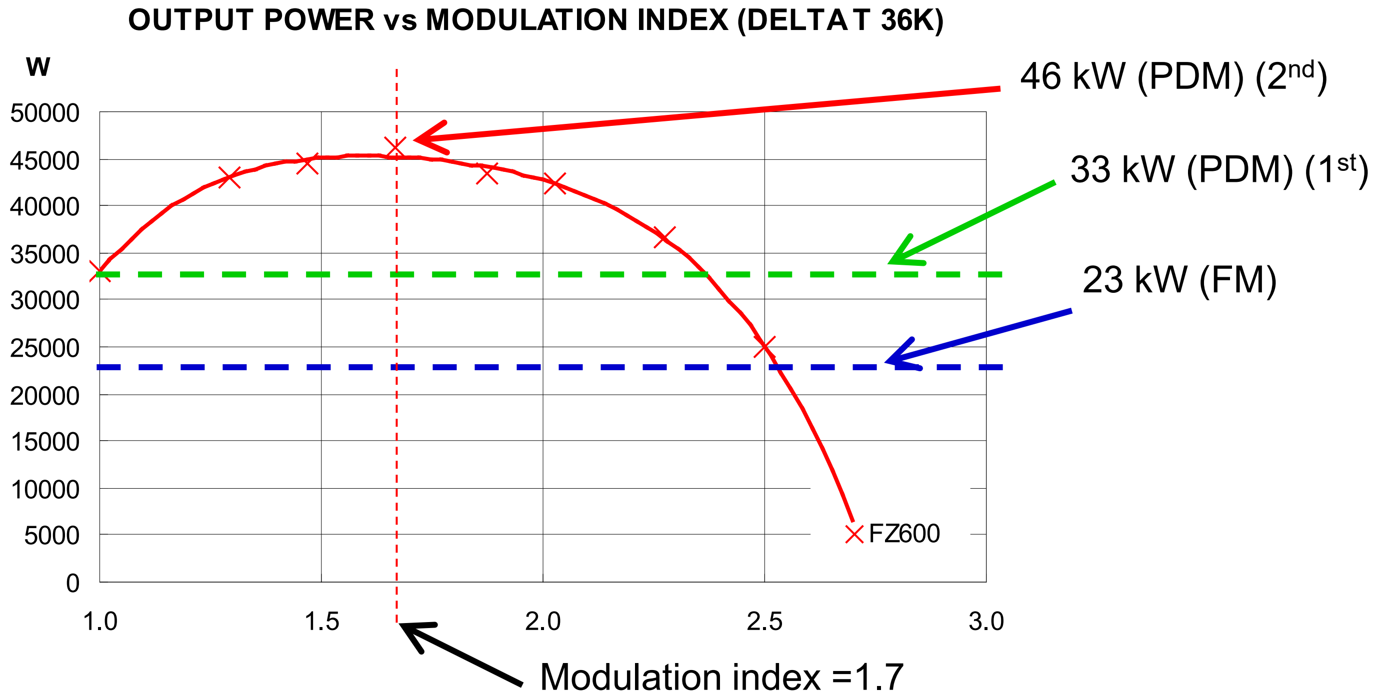
P = 46 kW
Ip = 250 A
Modulation index = 1.7

P = 42 kW
Ip = 300 A
Modulation index = 2

SECOND POWER UPGRADING INCREASING THE MAXIMUM CURRENT PICK

150 kHz

$\Delta T_j = 36$ K



SECOND UPGRADING FACTOR = **1.4**

TOTAL UPGRADING FACTOR = 1.4 x 1.4 ≈ **2** (150 kHz)

POWER REGULATION METHODS

PULSE DENSITY MODULATION VS. FREQUENCY MODULATION

FREQUENCY MODULATION

ADVANTAGES:

- ZVS condition
- Low current ripple

DISADVANTAGES:

- High power losses at low output power level
- Frequency variation

PULSE DENSITY MODULATION

ADVANTAGES:

- ZVS and quasi ZCS condition
- Constant current frequency
- Minimum switching power losses at any power level

DISADVANTAGES:

- High current ripple

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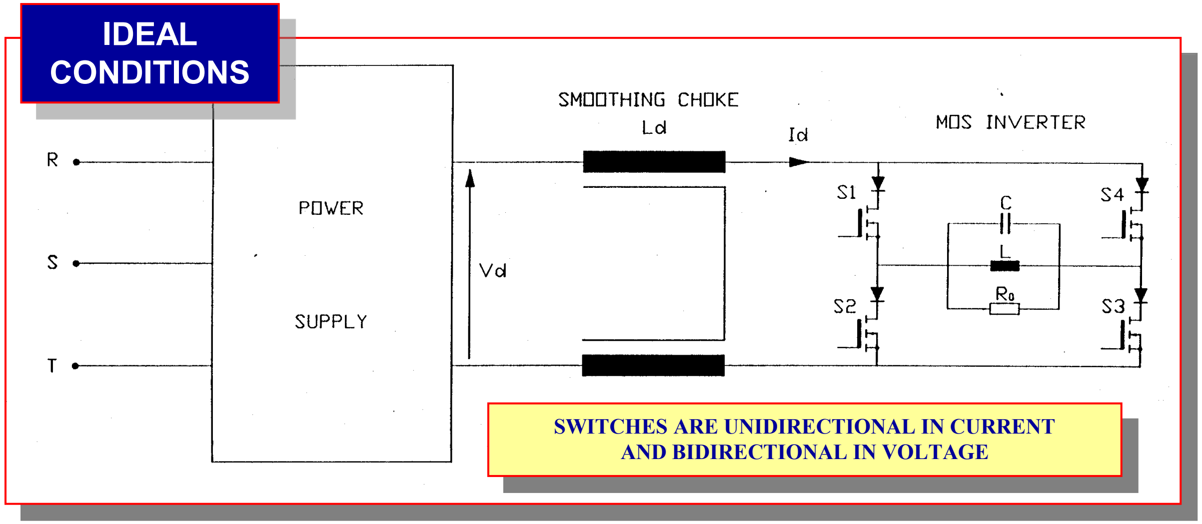
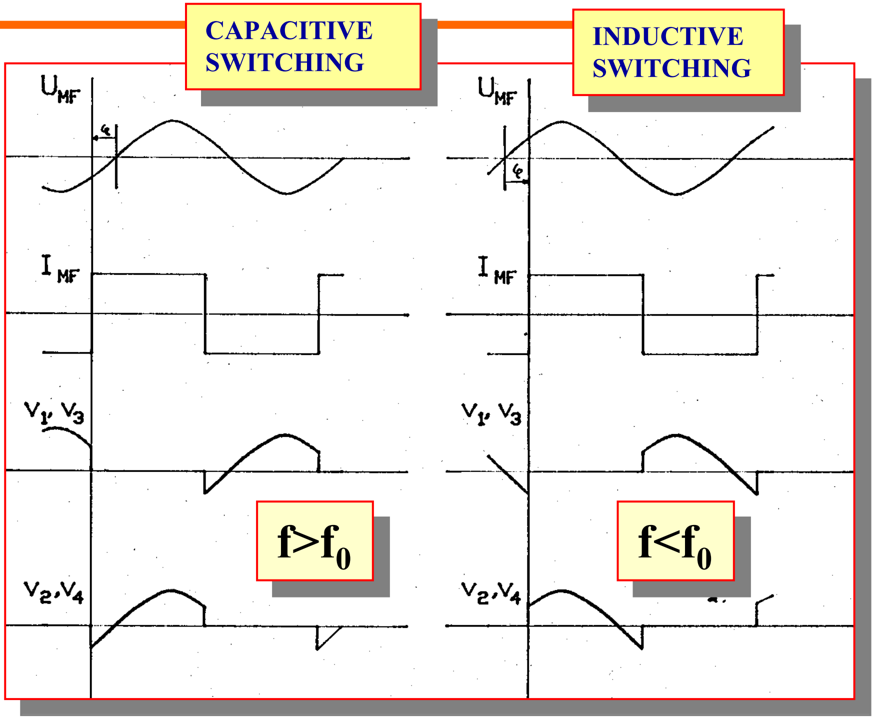
- ✓Roadmap

Basic Topologies Used



IDEAL CONDITIONS

SWITCHES ARE UNIDIRECTIONAL IN CURRENT AND BIDIRECTIONAL IN VOLTAGE

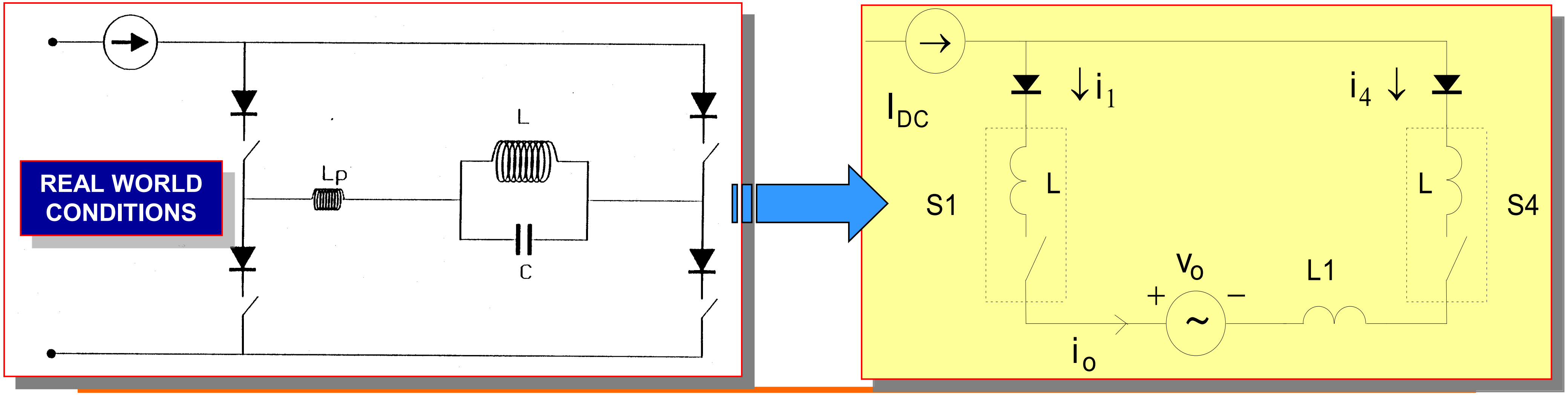


CAPACITIVE SWITCHING

INDUCTIVE SWITCHING

$f > f_0$

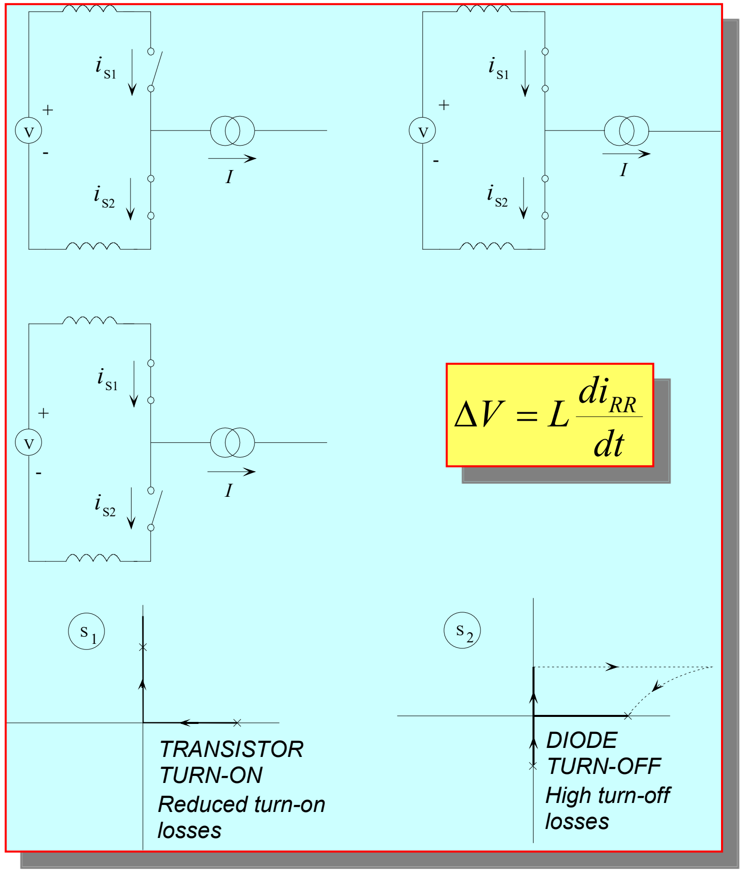
$f < f_0$



REAL WORLD CONDITIONS

Switching Modes in Parallel Inverters

ZCS COMMUTATION



$$\Delta V = L\frac{di_{RR}}{dt}$$

TRANSISTOR TURN-ON

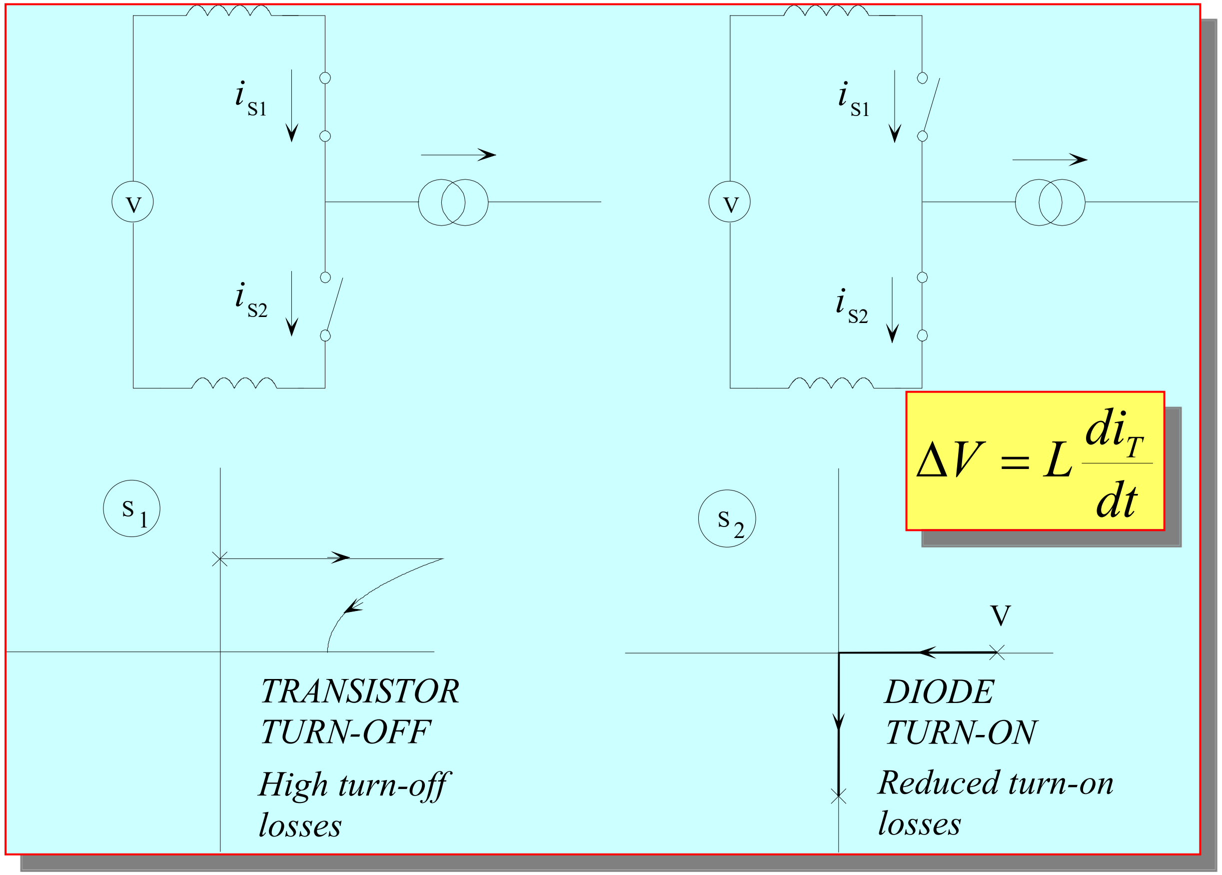
Reduced turn-on losses

DIODE TURN-OFF

High turn-off losses

AN OVERVOLTAGE GENERATED DUE TO THE REVERSE RECOVERY CURRENT IN THE SERIES DIODES

ZVS COMMUTATION



$$\Delta V = L\frac{di_{T}}{dt}$$

TRANSISTOR TURN-OFF

High turn-off losses

DIODE TURN-ON

Reduced turn-on losses

AN OVERVOLTAGE GENERATED DUE TO THE TURN-OFF OF THE TRANSISTOR

Switching Modes in Parallel Inverters

FOR INDUCTIVE PHASE
ZVS OR TURN-OFF CONTROLLED

	ON	OFF
S	*ZVS*	*HARD*
D	*HARD*	*ZCS*

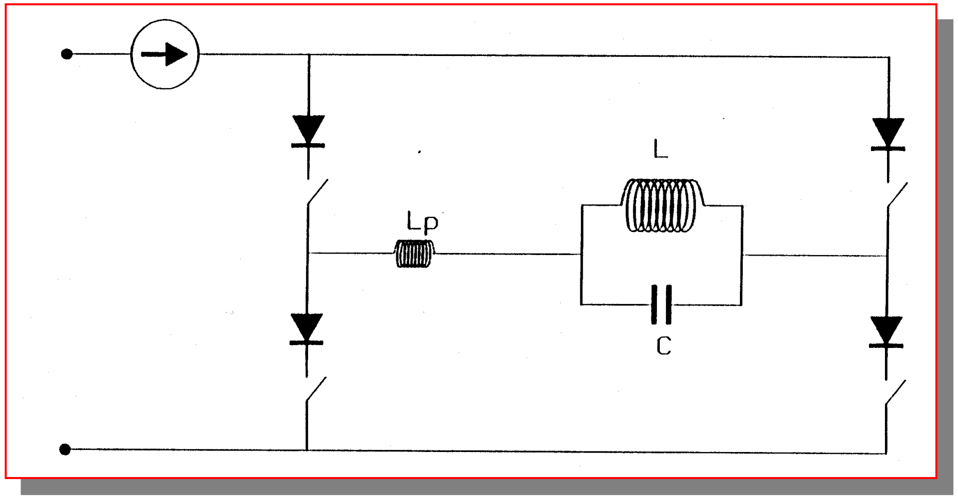
FOR CAPACITIVE PHASE
ZCS OR TURN-ON CONTROLLED

	ON	OFF
S	*HARD*	*ZCS*
D	*ZVS*	*HARD*

- **L ACTS LIKE A LOSSLESS TURN-ON SNUBBER**
- **REDUCED TURN-ON LOSSES FOR S**
- **HIGH TURN-OFF LOSSES FOR D**
- **HIGH OVERVOLTAGE DUE TO REVERSE RECOVERY DIODE CURRENT**

PREFERED SWITCHING AT LOW FREQUENCY: CAPACITIVE MODE

Switching Modes in Parallel Inverters



OPTIMUM SWITCHING

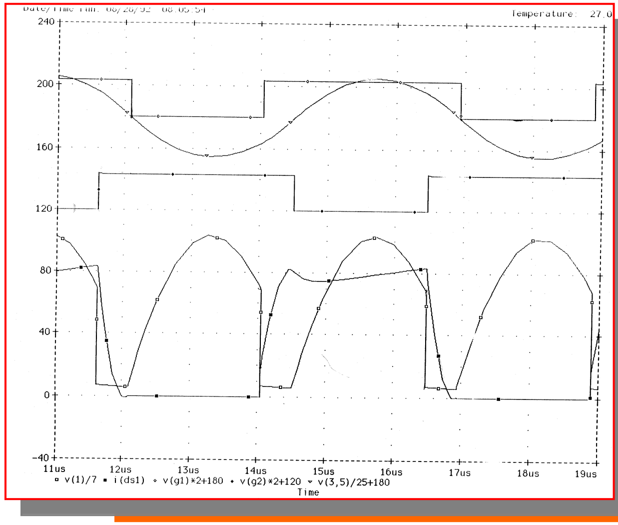
$$i = I_d - \frac{V_o}{L_p \omega}(\cos \omega t - \cos \beta)$$

$$i_1 = I_d - \frac{V_o}{2L_p \omega}(\cos \omega t - \cos \beta)$$

$$i_1 = \frac{V_o}{2L_p \omega}(\cos \omega t - \cos \beta)$$

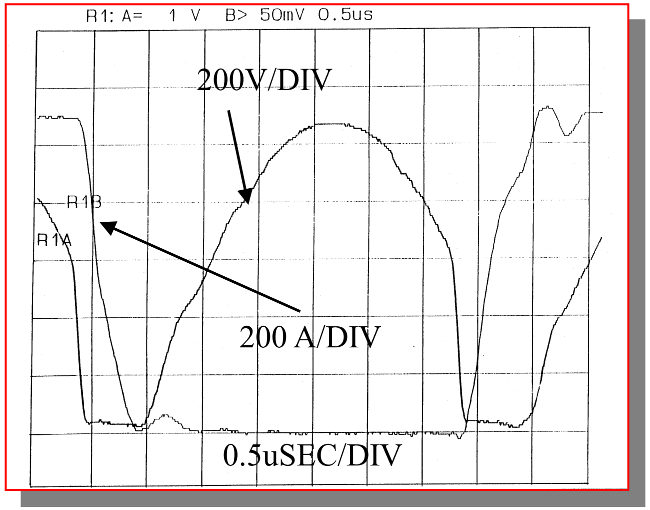
OPTIMUM TURN-OFF: AT THE ZERO CROSSING POINT OF THE OUTPUT VOLTAGE ($\alpha = 0$)

