Status and Trends in Magnet Power Converter Technology for Accelerators

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2014-06-19

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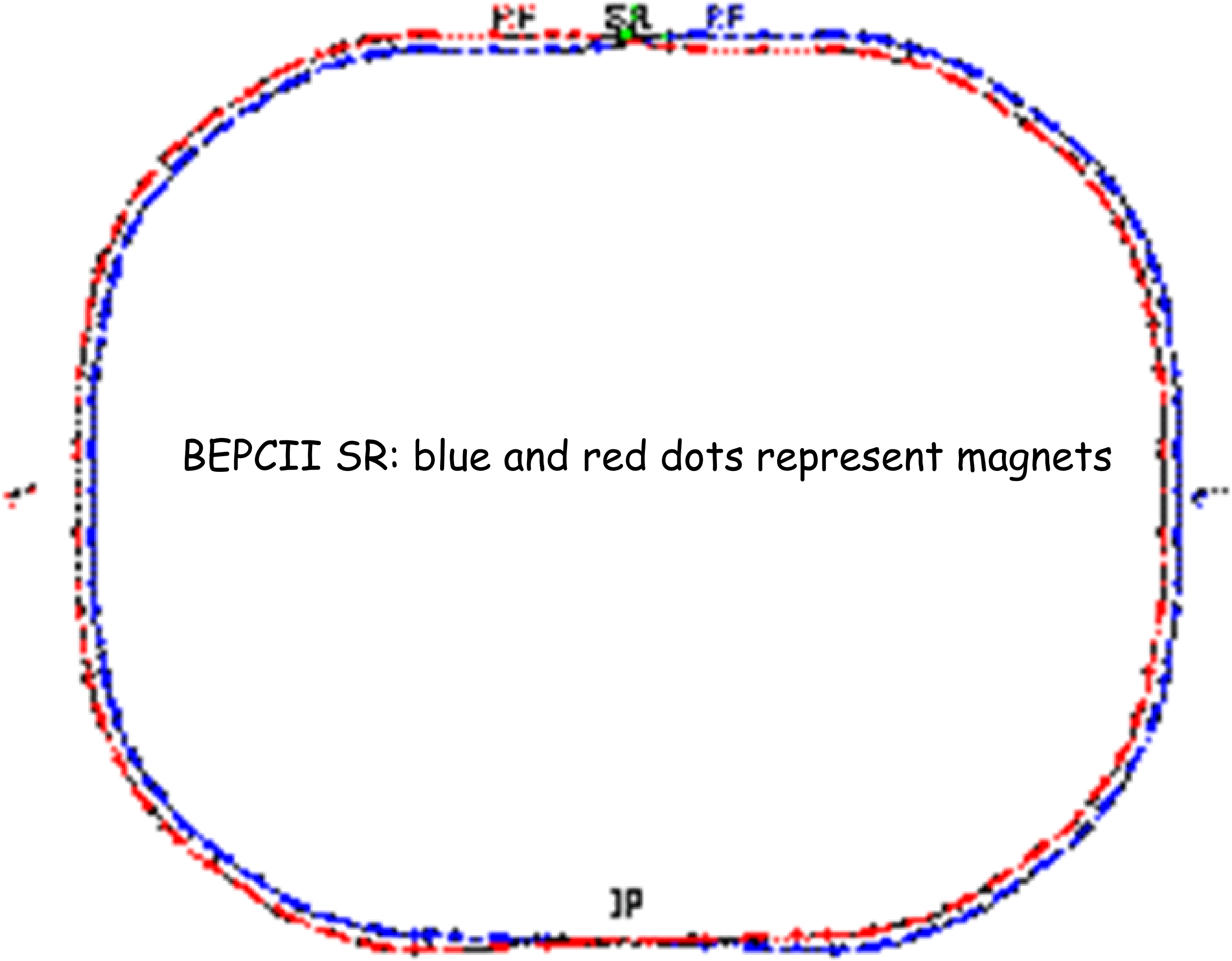
Introduction

- magnets are main components in accelerators



BEPCII SR: blue and red dots represent magnets

Introduction

- magnets are main components in accelerators

BEPCII: storage ring

crossing of the transport line

bending magnets: bend the beam
quadruple magnets: focus the beam
sextuple magnets: correct chromaticity
octuple magnets: Laudao damping

some special magnets for beam transferring:
  septum magnets
  kicker: very fast rise time a few ns ~ us, very special design, excluding in this topic