OPTIMUM TURN-ON: ADVANCED TO THE ZERO CROSSING POINT OF OUTPUT VOLTAGE SO THAT THE OUTPUT CURRENT CHANGES ITS POLARITY EXACTLY AT THIS POINT ($\beta = \beta 0$)

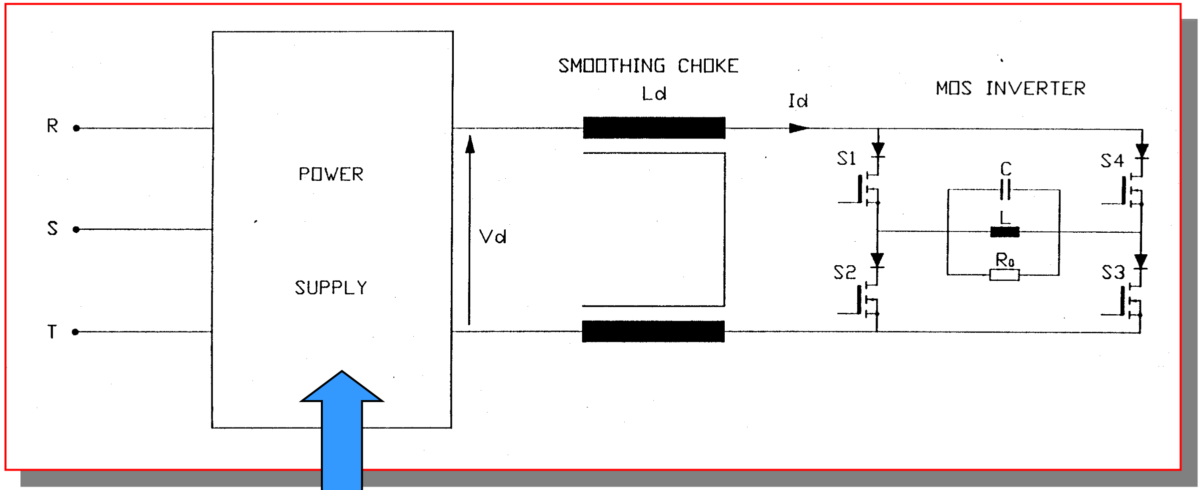


$$\cos \beta_0 = 1 - \frac{2L_p I_d \omega}{V_0} = 1 - \frac{kI_d f}{V_0}$$

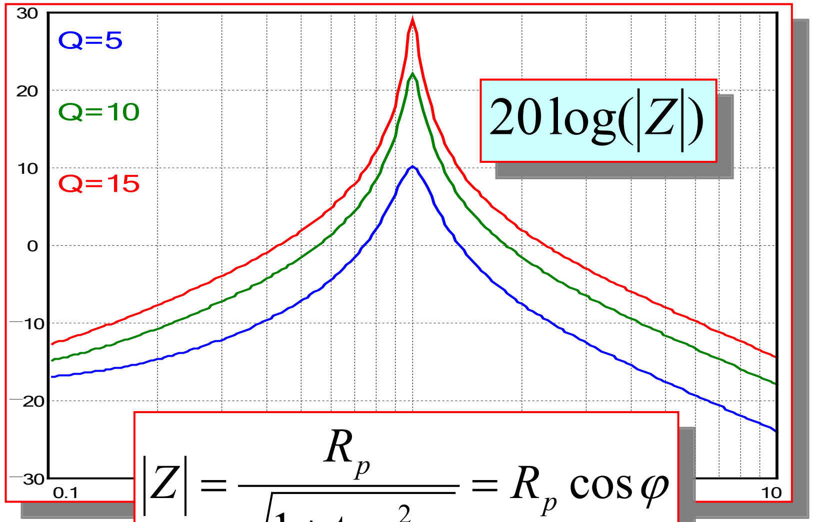
$$\alpha = 0$$



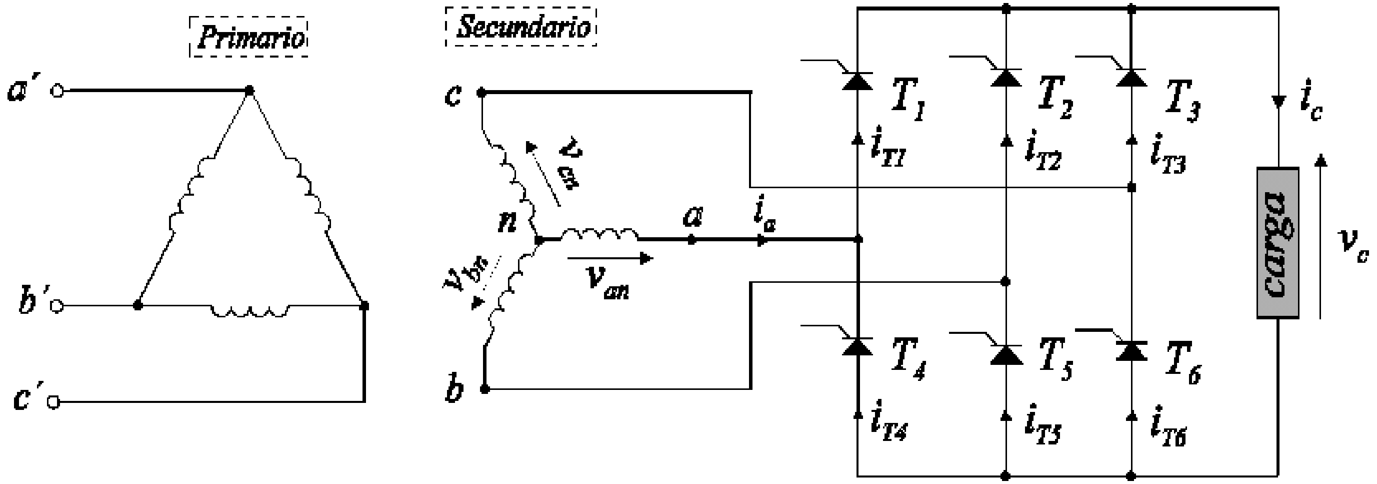
Power Regulation in Parallel Inverters



As the load impedance decreases with φ (Z= R cosφ) power regulation can only be achieved with a variable Power Supply and not by the inverters itself



$$|Z| = \frac{R_p}{\sqrt{1+\tan^2\varphi}} = R_p\cos\varphi$$



$$U_{DC} = U_{di}\cdot\cos\alpha$$

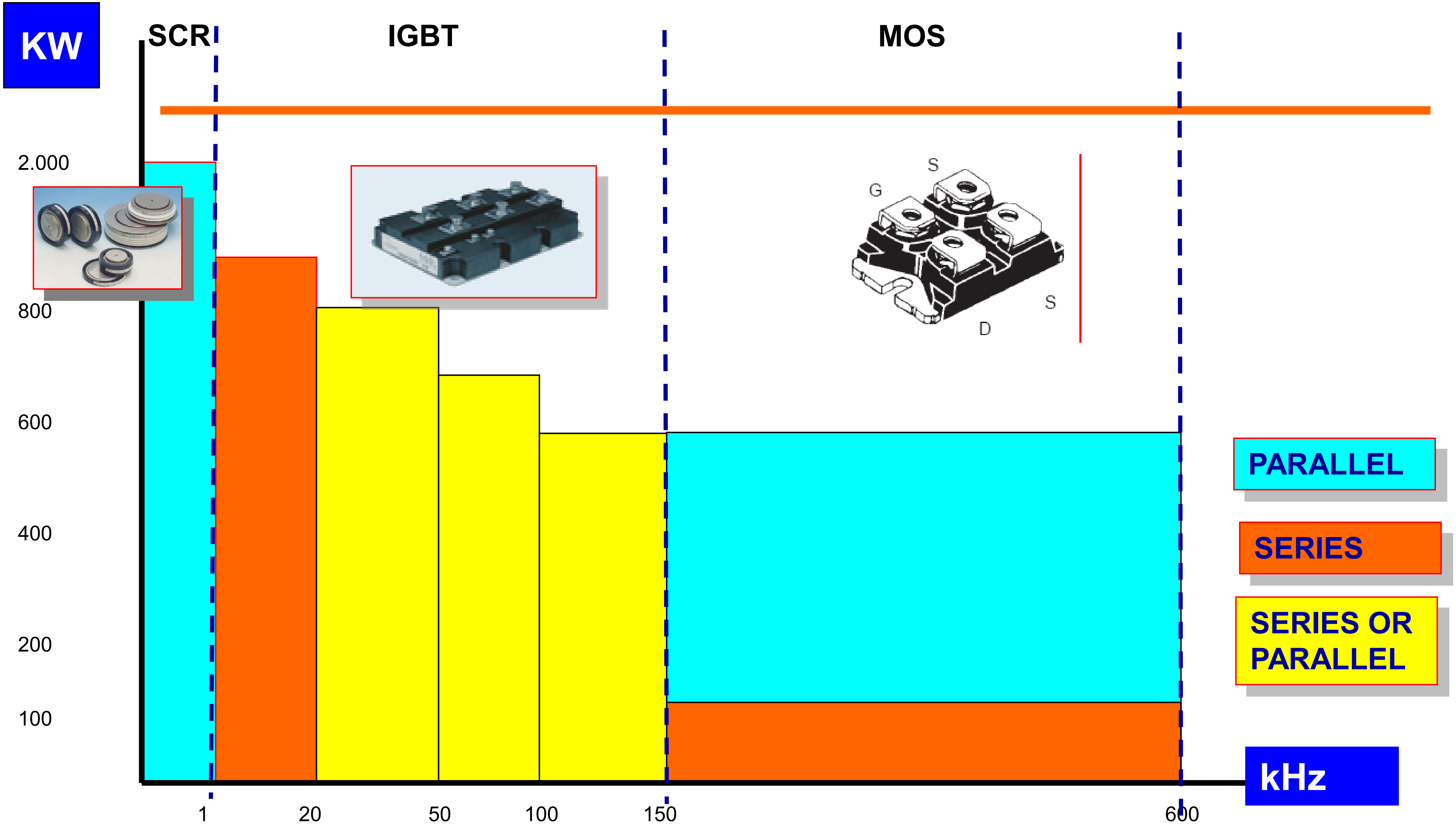
donde

$$U_{di} = \frac{3\cdot\sqrt{2}}{\pi}\cdot U_{20} = 1{,}35\cdot U_{20}$$

Outline

- ✓Basic Concepts in Induction Heating
- ✓ Compensation of the Load
- ✓Series Resonant Converters for IH
- ✓Parallel Resonant Converters for IH
- **✓Semiconductors used in IH**
- ✓Applications
  - ✓Forging
  - ✓Hardening
  - ✓Multipurpose Generators
  - ✓Bonding
  - ✓Welders
- ✓Controllers
- ✓Roadmap

Semiconductors used in IH



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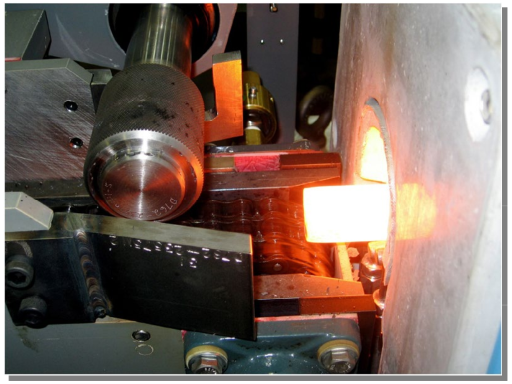
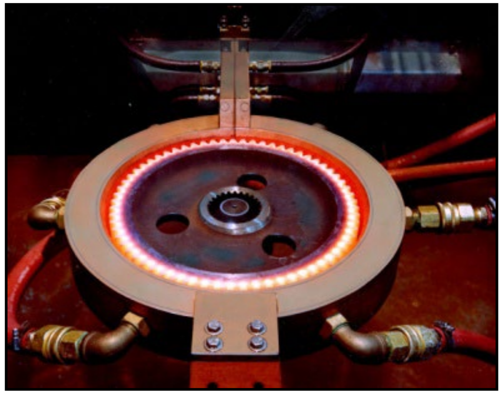
Applications of IH

Industrial processes

Domestic Applications

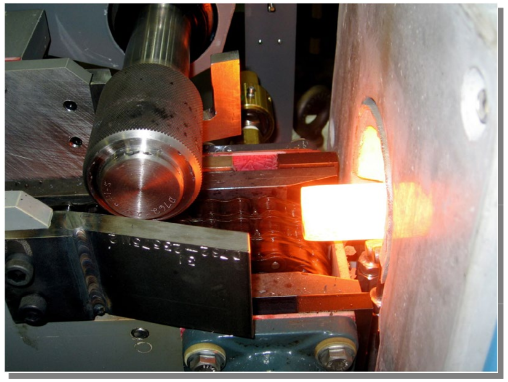
Main Advantages of IH in Material Processing

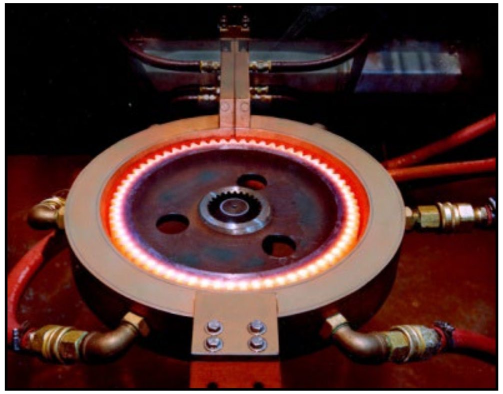




- ✓Fast, precise, efficient, repeatable
  - - Reduces energy, utility & operating costs
- ✓ Advantages of induction heating
  - - Efficiency & reliability
  - - Flexible, modular & reduced costs
- ✓ Less floor space
  - - Compact, modular & moveable
- ✓ No warm-up time
  - - Standby & hold circuitry
- ✓ Environmentally friendly
  - - Low energy consumption
- ✓ High quality results
  - - Reduced part distortion, less scale (forging)

Applications and Industries





Induction heating applications

- Heating & heat treating
- Forge heating
- Mass Heating
- Other applications

Industries that benefit from induction heating

- Automotive
- Aeronautics
- Electrical motor manufacturers
- Other Industries

Applications of IH

APPLICATION	POWER (KW)	FREQUENCY (KHZ)	TYPE OF GENERATOR
MELTING FOR INDUSTRY	***25-12.000***	***0,1-2,0***	***THYRISTOR***
FORGING	***5-5.000***	***0,25-5,0***	***THYRISTOR, IGBT***
SURFACE HARDENING > 2mm	***5-1.000***	***3-10***	***IGBT***
SURFACE HARDENING < 2mm	***5-500***	***3-150***	***IGBT***
TUBE WELDING	***100-1.000***	***100-600***	***MOS***

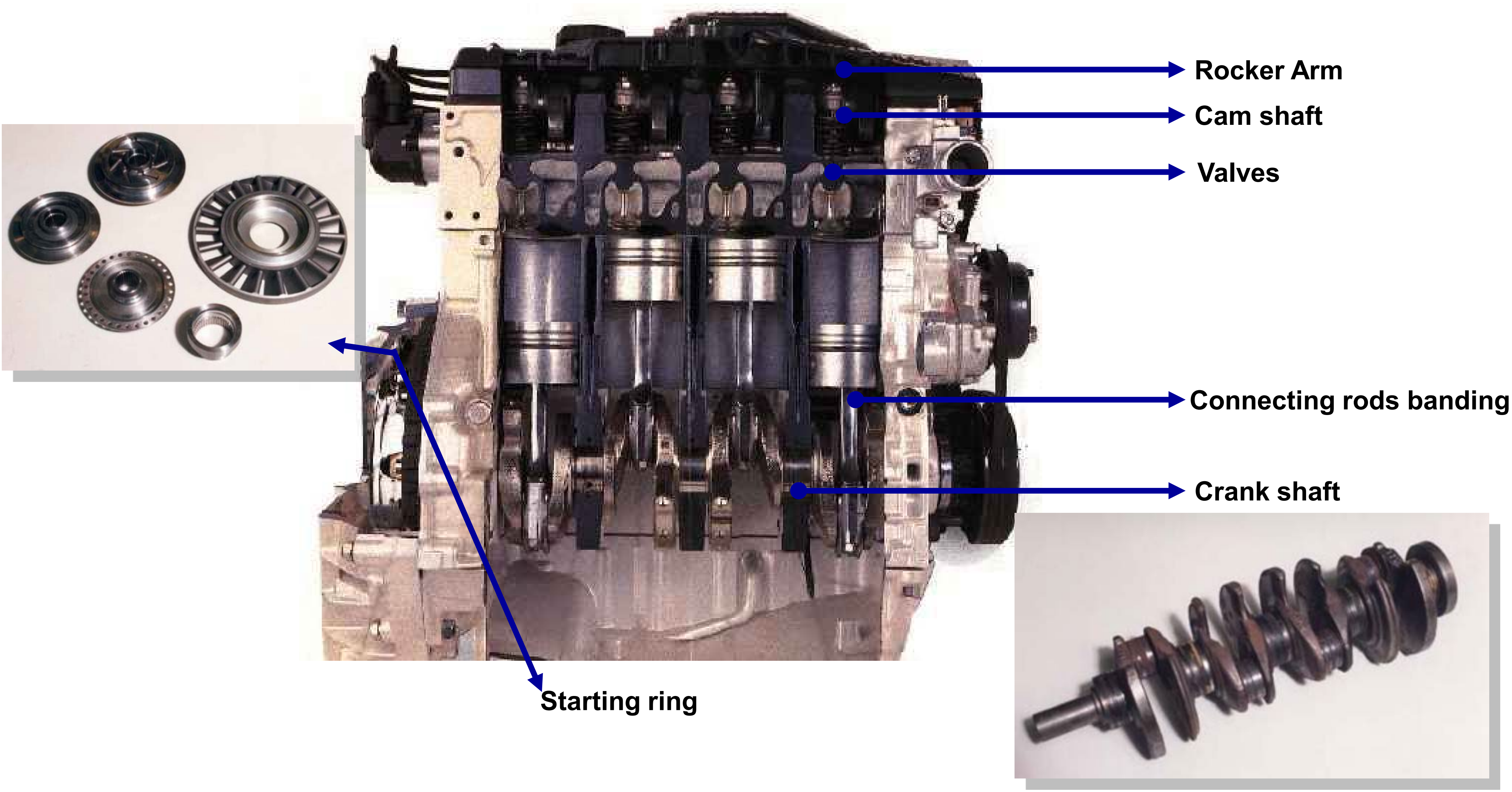
Several Applications by Industries

- Automotive
- Aerospace
- Oil & Gas
- Steel and iron industry
- White goods
- Wind energy
- Fastener
- Fibber Optic
- Medical
- Jewellery

Several Applications by Processes

- Adhesive curing
- Annealing
- Bonding
- Bonding rubber-metal
- Atmospheric brazing
- Brazing
- Catheter tipping
- Crystal pulling
- Forging
- Getter firing
- Hardening
- Pre-heating
- Staking metal-plastic
- Hot forming
- Levitation melting
- Material testing
- Melting
- MOCVD
- Pin Sealing
- Plastic reflow
- Sealing metal-glass
- Shrink fitting
- Soldering
- Susceptor heating

Automotive Industry



Rocker Arm

Cam shaft

Valves

Connecting rods banding

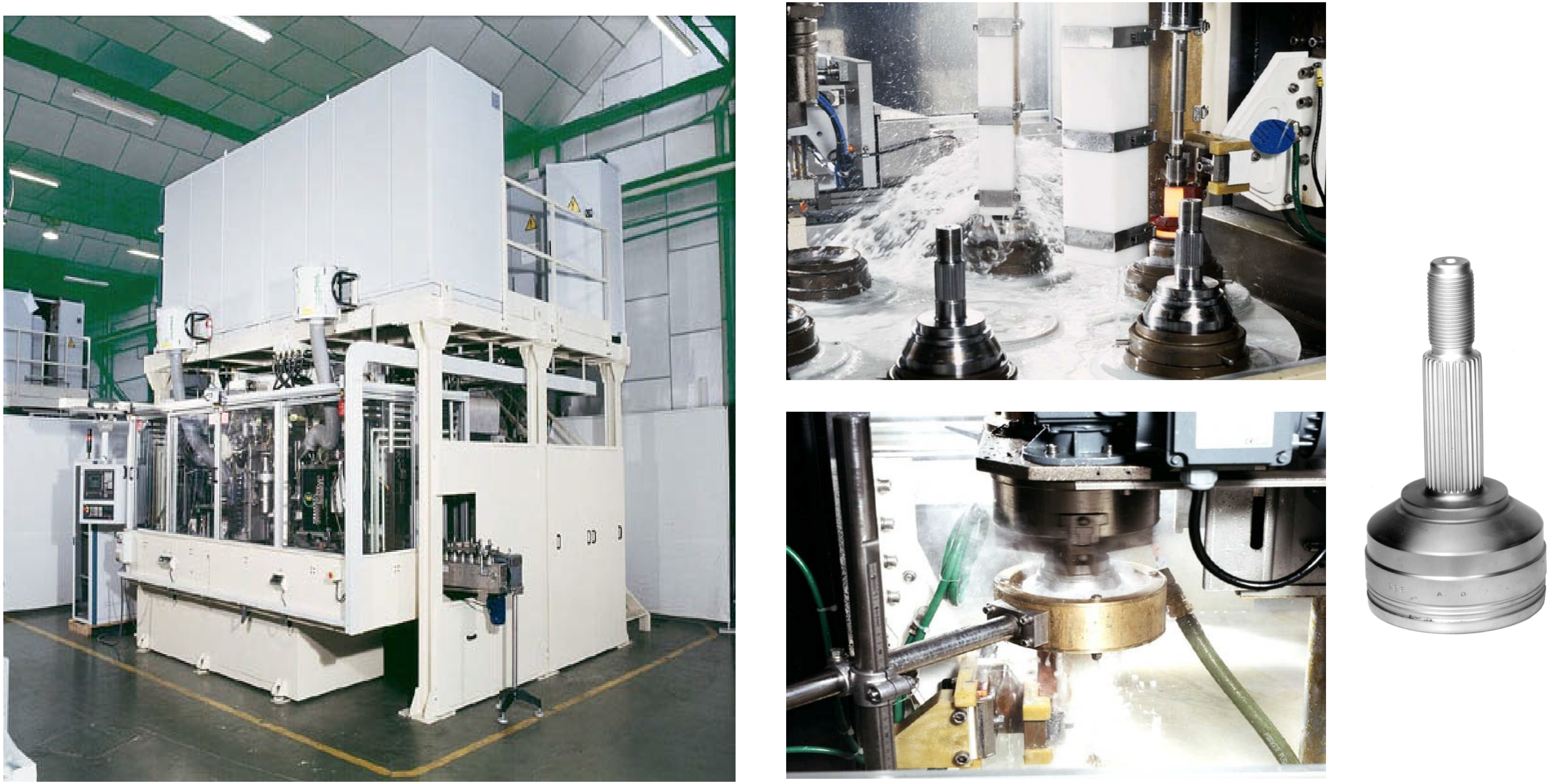
Crank shaft

Starting ring

Automotive Industry

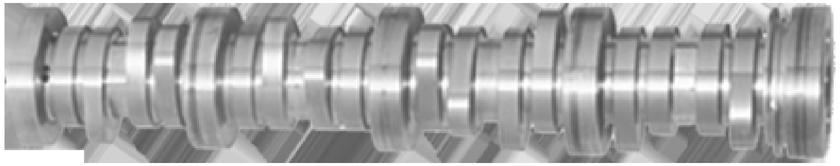
Drive Shaft Hardening & Tempering Installation