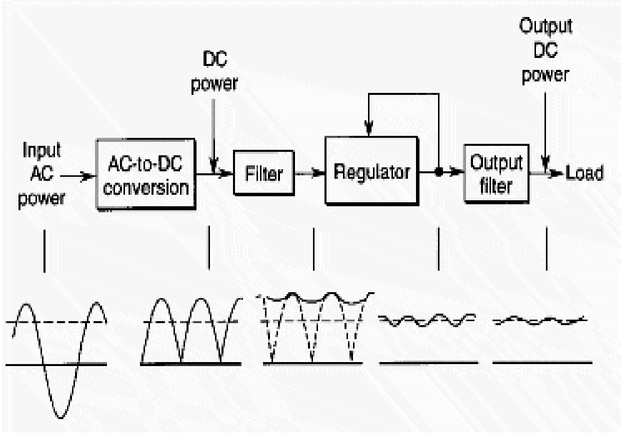
Introduction

- power converters: necessary to accelerators

a huge number of various power converters are used to feed various magnets:

DC power converters feed storage rings dipole magnet while the DC biased AC power converters with a pre-defined repetition rate for a cycling machine; the power converters of quadrupoles are employed for beam focusing and dynamic orbit, pulse power converter for beam injection or ejection,etc.

anyway: conventional AC power from the grid can't be used directly.



What does a power converter do?
With the power semiconductor devices, in combination with the control theory, fulfilling the conversion from "coarse" power to refined power, which can meet the variety of requirements from different accelerators.

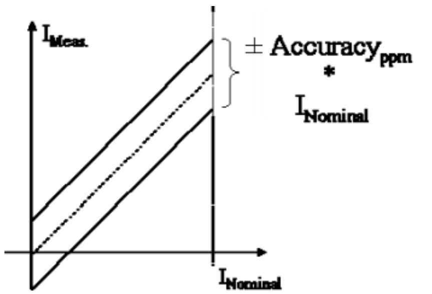
Introduction

- power converters: basic definition

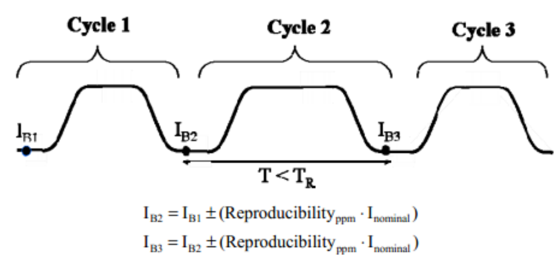
precision

- 'precision' includes the following terms: accuracy, reproducibility, stability

accuracy:
the closeness of agreement between the measured value and the reference value; expressed in ppm of the nominal current for a given period

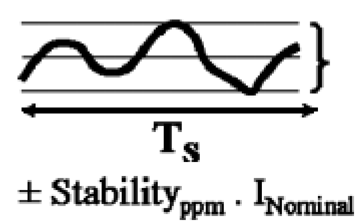


reproducibility:
the uncertainty in returning to a set of previous working values from cycle to cycle of the machines;



stability:
the maximum deviation over a period with no changes in operating conditions.

resolution:
the smallest increment that can be induced or discerned.



Topologies

- three main power converter topologies
  - Linear Power Converter
  - SCR power converter (line-commutated thyristor power converter)
  - Switch-Mode Power Converter

each topology has ad/disadvantages

requirements of the performance, space (weight and size), cooling and budget etc,

close collaboration with the magnet designers and beam physicists,

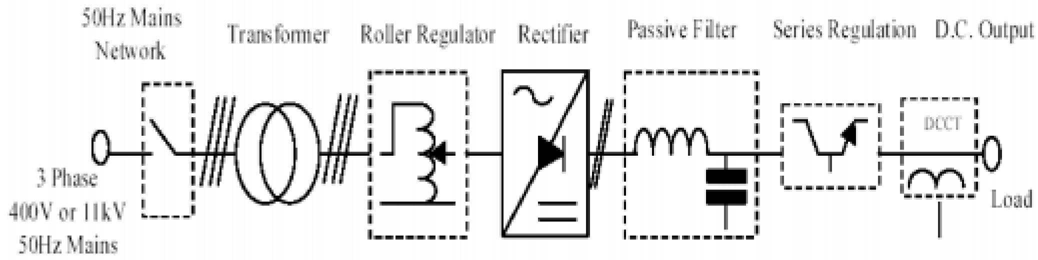
then to make an appropriate selection.