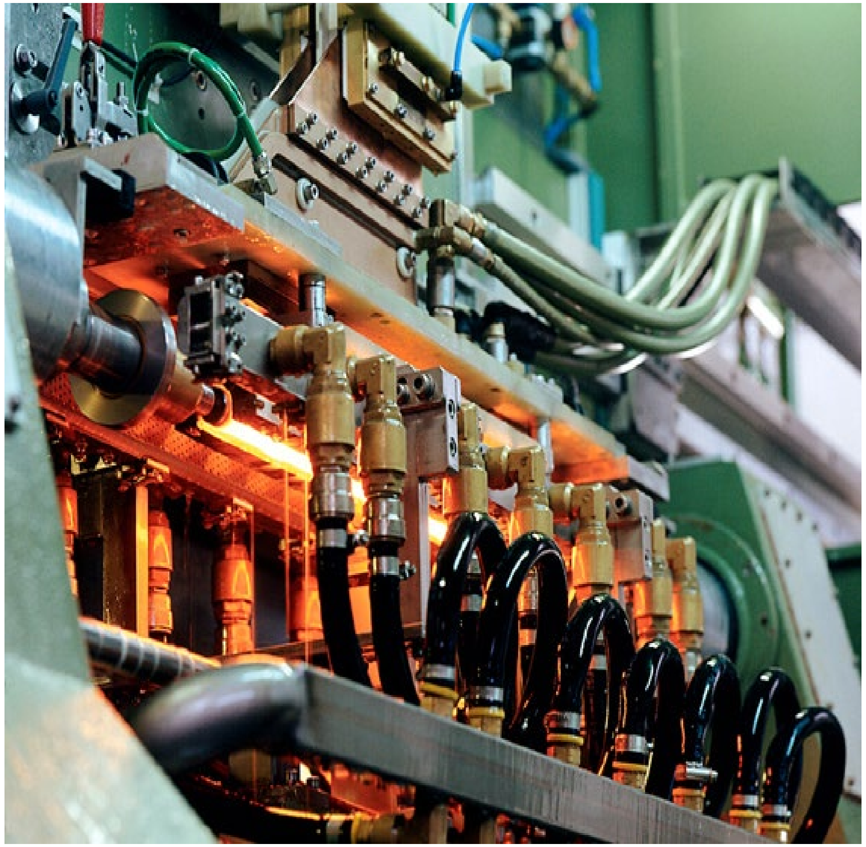
Automotive Industry



CV Joint Hardening Installation

Automotive Industry





Drive Shaft Hardening Installation

Aeronautic Industry

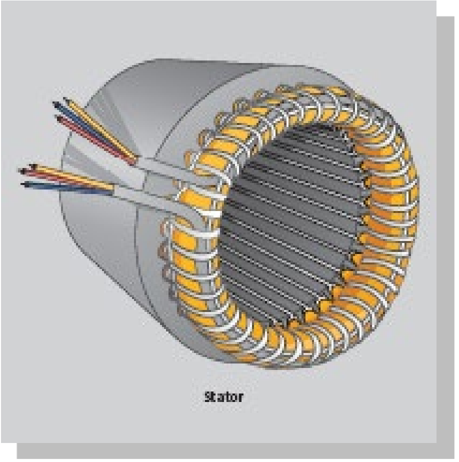
- Wing to wing thermal processing

- Turbine engines
- Piston engines
- Connecting rods, crankshaft, gears
- Turbojet, turboshaft & turboprop engines

Electric Motor Industry

- Inductions applications

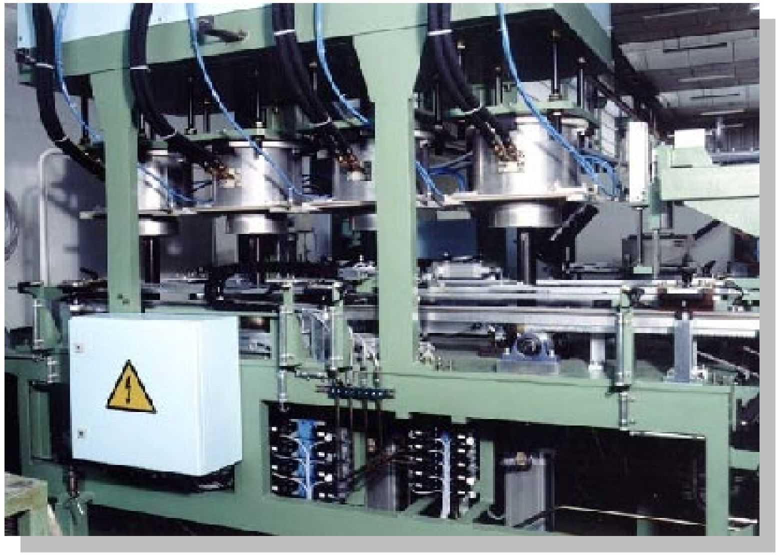
- Shrink fitting
- Paint drying
- Brazing & soldering
- Curing of encapsulates



- Various induction heated parts

- Housing for motor assembly
- Stators & rotors
- DC motor armatures
- Gears & bearings

Other Industries



- Other industries that benefit

- Hand & mining tools

- Marine engines

- Railroad: train engines, tracks

- Off-road vehicles: motorcycles, bicycles

-Household cooking buttons

- Various induction heated parts

- Hammers, shovels, bits, fubars

- Cranks & cams

- Gears, sprockets, bearings

-Pan Button Brazing

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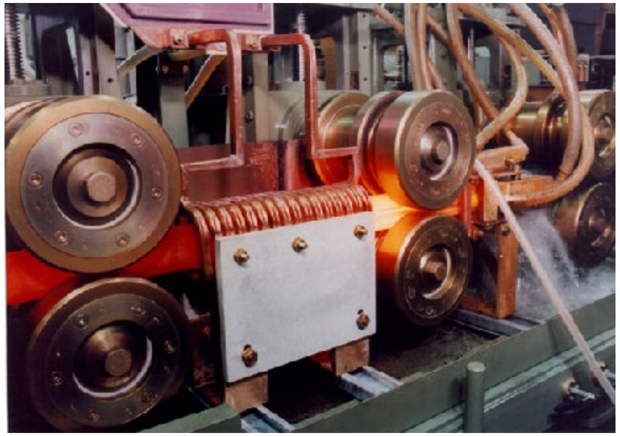
Mass Heating and Forging



Mass Heating (hot & warm forging)

Slab & strip Heating

Wire & cable heating

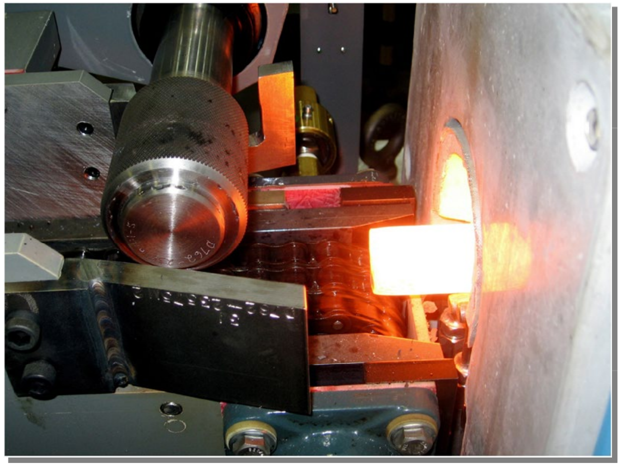
Tube & pipe heating

Forming: bending, expanding & spinning

Extrusion: squeezing metal through a die

Rolling: made from ingots or continuous cast metals

Mass Heating and Forging



- Forging

  Forging: billets or bars heated and are forged in press hammers or up setters

  Steel components represent the majority

  Aluminum, copper, brass, bronze, cobalt, nickel and titanium as well
- Ideal billet temperature: 1200 ºC

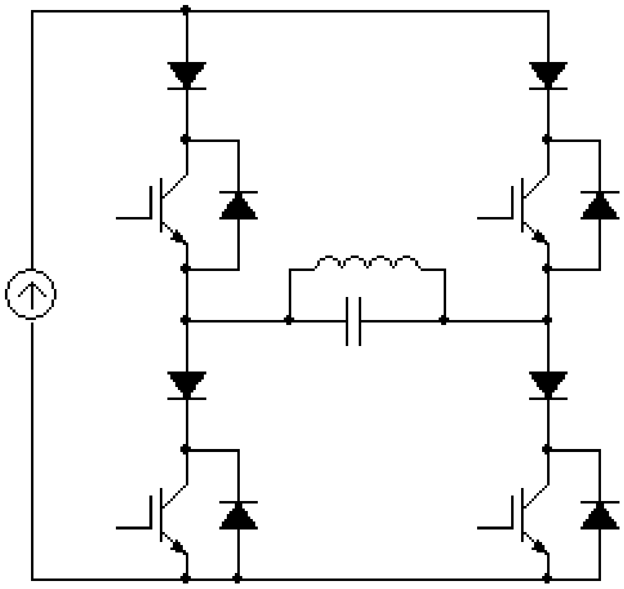
\- Advanced Temperature Profile Modeling

Mass Heating and Forging

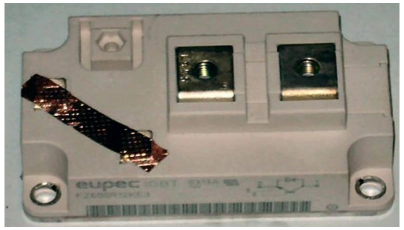
Power Range:

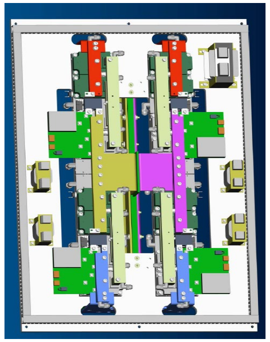
500 Vef MF (1-5 kHz)	500 kW - 800kW
800 Vef MF (1-3kHz)	500kW - 800kW - 1000kW - 1200kW
1200 Vef MF (1-3kHz)	800-1500kW – 2000kW

Current-fed inverter



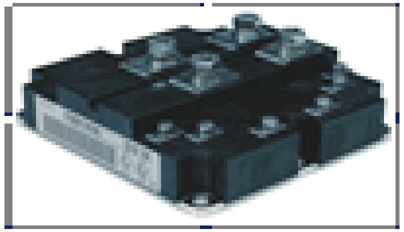
Mass Heating and Forging

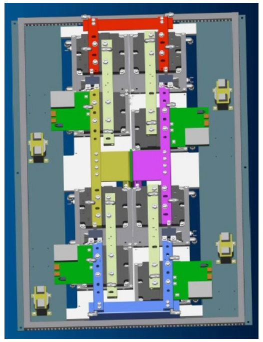




CONFIGURACIÓN nº 1

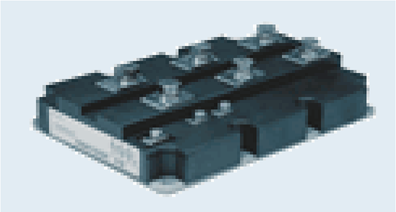
MÓDULOS DE 140 mm. x 130 mm.

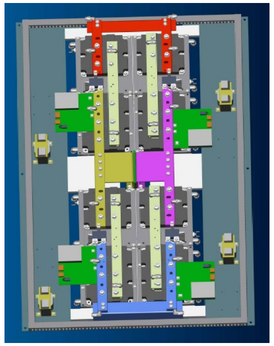




CONFIGURACIÓN nº 2

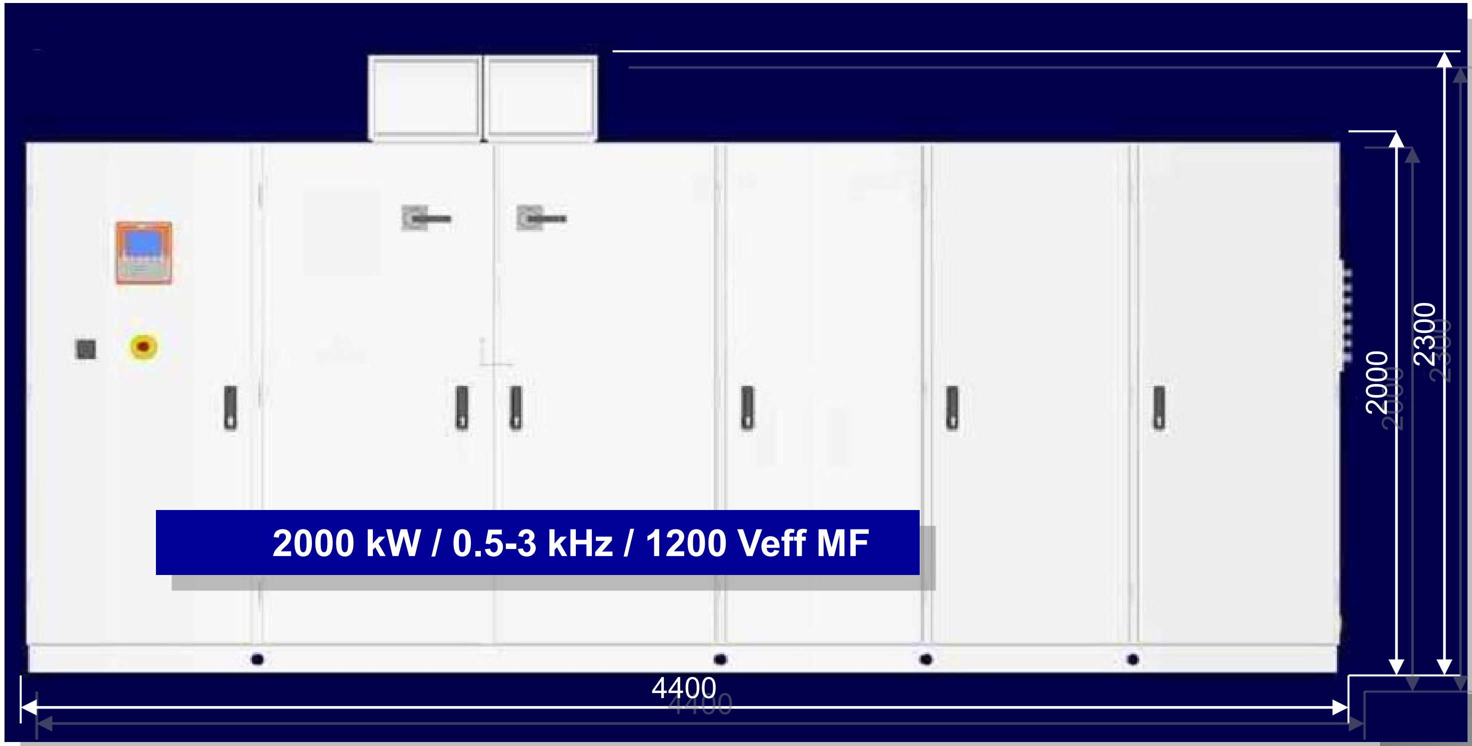
MÓDULOS DE 140 mm. x 190 mm.



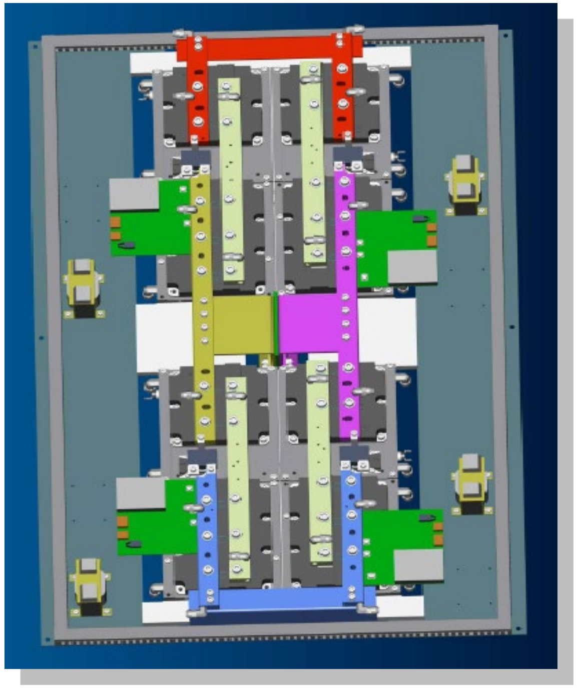


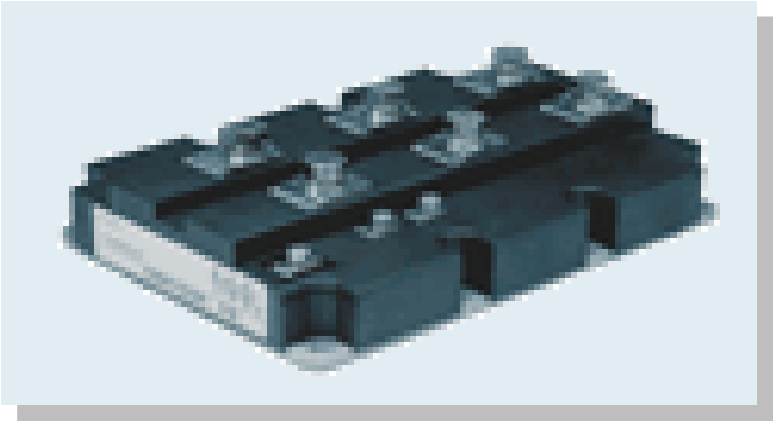
CONFIGURACIÓN nº 3

Mass Heating and Forging



2000 kW / 0.5-3 kHz / 1200 Veff MF





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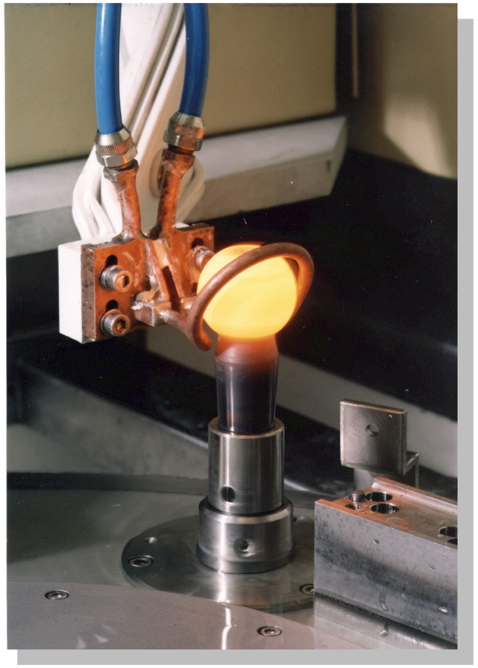
Hardening