Topologies

- LPC

the only topology: power semiconductor devices working in the linear region.

- basic structure includes:
  - **a line-frequency transformer for isolation and impedance matching;**
  - **a roller regulator for course adjustment of the voltage**
  - **a uncontrollable diode rectifier**
  - **a LC passive filter**
  - **a series regulator (transistor bank)**
- regulation is accomplished by controlling the voltage drop on the series regulator, which is dependent on the base current of the transistors



Topologies

- LPC
  - advantages:
    - **'clean' output: no switching element, low level noise/small output ripple**
    - **excellent transient response**
  - disadvantages:
    - **poor efficiency: continuous dissipation of excess power in series regulator**
    - **big size: line-frequency transformer; and large LC filter**

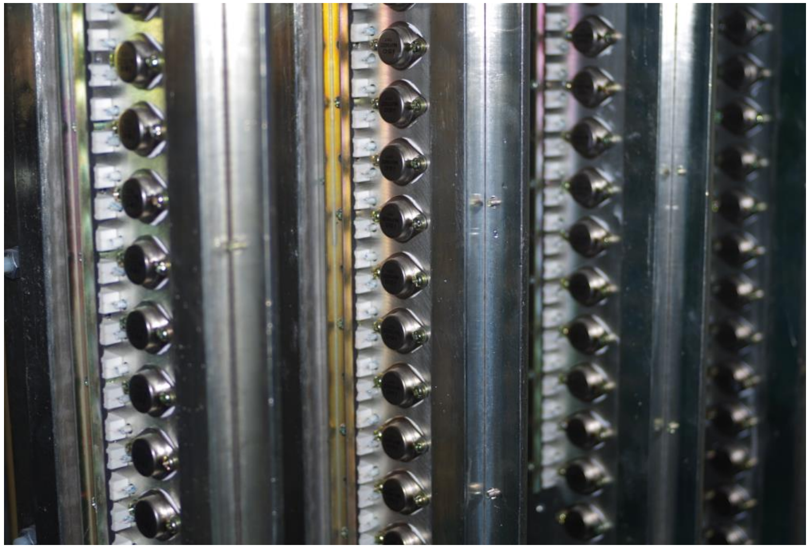
    increasing both running costs and the loading on the cooling system
  - Used: PCs required ultra low ripple, such as magnetic field measurement PCs; and PCs required a very fast response, such as some correction magnet PCs combined with the orbit feedback system.