Heating & Heat Treating

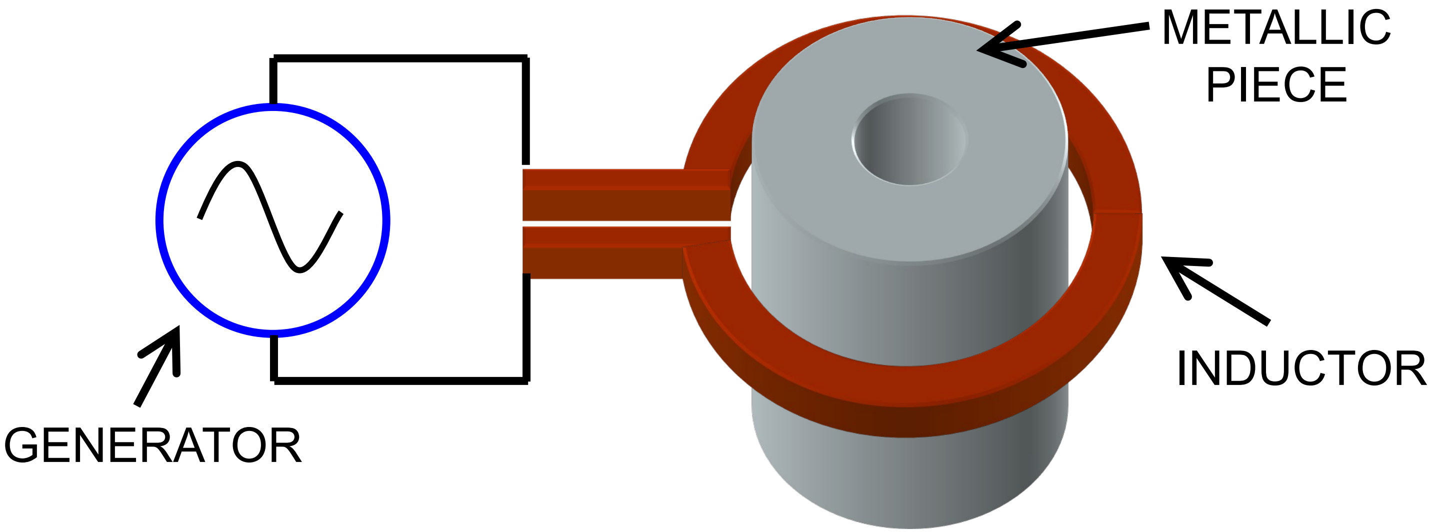
Harden: surface hardening of steel (increases wear resistance & strength)

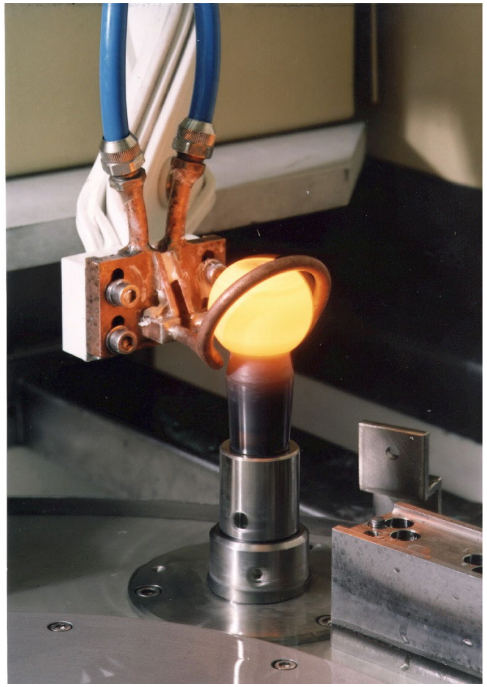
Temper: reheating & quench cooling (improves hardness & elasticity)

Annealing: remove internal stresses improving ductility of material



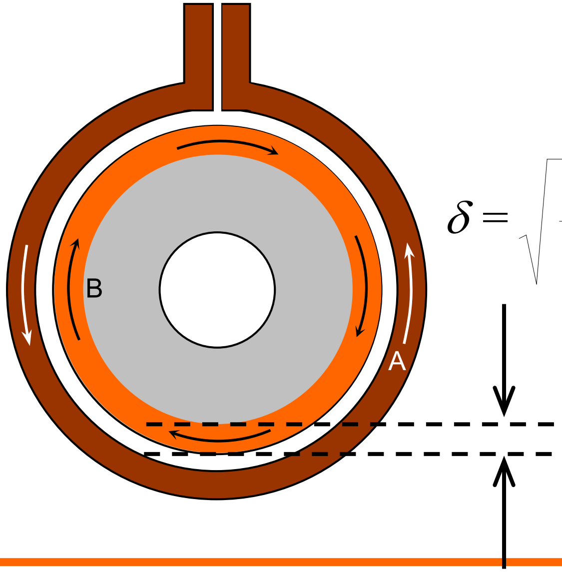
Hardening



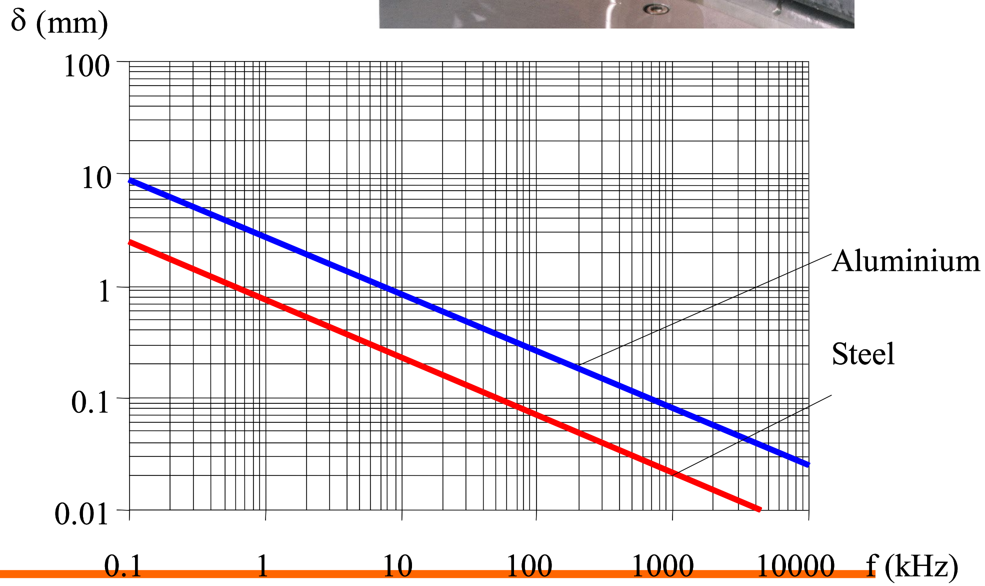


A: Inductor current

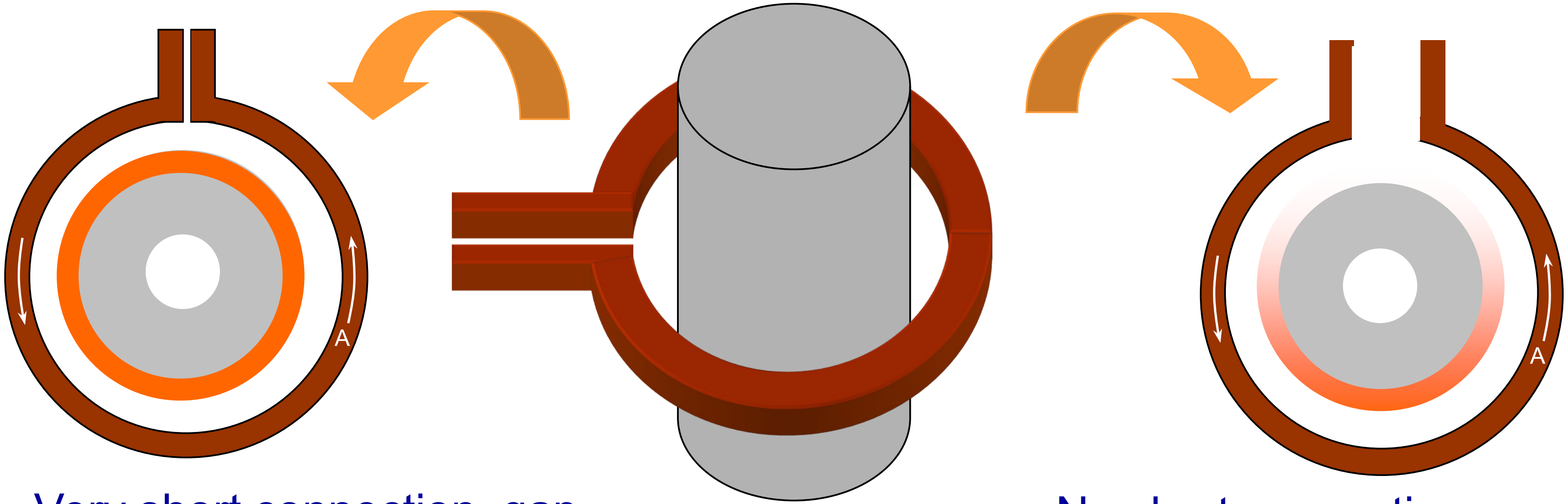
B: Induced current



$$\delta = \sqrt{\frac{\rho}{\pi \, f \, \mu}}$$



Hardening

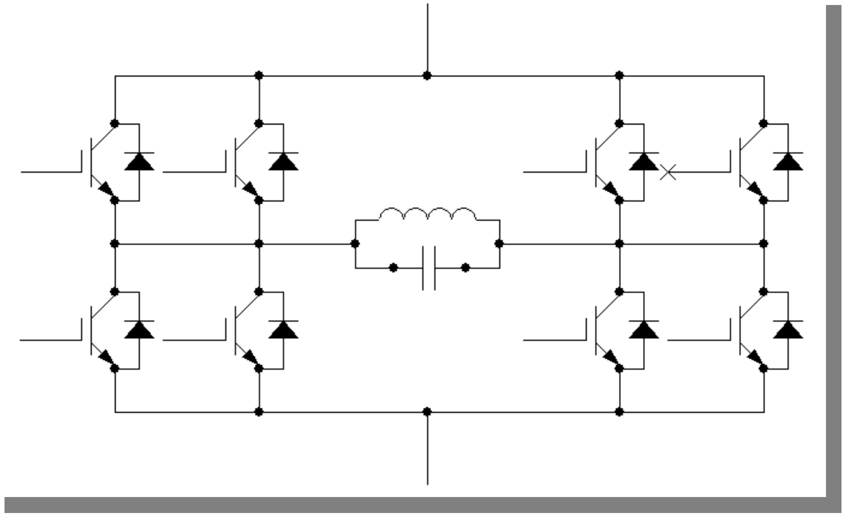


- Very short connection gap
- Piece is centred
- ➡ Uniform magnetic field
- ➡ No rotation is needed

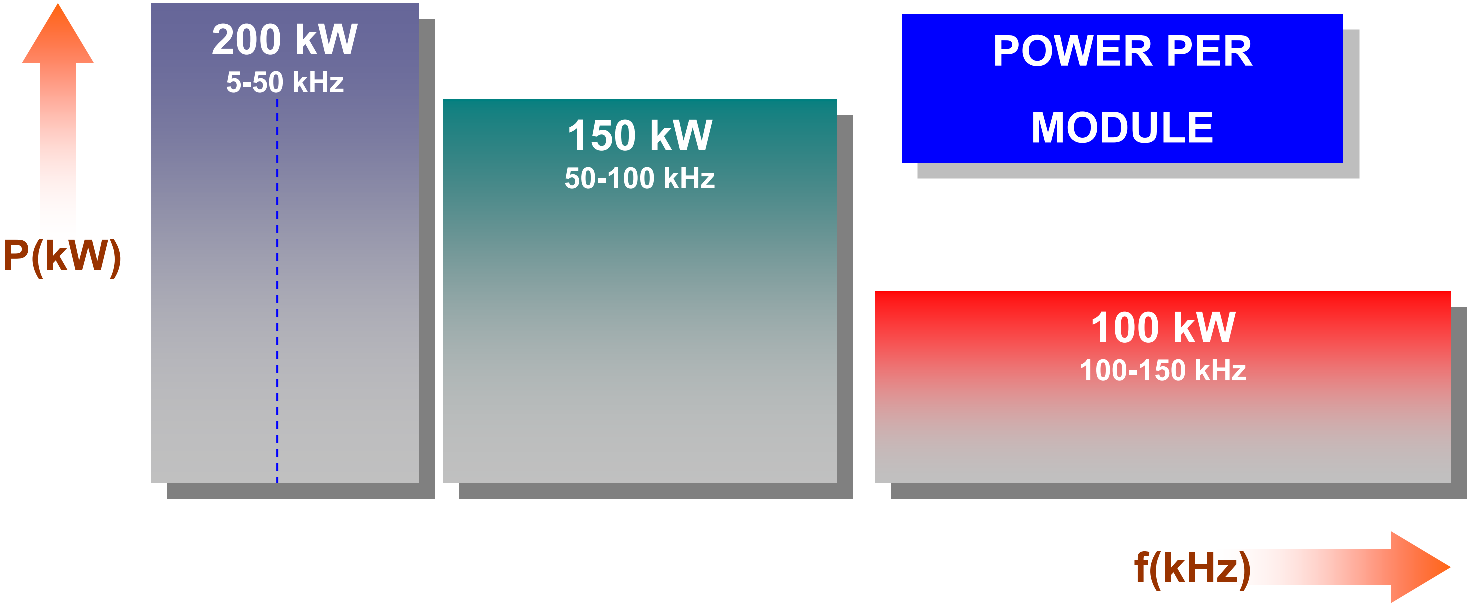
- No short connection gap
- Piece is centred
- ➡ Non uniform magnetic field due to the gap
- ➡ Rotation is needed
- ➡ Piece or inductor can rotate, there is no difference in the magnetic pattern

Monofrequency Hardening

BASIC INVERTER BRIDGE:



- **Current- Fed Inverter with no diodes in series with transistors.**
- **Frequency = 5 ÷ 150 kHz**
- **VMF= 500Veff**
- **Two frequencies are possible if both are in the same range: (5-30kHz),(30-50kHz)(50-100kHz)(100-150kHz).**
- **Drives cards, Peak detectors and RC networks limit the frequency range.**
- **Output power for reliability of 3 ÷ 6 million cycles (*).**

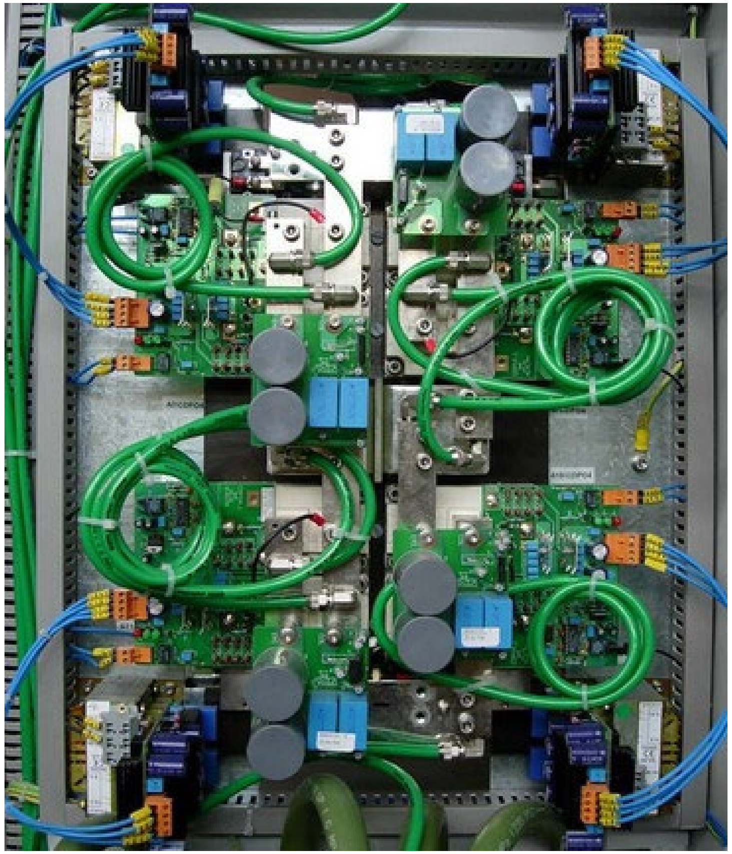


IGBT FZ600R12KS4

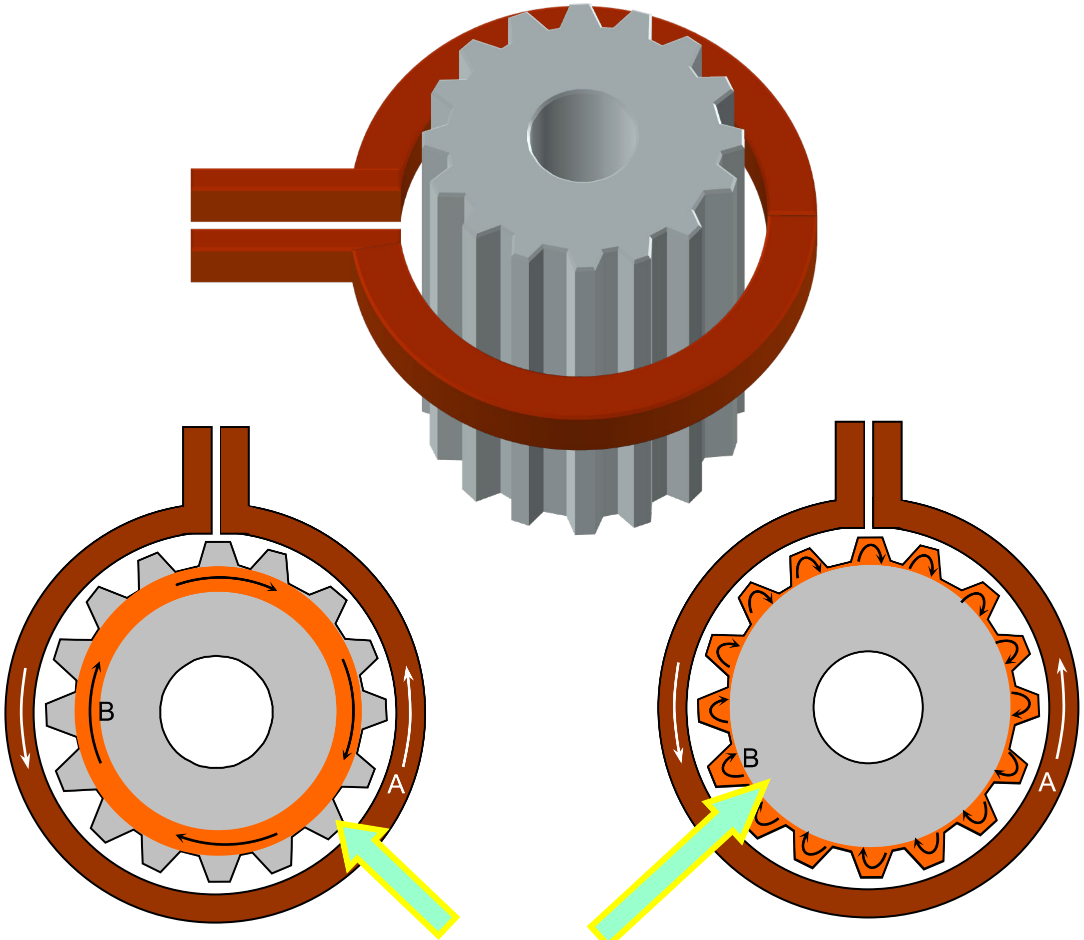
Monofrequency Hardening

INVERTER SIZE:

- ☐ **480 x 580 mm.**
- ☐ **8 IGBTs FZ600R12KS4 are used- 62mm**



APPLICABLE TO UNREGULAR SURFACES



MEDIUM FREQUENCY

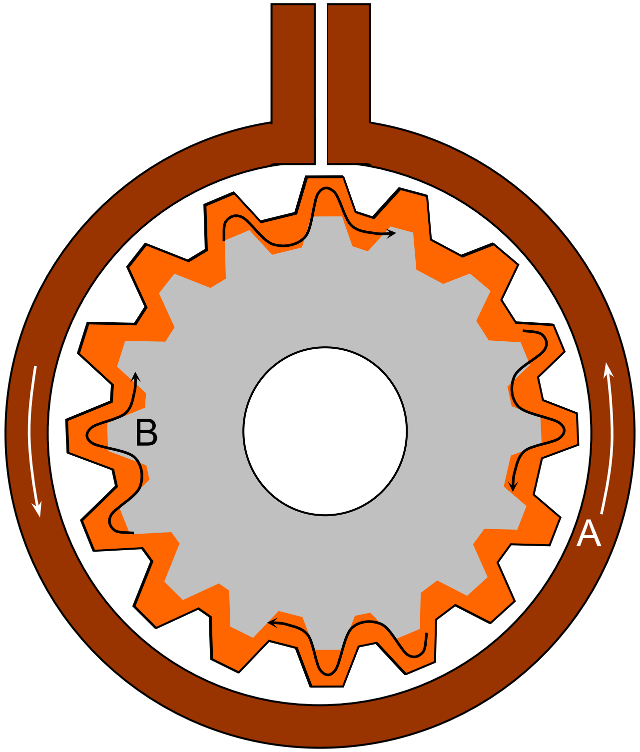
Current flows in the minimum *resistance* path

HIGH FREQUENCY

Current flows in the minimum *inductance* path

NON UNIFORM PENETRATION DEPTH

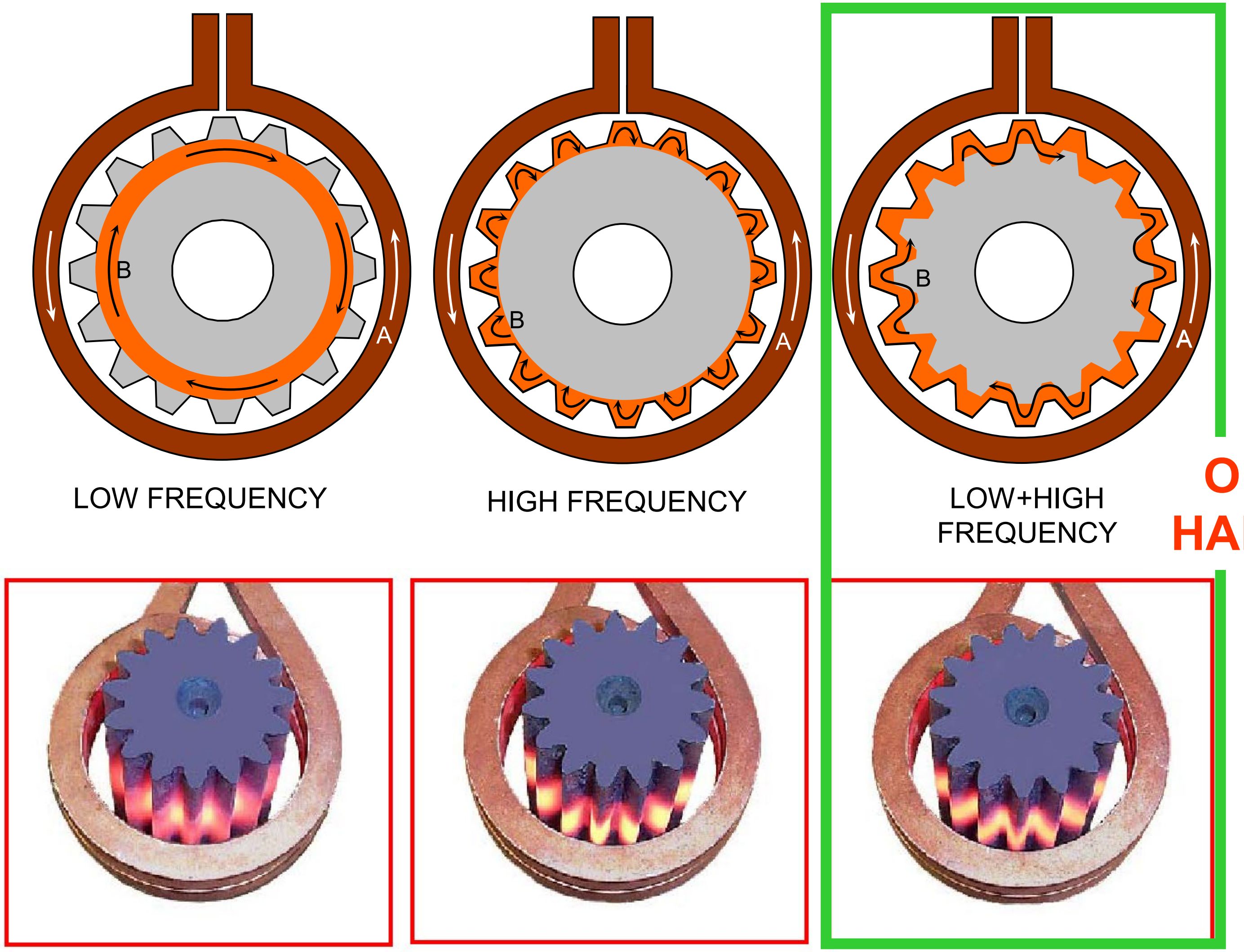
MEDIUM AND HIGH FREQUENCY SIMULTANEOUSLY APPLIED



OPTIMAL

PENETRATION DEPTH QUASI UNIFORM

Bifrequency Hardening



LOW FREQUENCY

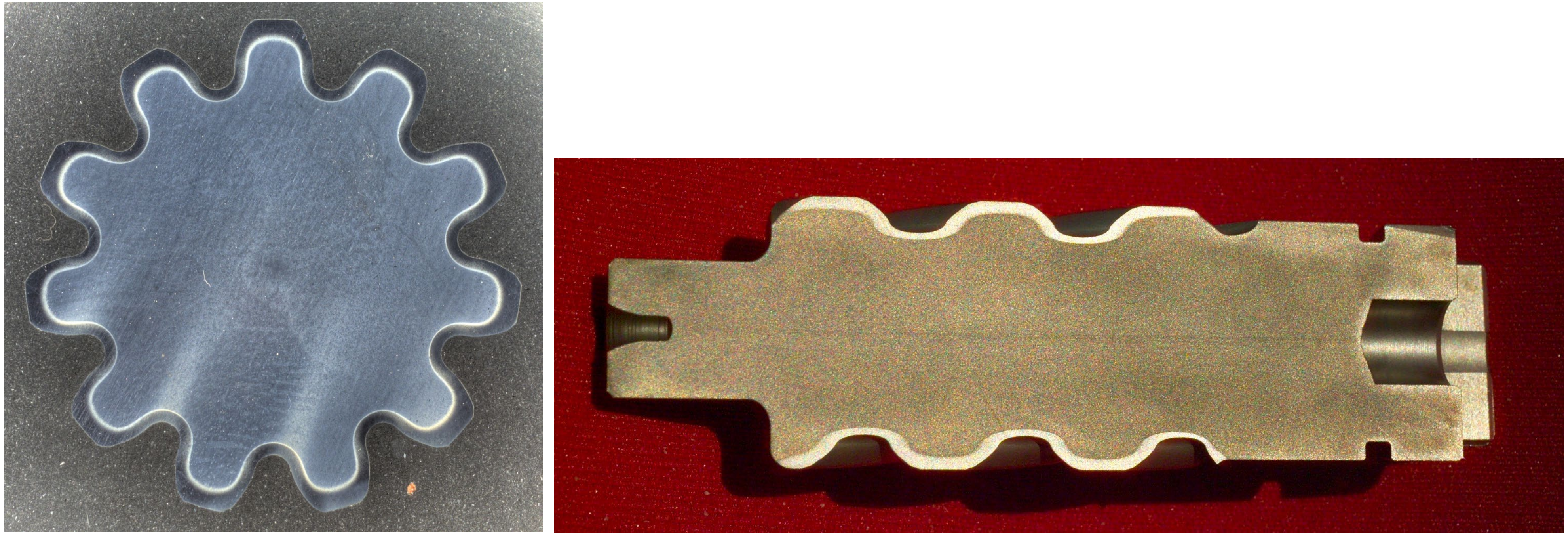
HIGH FREQUENCY

LOW+HIGH
FREQUENCY

**OPTIMUM
HARDENING**

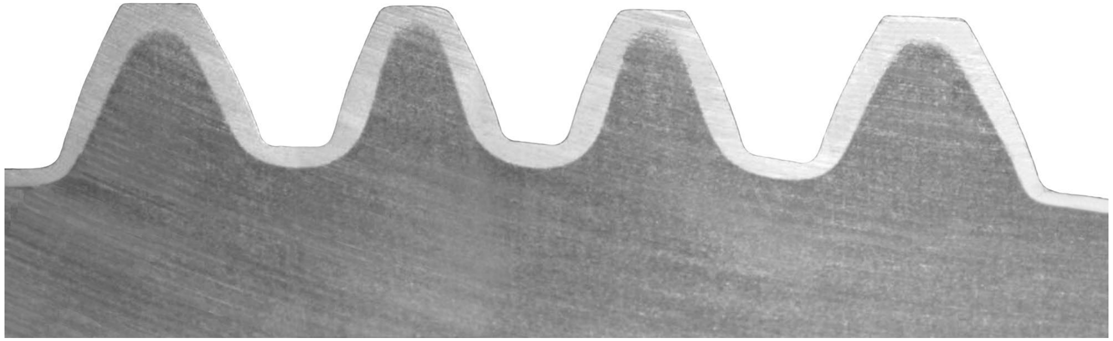
Example: Steering Pinion

Heating time: 90 ms
Applied power: 450 kW MF + 480 kW HF simultaneously
Frequencies used: 11 kHz MF and 320 kHz HF

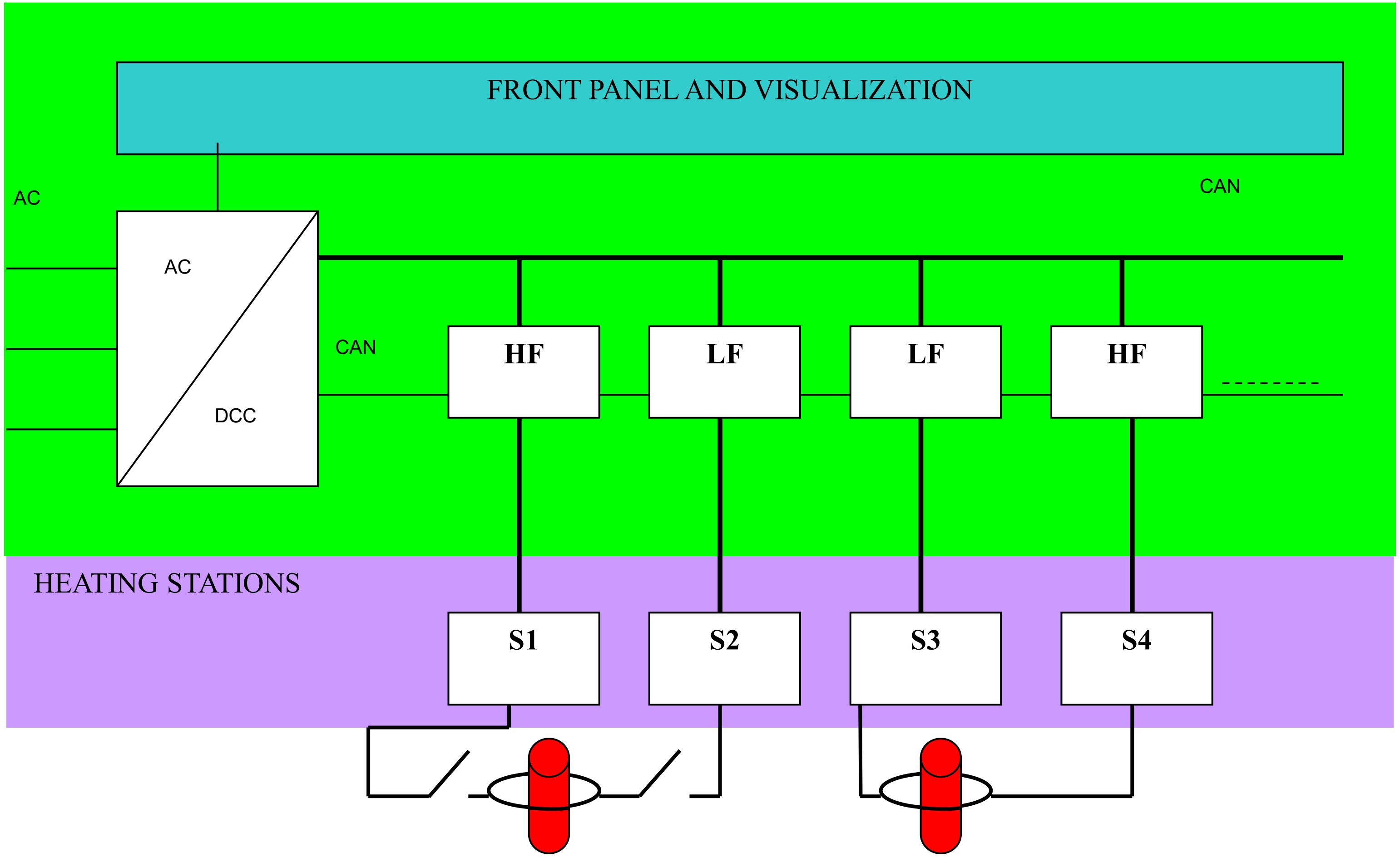


Example: Bevel Gear

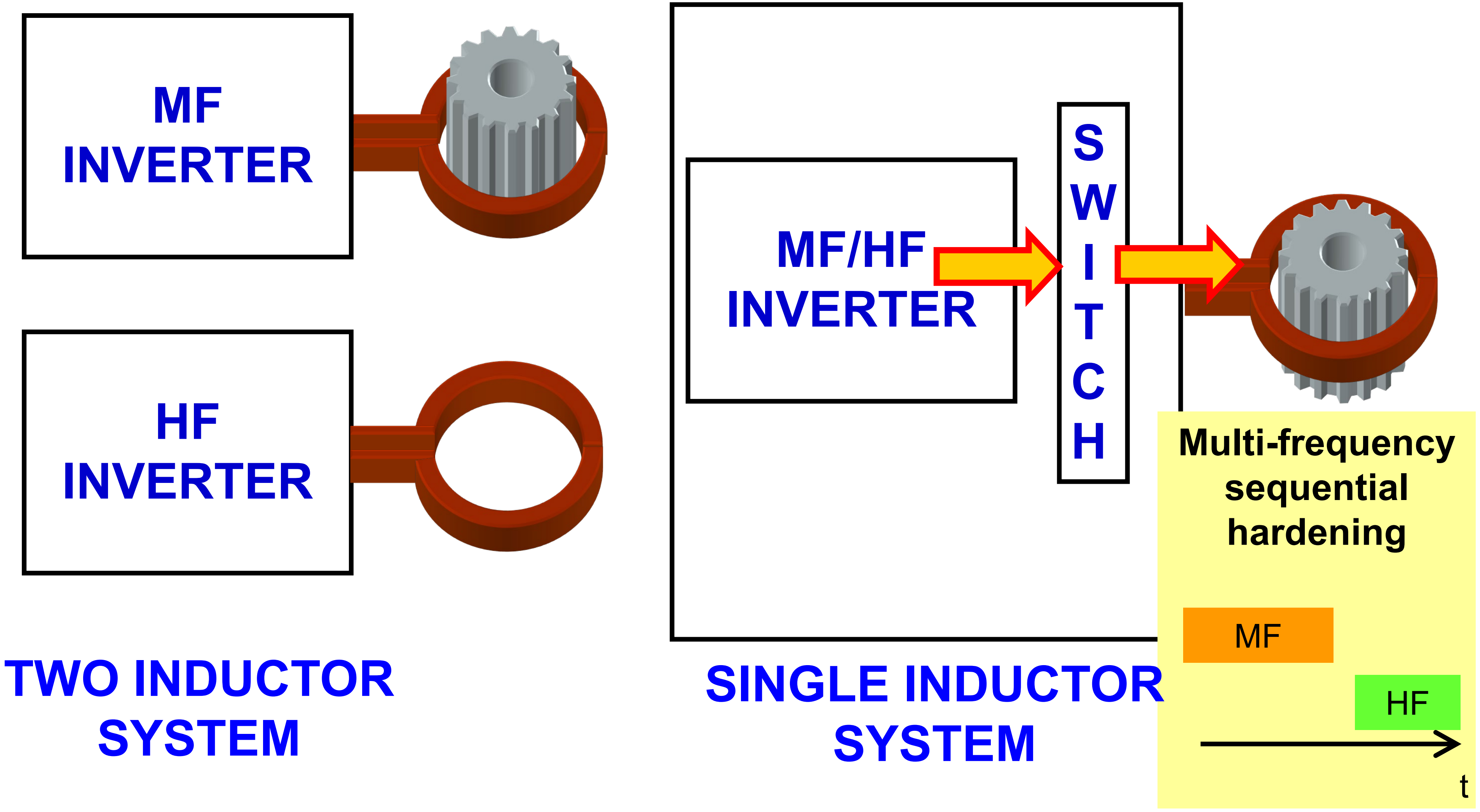
Heating time: 200 ms
Applied power: 580 kW MF + 580 kW HF simultaneously
Frequencies used: 10 kHz MF and 230 kHz HF