Topologies

- LPC
  - CSNS: DC magnetic field measurement PC

2500A/90V

transistor bank

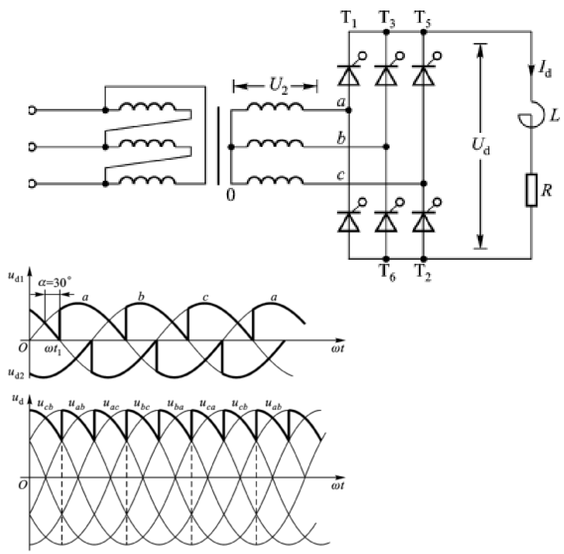


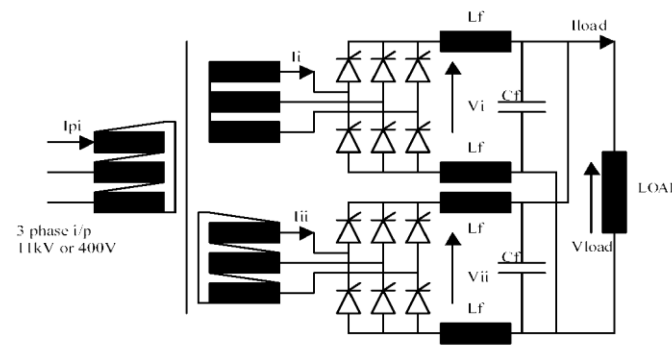
Topologies

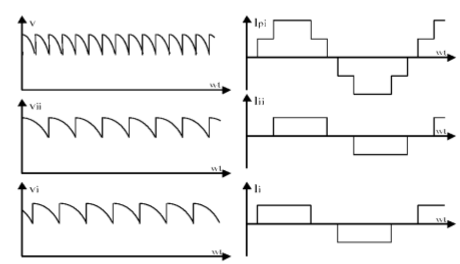
■ SCR

The used power device is thyristor, which has been developed more than a half century.

- basic structure :
  - **for a 6-pulse SCR: input transformer, a 3-phase full bridge, a LC filter**
  - **for higher power and better performance: a 12-pulse or higher configuration comprising two or more 6-pulse bridges connected in series or in parallel**







Topologies

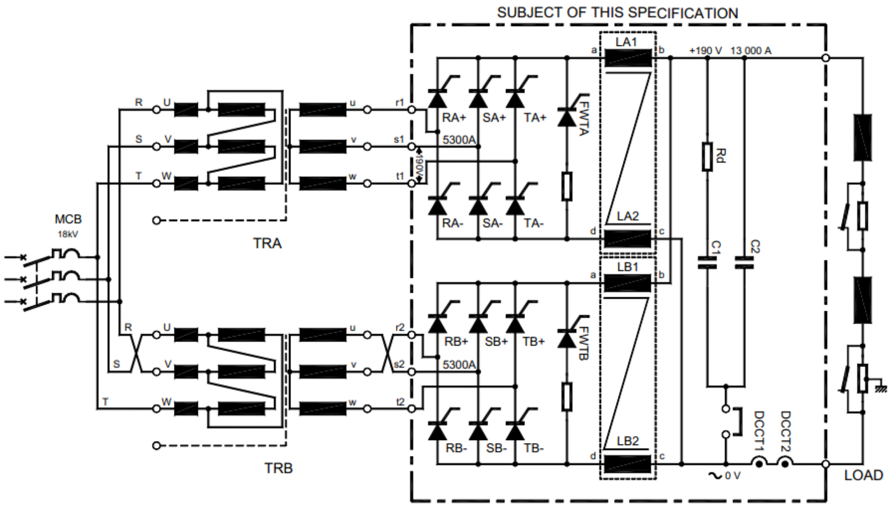
- SCR
  - advantages and disadvantages:
    - widely used technology, simple design, high reliability, suitable for high power applications generally greater than a few hundred kW.
    - the power factor: determined by the firing angle that will incur additional costs for power factor correction
    - input current harmonics: improved if 12-pulse (or higher) design employed
    - options for lower ripple: such as adding a linear regulator in the main circuit or adding a switch-mode power converter to suppress the ripple
    - unsuitable for low power applications: large and heavy magnetic elements (line-frequency transformers and chocks etc)
    - low or moderate bandwidth: dependent on the number of pulses

Topologies

- SCR

    used for high power applications.