INVERTERS: Voltage-fed



SEQUENTIAL SYSTEMS



MF INVERTER

HF INVERTER

TWO INDUCTOR SYSTEM

MF/HF INVERTER

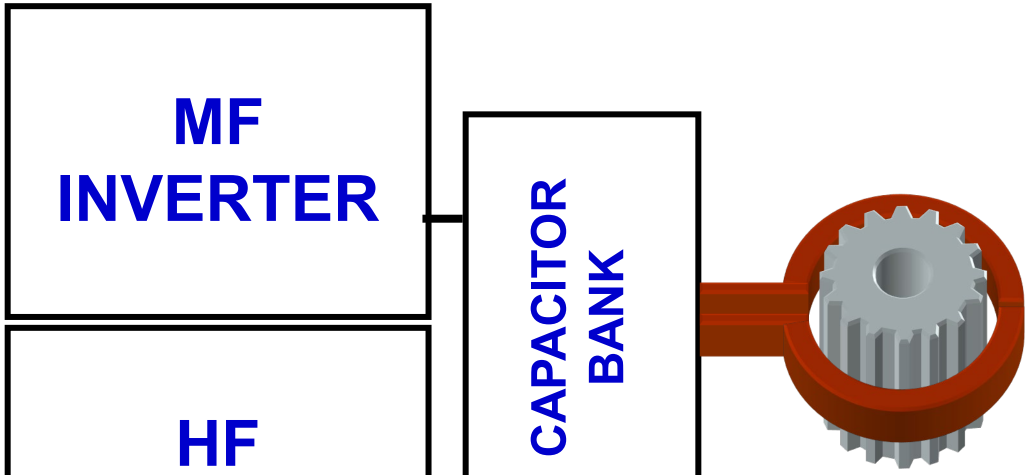
SWITCH

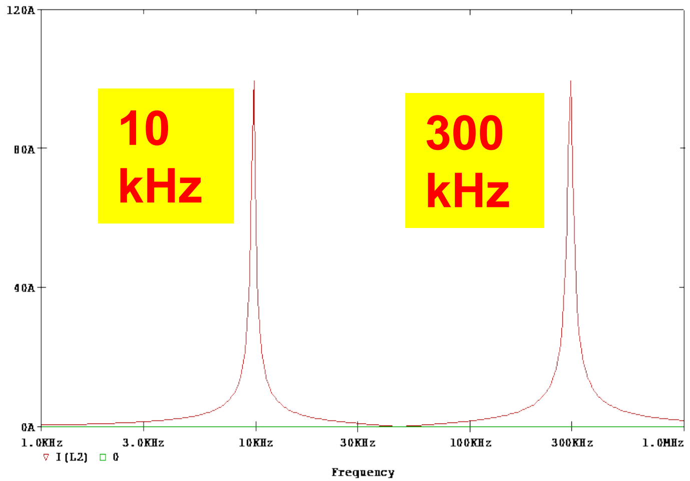
SINGLE INDUCTOR SYSTEM

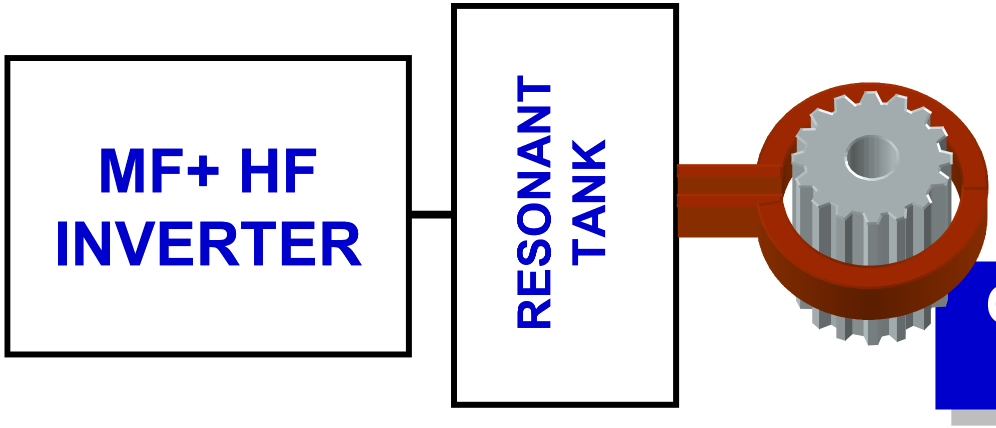
Multi-frequency sequential hardening

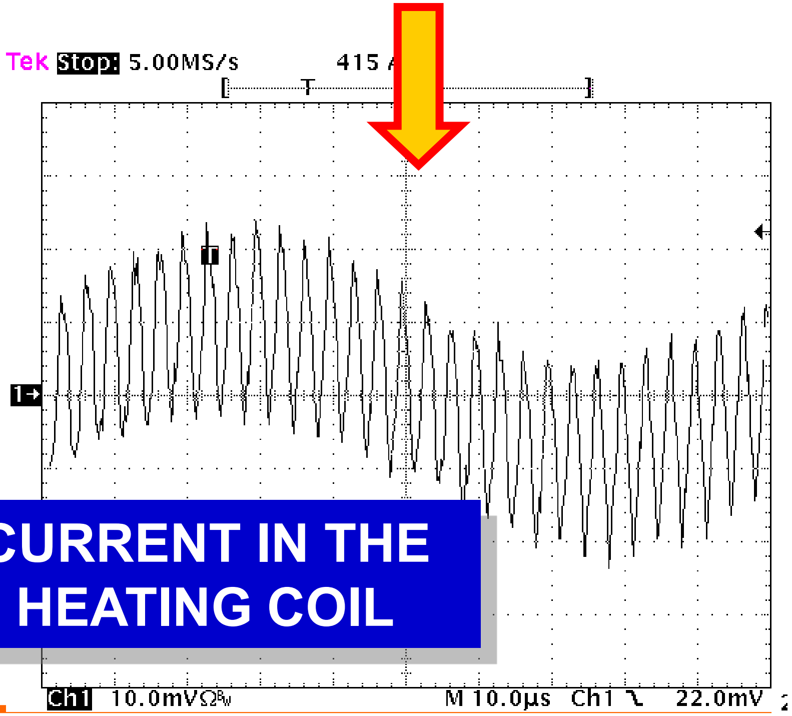
Bifrequency Hardening

SIMULTANEOUS SYSTEMS



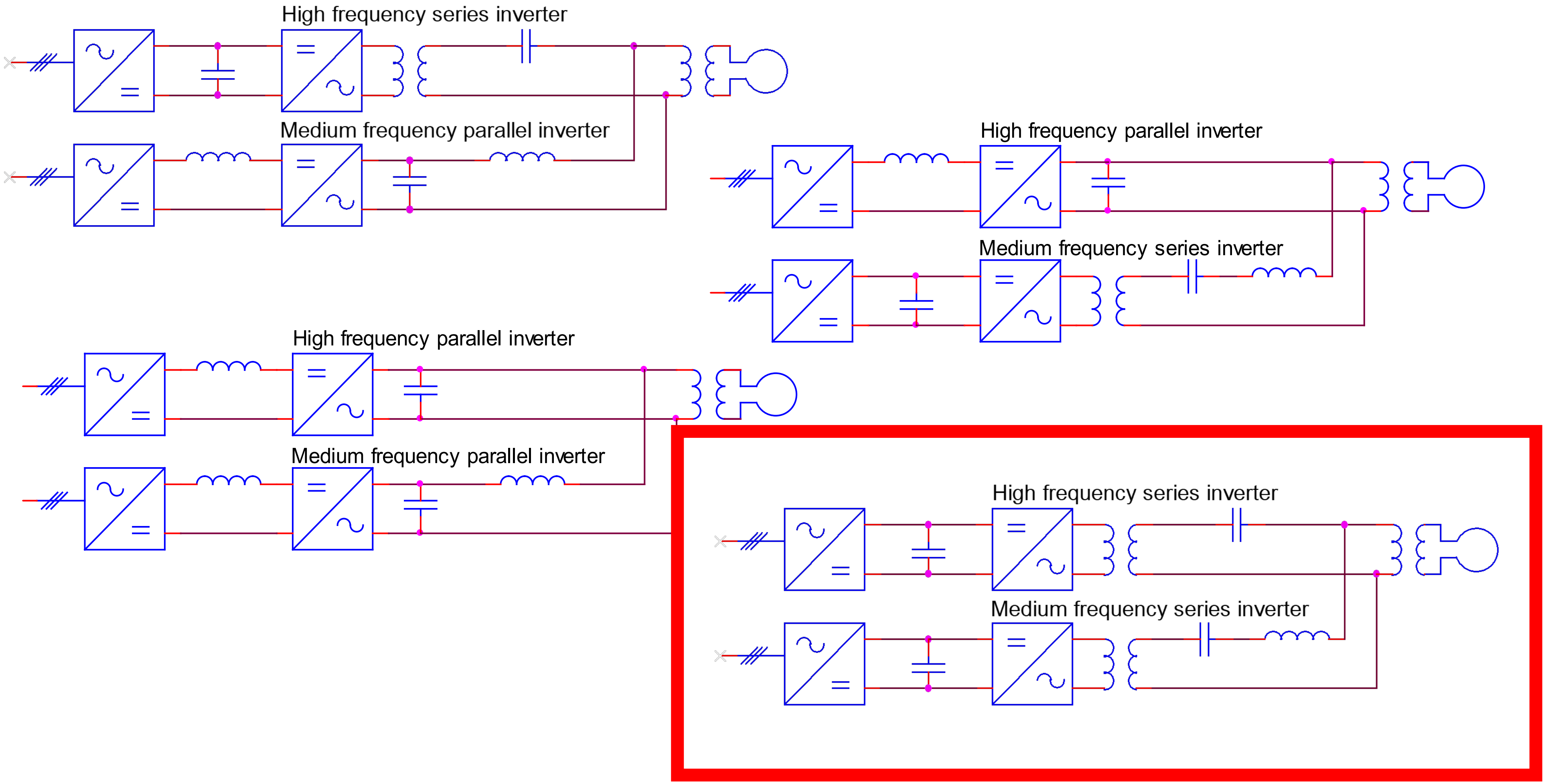






CURRENT IN THE HEATING COIL

4 REACTIVE COMPONENTS



Outline

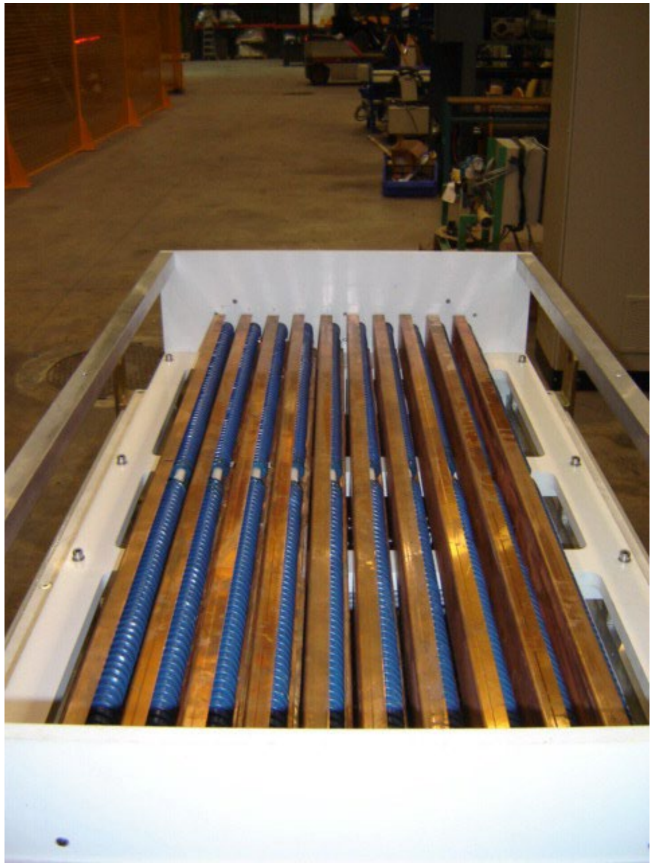
- ✓Basic Concepts in Induction Heating
- ✓ Compensation of the Load
- ✓Series Resonant Converters for IH
- ✓Parallel Resonant Converters for IH
- ✓Semiconductors used in IH
- ✓**Applications**
  - ✓Forging
  - ✓Hardening
  - ✓**Multipurpose Generators**
  - ✓Bonding
  - ✓Welders
- ✓Controllers
- ✓Roadmap

APPLICATIONS

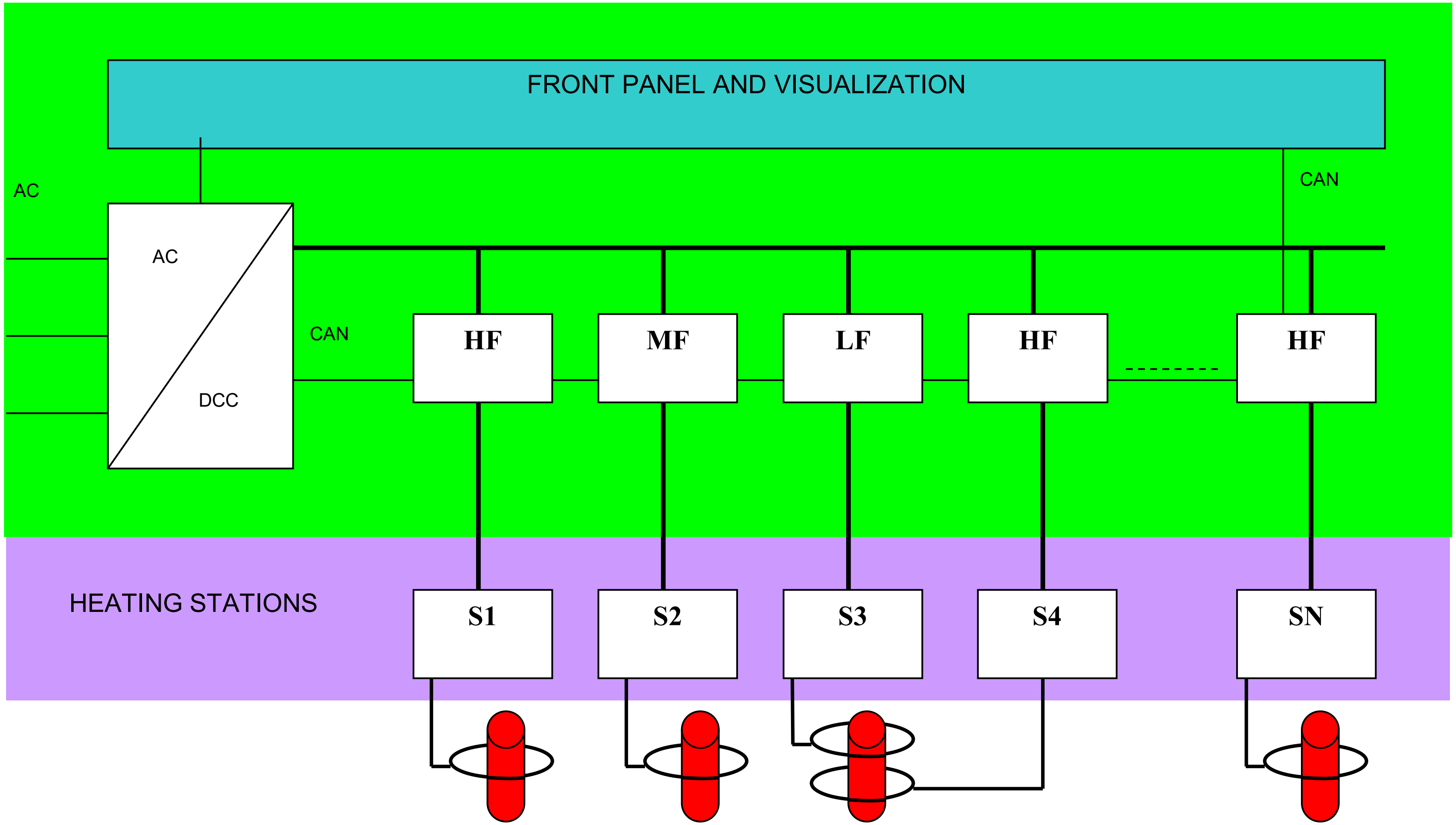
- **Processes which require more than one heating treatment, and usually two generators: HARDENING AND TEMPERING.**

- **WIRE HEATING: Several heating lines, with independent power control.**

- **PAPER DRYING: With power control at different areas of the roller.**



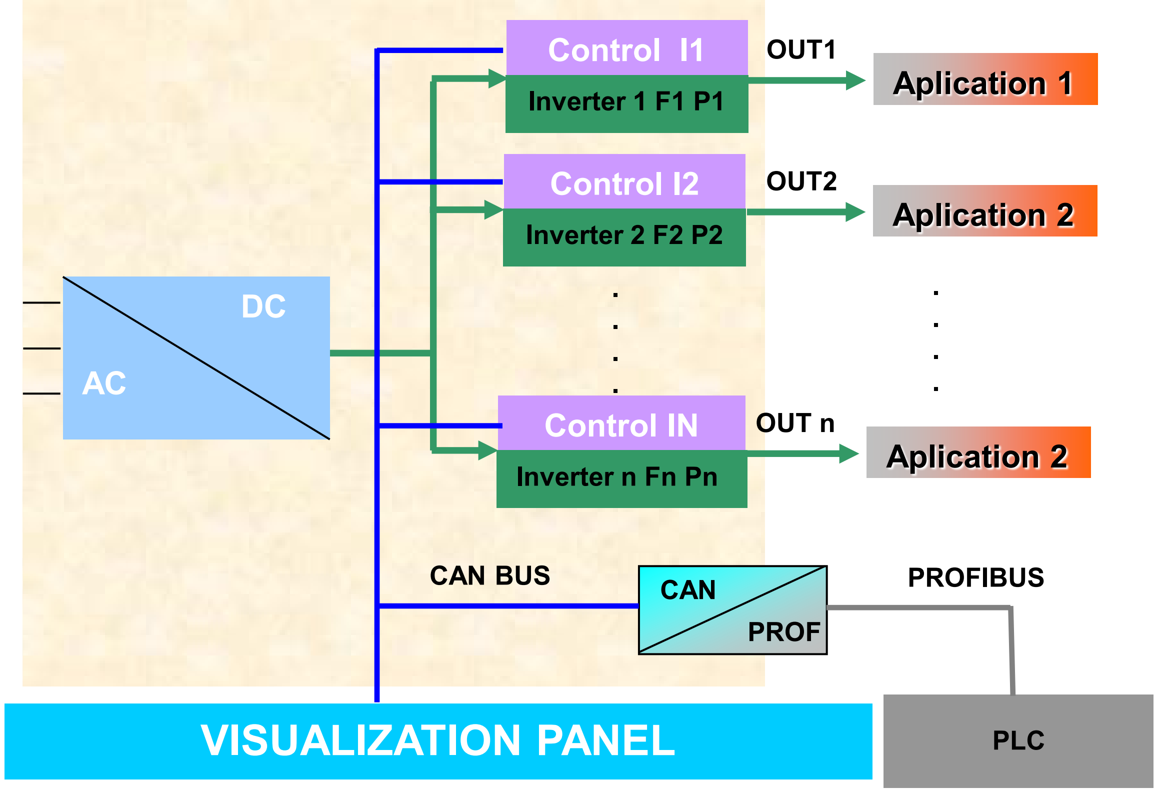
MULTI-OUTPUT



Multi-Purpose Generators

- **It has several independent outputs. Power can be regulated separately. It is, in fact, as several generators in one single system.**
- **It has as many inverter bridges as outputs.**
- **It has as many controllers as outputs.**
- **It has one single control panel.**
- **Communication system integrated in the control panel.**
- **Total power of the system is the addition of all output powers.**

Block diagram



MULTI-OUTPUT GENERATOR

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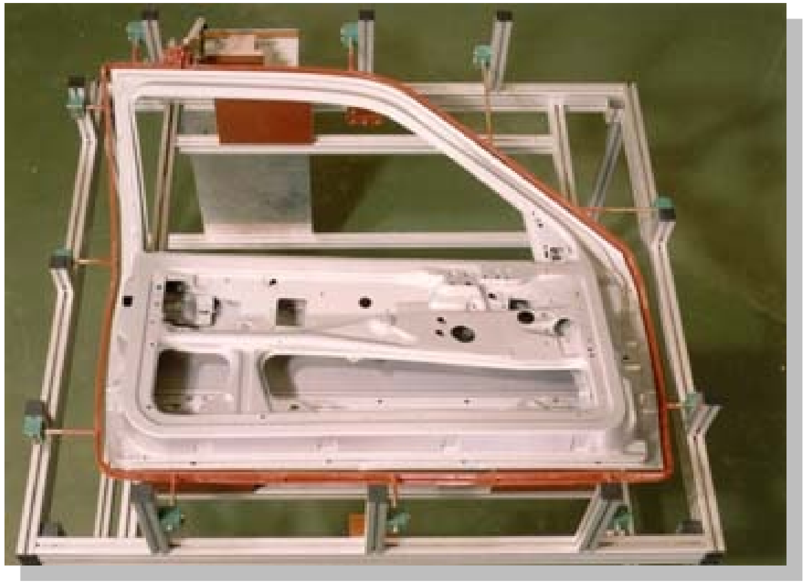
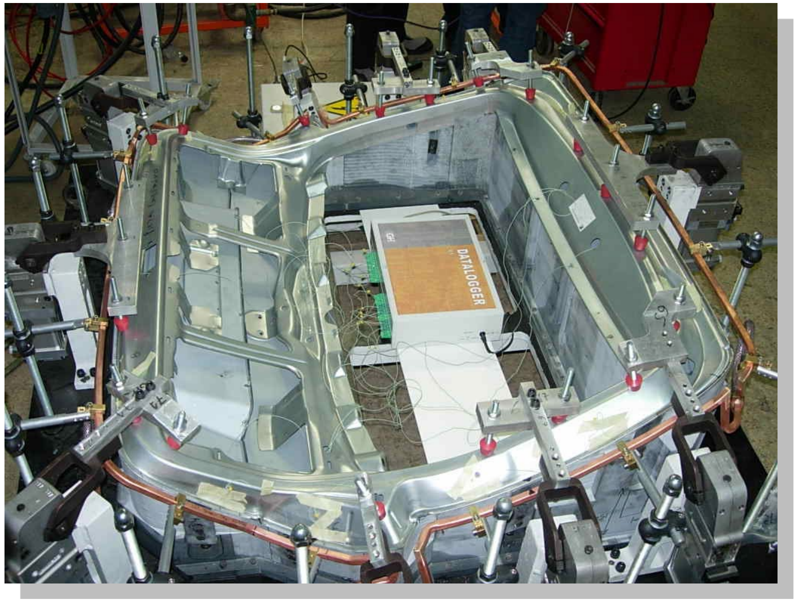
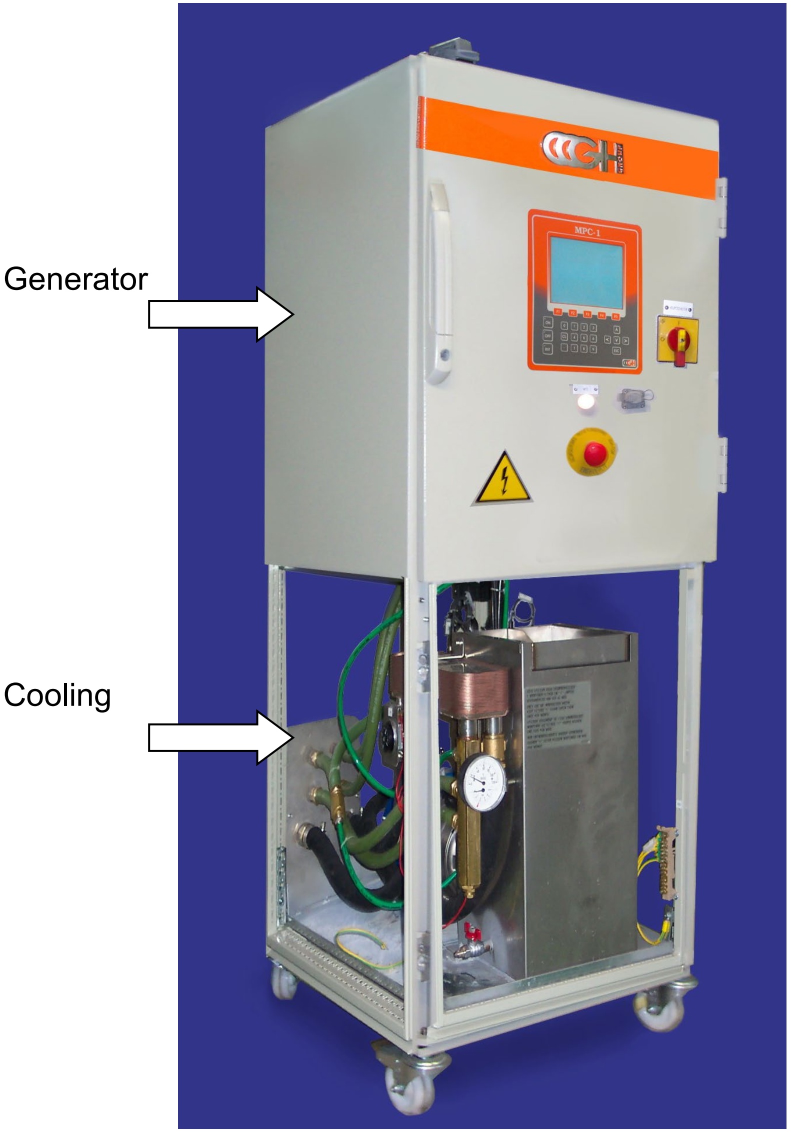




Bonding

Is a process used in the automotive industry for increase the resistance to corrosion the doors, hood of the car etc. It consists in heating a glue to about 200 ºC so that it polymerises. This process is usually done by induction heating

Digital Bonding Systems



POWER SECTION :

- **Output power: 30 kW (inverter with half-bridge) and 40 kW.**
- **Up to 3 heating stations (commutation system included in the generator).**

CONTROLLER:

- **Digital controller for converter and process control in only one PCB.**
- **Industrial communication: Interbus, Profibus, Device-Net or conventional wiring.**
- **Graphical display.**

Digital Bonding Systems

TYPICAL FEATURES:

Programmable from the control panel or from a PC, through USB port or Ethernet.

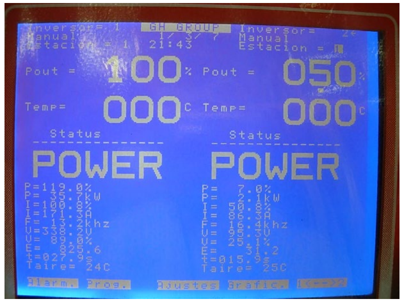
Graphical or numerical representation of the temperature, power and energy evolution of any heating cycle.

Up to 8 temperature sensors for signal regulation. It is possible to select a master sensor or calculate the average value of all of them.

Up to 15 programs with 9 phases each (heating, stop and cooling).

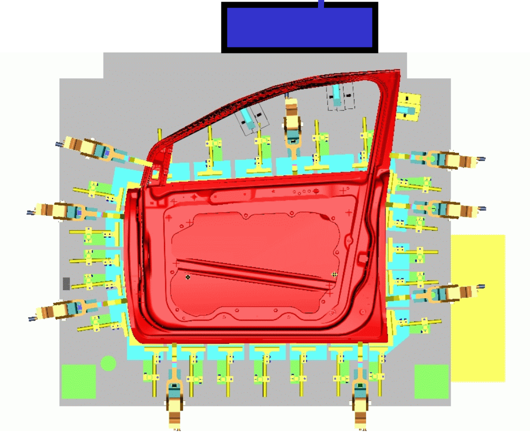
- **Storage of up to 1000 heating cycles in the control panel.**
- **Quality control functionality via Ethernet. Unlimited heating cycles storage in an SQL database.**
- **Several user level with password protection (security control).**

Dual Bonding Systems

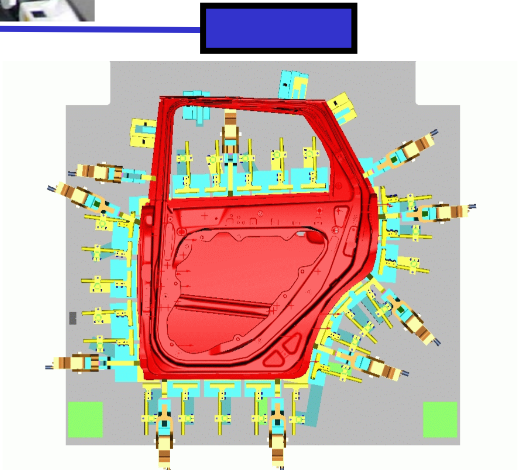


ADDITIONAL TYPICAL FEATURES:

- **Simultaneous heating in two working power sections. One control panel.**
- **It works like two independent converters.**
- **Output power = 2 x 30 kW or 2 x 40 kW**
- **Each power section can have up to three output power outlets so that Dual System can manage up to six heating stations (only two simultaneous).**



Heating station 1

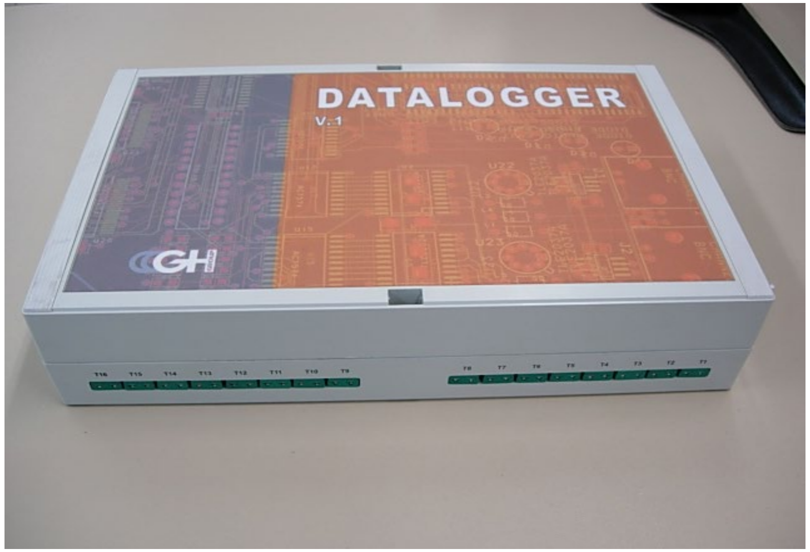


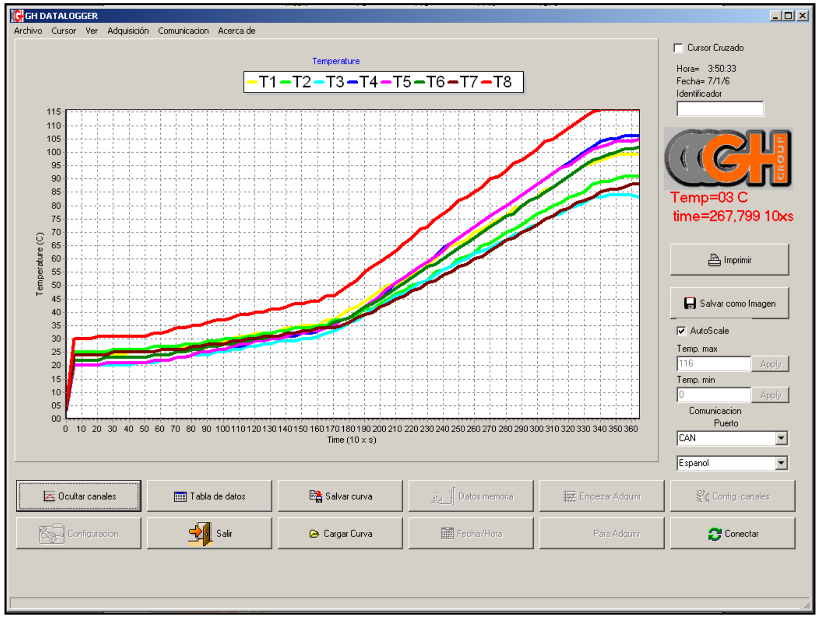
Heating station 2

Process Quality Controllers

TYPICAL FEATURES:

- **Temperature measurement of up to 16, 32 or 48 channels.**
- **Data can be shown by graph or by table. Table can be exported to MS Excel file format.**
- **Data visualization and acquisition directly from PC software. Acquisition via USB or CANBus.**
- **Can be supplied from batteries (online) or mains power supply (offline). Battery level and charge led indicator.**
- **High noise rejection. Channels with galvanic isolation eight by eight.**
- **Mass storage memory. It can save up to 1000 heating process.**
- **Temperature data and graphs can be printed.**





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Identificador

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Espanol

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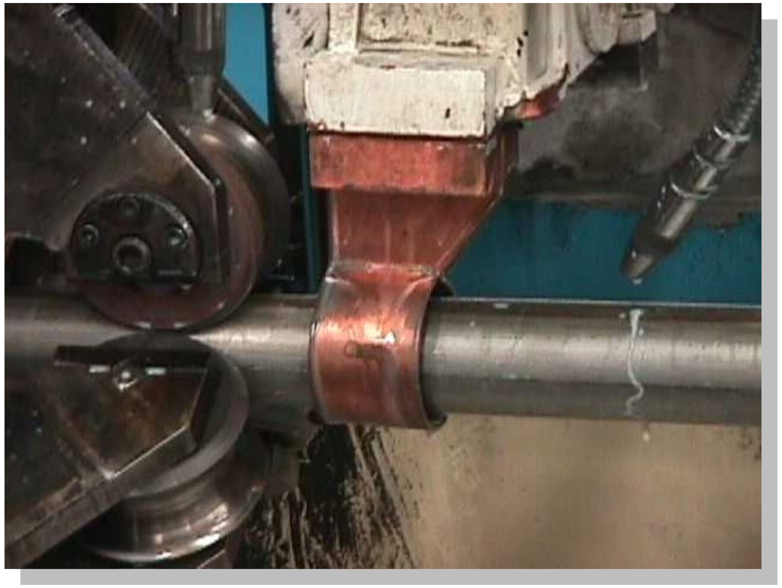
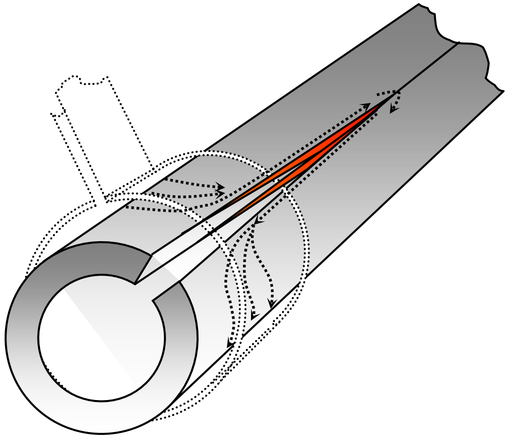
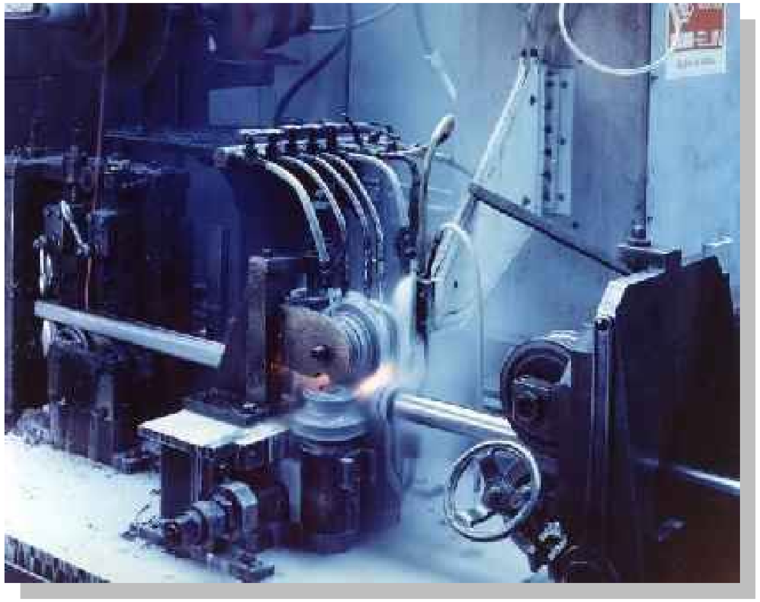
  - ✓**Welders**
- ✓Controllers
- ✓Roadmap

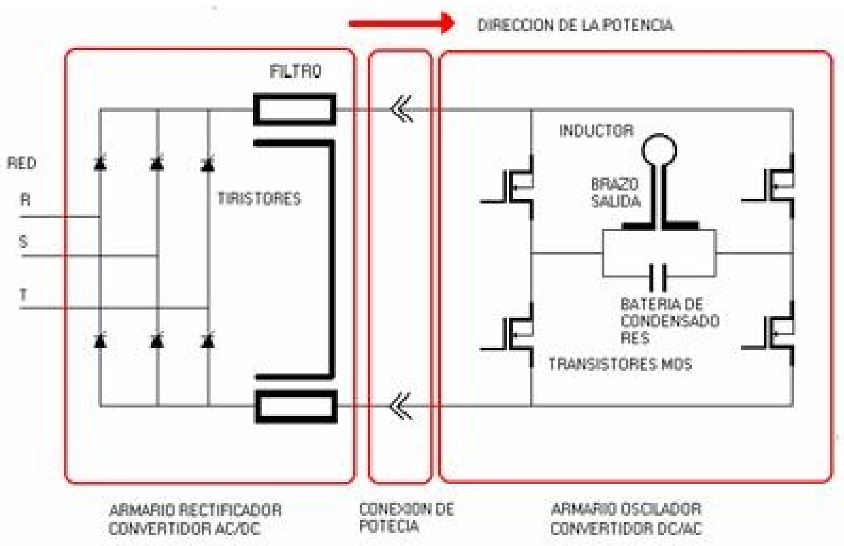
Tube Welding





Tube Welding





Tube welding is industrial heating application that requires in general the combination of high power and high frequency. Power ranges from 100 kW to 1,5 Mw or even higher and typical frequencies are between 200 and 400 kHz.

Basic welders are current-fed as well as voltage-fed inverters a used in practice although the first topology is preferred due to the fact that the power supply can be separated from the inverter, which has to be very close to the application. In this case a lighter coordinate table is required.

Tube Welding

Basic Welders

- ☐ Current-fed or Voltage-fed structure
- ☐ In Current-fed Converters the inverter can be separate from the power supply enabling a lighter coordinate table
- ☐ Frequencies in the range 200-500 kHz for most of the welding applications
- ☐ Power levels in the range 100-1.000 kW
- ☐ MOS (up to 500 kHz) or IGBT (up to 300 kHz) technology.

Load Independent Welders

GOAL:

✓To obtain the maximum output power from the generator for every tube of the inductor range.

✓To get maximum generator output power for a range of pipes, regardless its thickness.

TUBE LOAD MATCHING SYSTEM:

-One method consists of an increase of the inverter current according to the following equation:

$$I_{dc} = \sqrt{\frac{Qmax}{Qmin}} \cdot Idcn$$

-The apparent power of the input transformer and the current rate of the rectifier has to be increased.

-The capacitor bank has to be increased.

-Higher number of inverters is needed.

MAIN FEATURES:

-Automatic load matching while system is running.

-No moving parts.

-Good efficiency.

-Minimum reactive power needed, compared with other solutions.

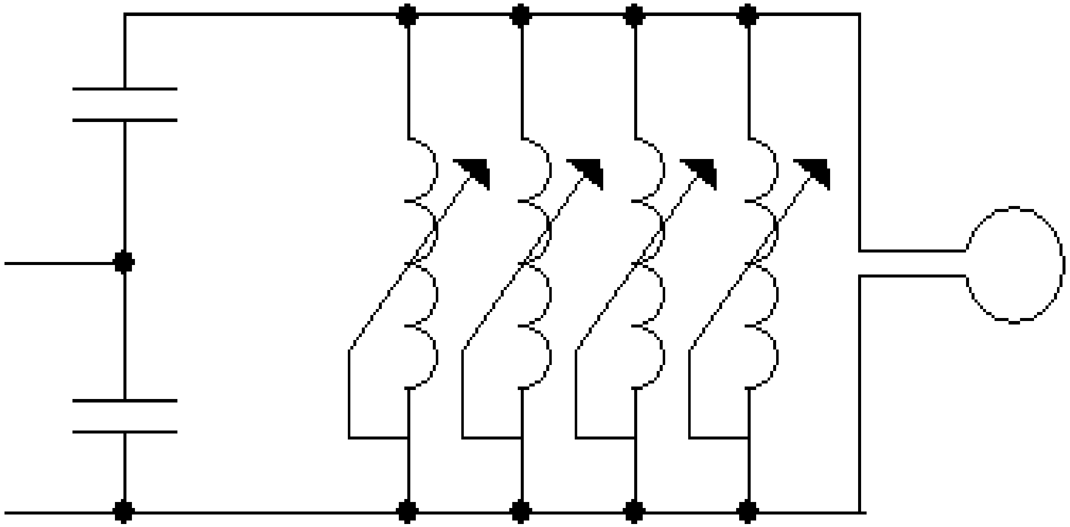
Variable Frequency Welders

GOAL:

✓To modify the working frequency of the generator while running, in order to weld different materials with the same equipment and to select the best frequency for every tube:

- **The higher the frequency, the less the power is required.**
- **Lower Frequency provides a more ductile welding**
- **Lower frequency is preferred for internal scarfing as the tools have longer life**

VARIABLE FREQUENCY SYSTEM:



- The system consists in four coils (3 turns) with a moving copper watercooled core.

- The power of the generator is increased in order to compensate the losses of the system.

Variable Frequency Welders

GOAL:

-To modify the working frequency of the generator while running, in order to weld different materials with the same equipment and to select the best frequency for every tube:

-The higher the frequency, the less the power is required.

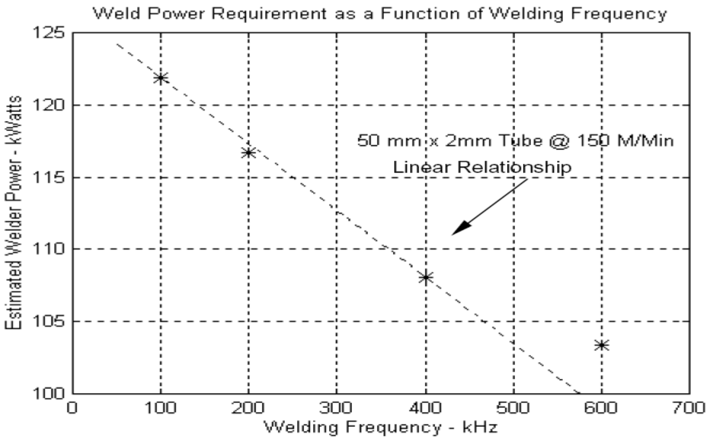
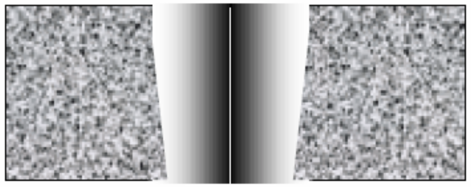


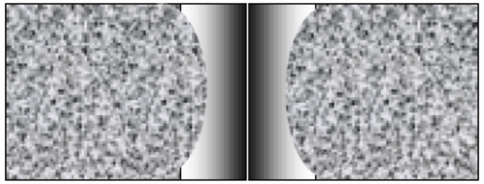
Figure 15

-Depending on the specification of the customer, varying the frequency results in different mechanical properties of the welding beam:

Ductile welding



Typical Heat Affected Zone for a 200 kHz welder.



Typical Heat Affected Zone for a 400 kHz welder.

Fragile welding

-Variable frequency results in repetitive quality of the welding by readjusting the optimal frequency.

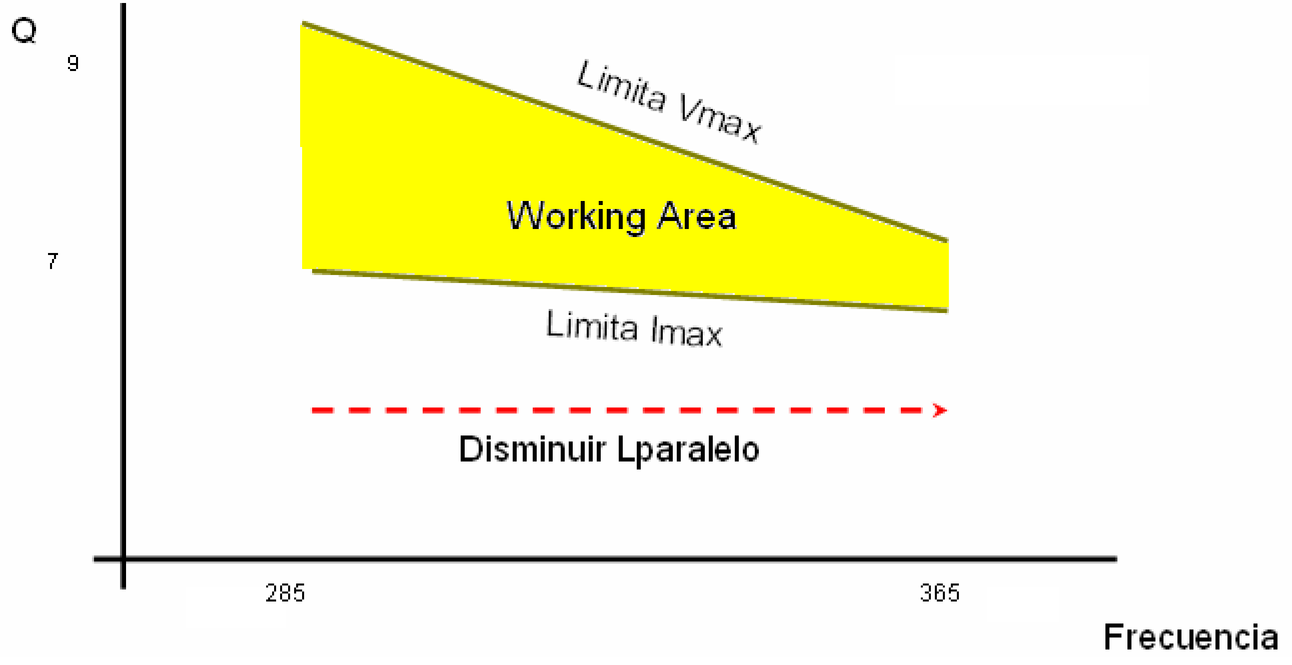
-Lower frequency is preferred for internal scarfing as the tools have longer life

Variable Frequency Welders

fmin

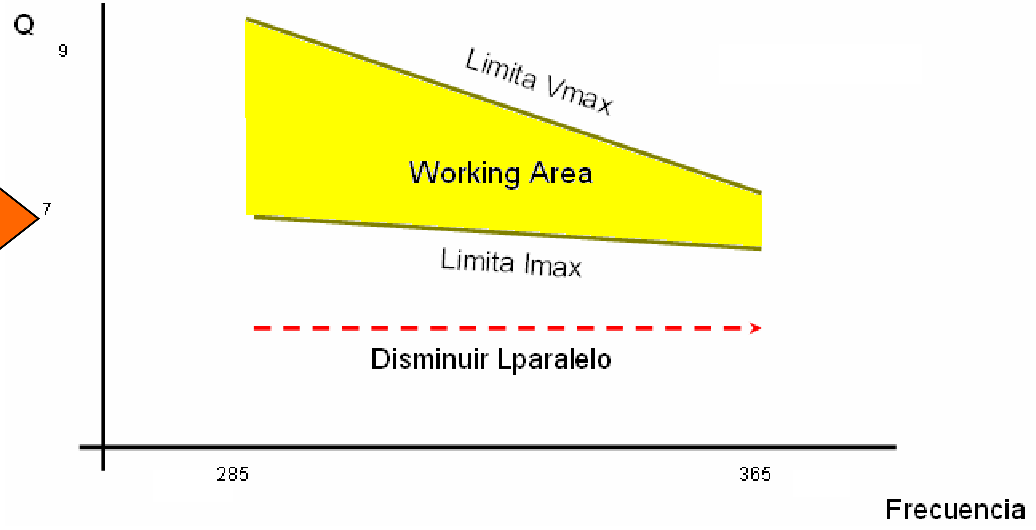
fmax

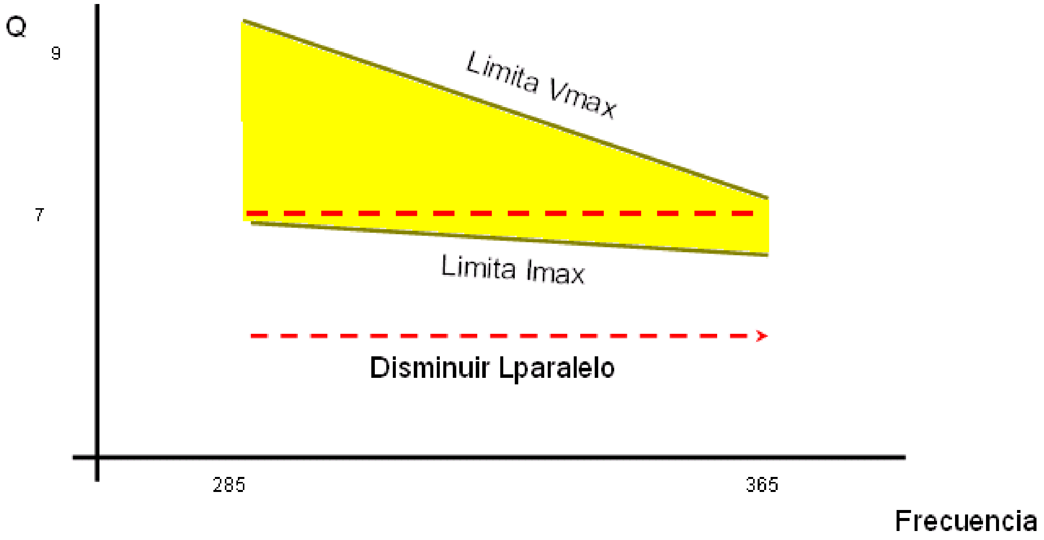
$$I_{dc}=\sqrt{\frac{Q\max}{Q\min}}\cdot\sqrt{\frac{f\max}{f\min}}\cdot I_{dcn}$$



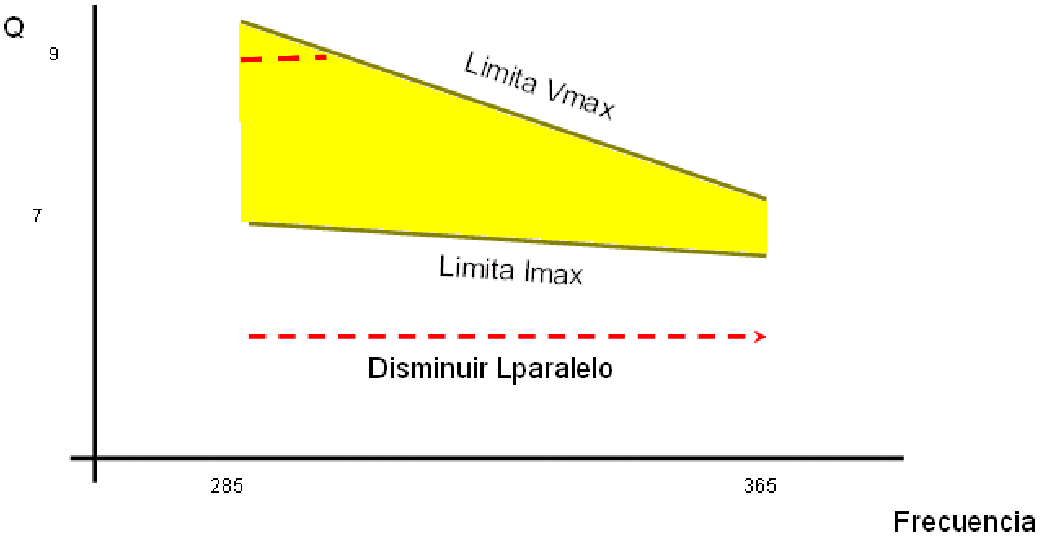
Variable Frequency Welders

$$I_{dc} = \sqrt{\frac{Q\max}{Q\min}} \cdot \sqrt{\frac{f\max}{f\min}} \cdot I_{dcn}$$





Wide range of frequency variation for steel tubes



Other non-ferrous materials can be welded even though higher Q is needed

Process Controllers for Tube Welding

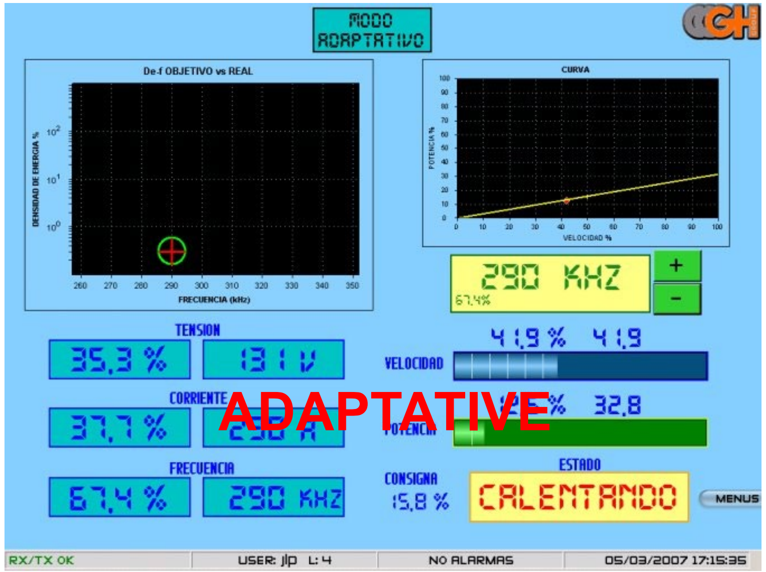
BASIC TUBE WELDING CONTROL:

- -Manual mode.
- -Automatic mode (Power-Speed control).
- -Adaptative mode (Easy Power-Speed control).
- -Graphs: Generator parameters (Voltage, Current, Frequency, Power).
- -Alarms.

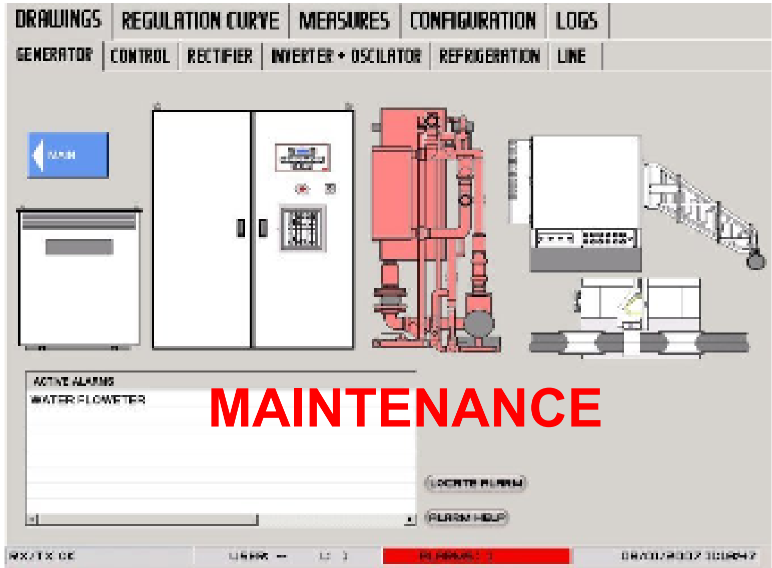
ADVANCED TUBE WELDING CONTROL:

- -Manual mode.
- -Automatic mode (Power-Speed control).
- -Adaptative mode (Easy Power-Speed control).
- -Graphs: Generator parameters (Voltage, Current, Frequency, Power).
- -Alarms.
- -Advanced system for maintenance.
- -Frequency variable control if present in the generator.

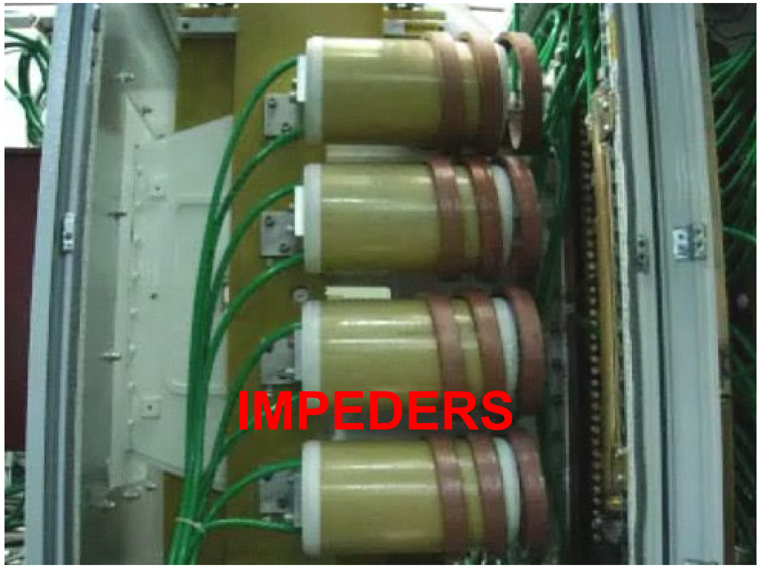
Process Controllers for Tube Welding



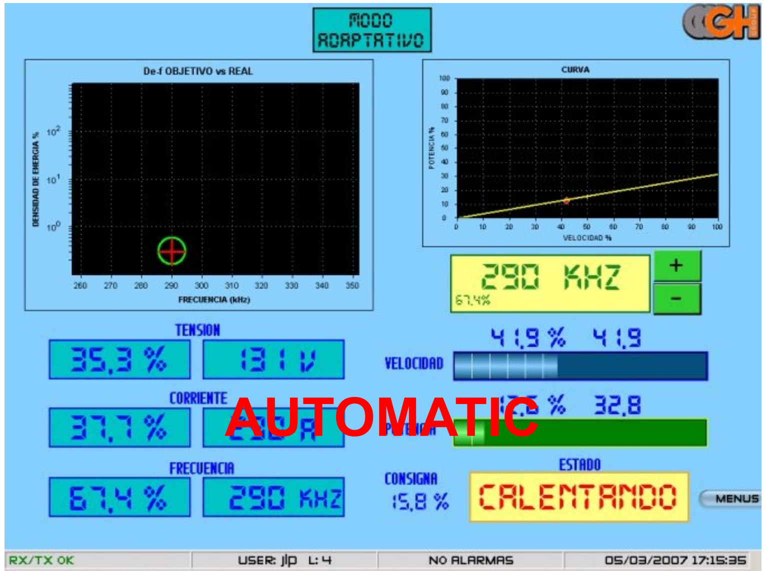
ADAPTATIVE



MAINTENANCE



IMPEDERS



AUTOMATIC

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  - ✓Welders
- **✓Controllers**
- ✓Roadmap

New Digital Controller for Parallel Generators

PAST

ANALOG CONTROL

PRESENT

FUTURE

CAN

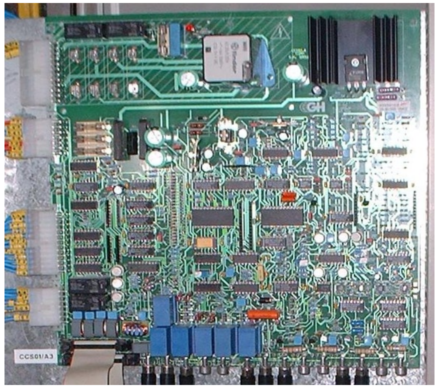
FULL DIGITAL CONTROL

FEATURES OF THE FULL DIGITAL CONTROL

- **The new digital control gives a new look to our generators and also new functionalities.**
- **The graphical screen shows the information more clearly in a wider screen.**
- **The settings of the generator are entered in a configuration screen through the keyboard instead of using potentiometers. Different settings can be stored in the memory for different running conditions.**
- **It is possible to manage the generator from a PLC system through a PROFIBUS network.**
- **The cooling system can be configured and monitored from the visualization pannel MPC-1.**

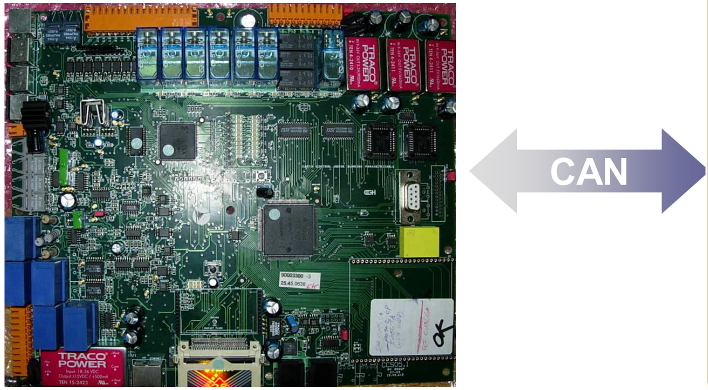
New Digital Controller for Series Generators

PRESENT



ANALOG CONTROL

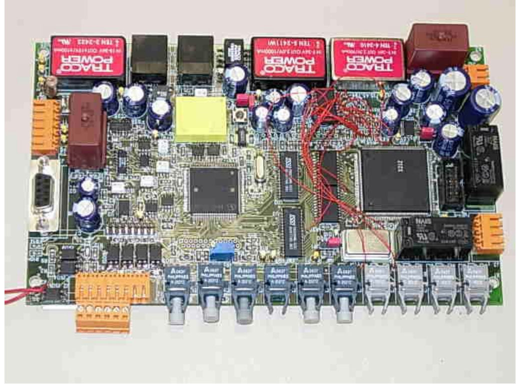
DIGITAL VISUALISATION



DIGITAL CONTROL

DIGITAL VISUALISATION

FUTURE



FULL DIGITALCONTROL

DIGITAL VISUALISATION

New Digital Controller for Series Generators

FEATURES

- **Power section control loops are fully digital.**
- **Inverter control and application control parameters could be upgraded from a PC software.**
- **High and low frequency applications.**
- **Inverter bridge alarms management and application data acquiring included on board.**
- **CAN-BUS module connection. It simplifies and decrease wiring and error possibility.**
- **Through CAN-BUS system could be expanded for more stations, application measuring channels, etc.**
- **Energy measurement with high accuracy.**
- **Mass data storage. It can save heating process data, alarms history, etc.**
- **Heating process could be adjusted with a cycle controlled with 9 different heating phases. Energy or temperature cycles. On this way, this cycle could be adjusted for any type of part.**
- **Could control continuous applications. For example Power/Speed control.**
- **Could manage visualization and control for small size generators**

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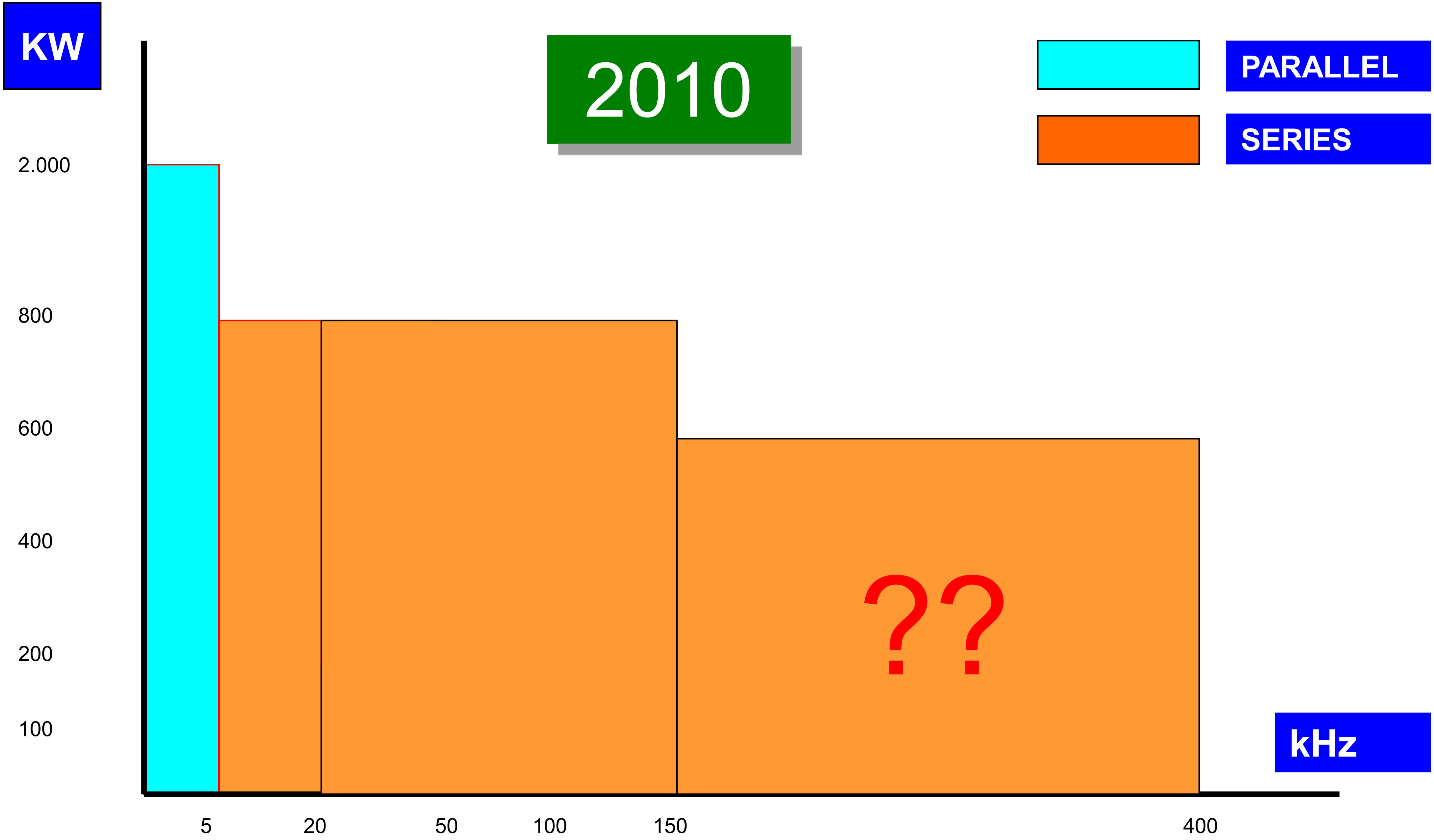
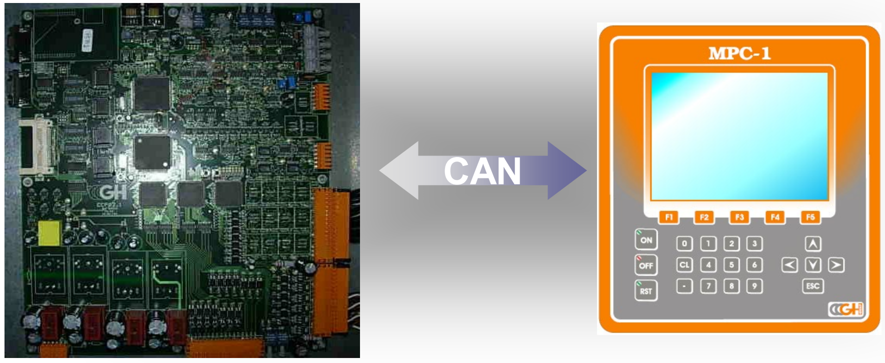
Roadmap on Power Converters



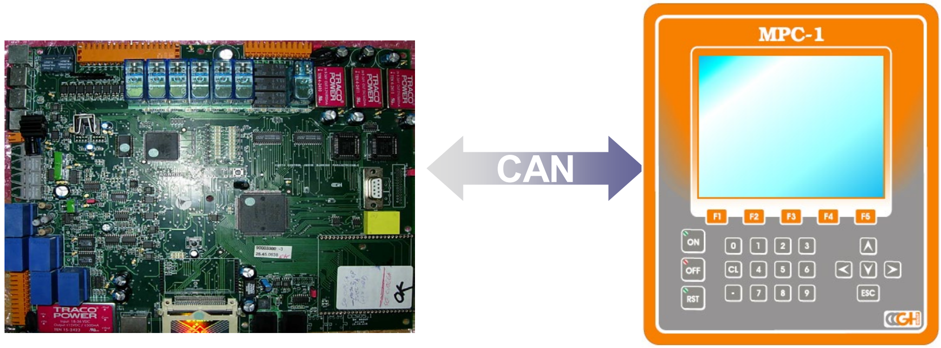
Seminario: Aplicaciones industriales del calentamiento por inducción

Roadmap on Controllers

2007/08

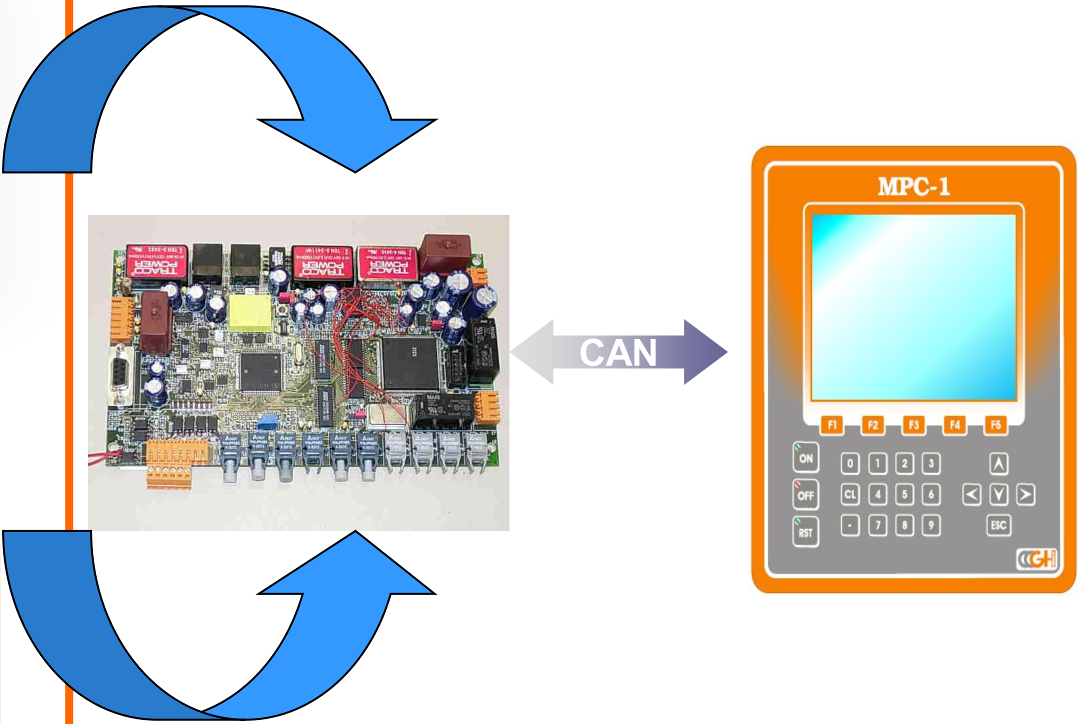


Digital Parallel Controller



Digital Series Controller

2010



Full Digital Series/ Parallel FPGA Controller

THANK YOU VERY MUCH FOR YOUR ATTENTION

GH GROUP

Escola Tècnica Superior d'Enginyeria

VNIVERSITAT DE VALÈNCIA