    - LHC : main bending magnets PC 13kA/±190V



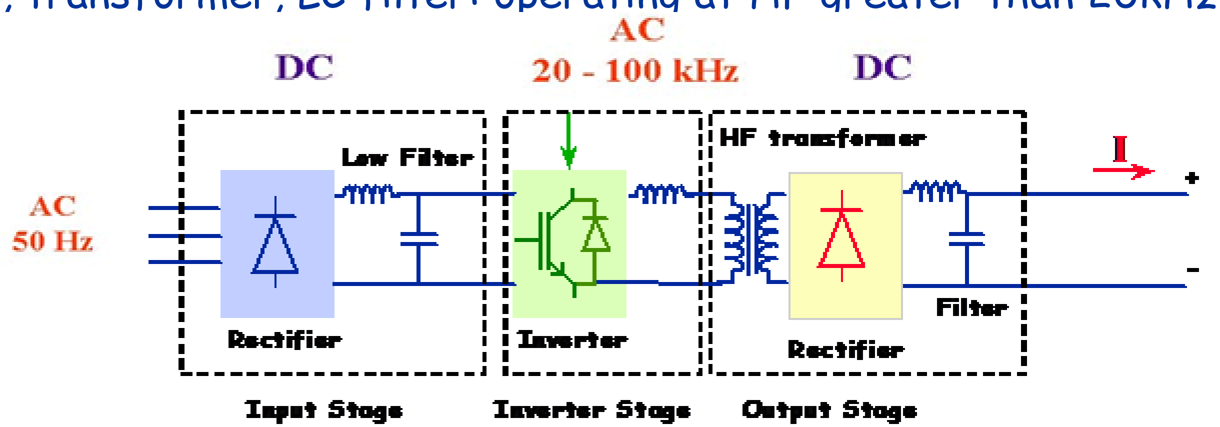
Topologies

SMPC

Based on the development of power devices, it is now the most commonly chosen topology for magnet PCs.

- basic structure:
  - input stage: provides the dc-link voltage (interface to the mains, and rectifier of the input voltage)
  - inverter stage: performs high frequency switching and modulation of an AC voltage that drives the HF transformer.
  - Output stage: performs the rectification, filtering and impedance matching to the load.

power devices, transformer, LC filter: operating at HF greater than 20kHz



Topologies

- SMPC
  - advantages and disadvantages:
    - Efficient is high: the most loss is during switching
    - Reduced size and weight of output filter and transformer at HF operation, therefore portability increases for the converter
    - Higher bandwidth due to high switching frequencies versus SCR type
    - Easy interface for digital regulator
    - Higher order output voltage ripple components are less affecting on magnet current, but might cause a EMI problem in some cases
    - The cost is high and technique is complex to build a high power /current/voltage power supply comparing with the one of SCR type

In some modern accelerators, the whole magnet PC system is PWM SMPC such as the SLS, and CSNS…

Topologies

SMPC: CSNS painting magnet PC

- a brief introduction of CSNS

The CSNS is designed to accelerate proton beam pulses to 1.6 GeV at 25 Hz repetition rate, striking a solid metal target to produce spallation neutrons The accelerator provides a beam power of 100 kW on the target in the first phase. It will be upgraded to 500kW beam power at the same repetition rate and same output energy in the second phase.

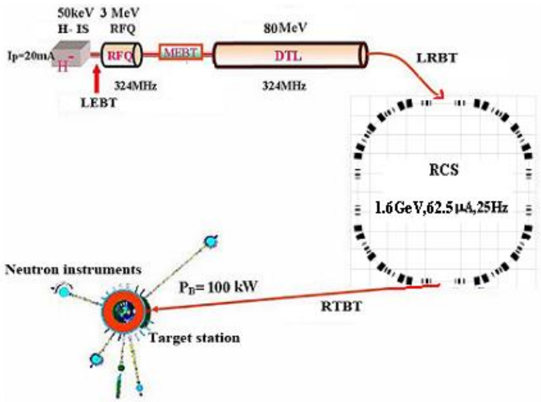
-an ion source produces a peak current of 25 mA H- beam.

- RFQ linac bunches and accelerates it to 3 MeV.

- DTL linac raises the beam energy to 80 MeV.

After H- beam is converted to proton beam via a stripping foil, RCS accumulates and accelerates the proton beam to 1.6 GeV before extracting it to the target.

20 neutron channels are designed surrounding the target, but only 3 spectrometers will be built in the first phase due to limited budget.



Topologies

artifical view of CSNS campus at DongGuang

Topologies

SMPC: CSNS painting magnet PC

To minimize the space charge effect and control the emittance of the beam, painting injection method was selected, the painting PCs needed controlling the output current at falling period accurately.

- High slew rate;
- High peak power up to several tens MW, much lower average power several hundreds kW, huge power variation.

	REQUIREMENTS
I_N	> 18000A
Rising time	< 1000 us (fixed)
Time of $I_{flat\ top}$	50us
Falling time	300~550us (adjustable)
Max. falling rate	260A/us
Falling tracking err.	< 2%
Equivalent switching freq.	> 800 kHz
Stability of $I_{flat\ top}$	+/- 0.5%
V_{peak}	> 3150V
Repetition rate	25 Hz
Load Impendance	Inductance: 12 uH Internal resistor: 1.68mOhm

Topologies

- SMPC : CSNS painting magnet PC

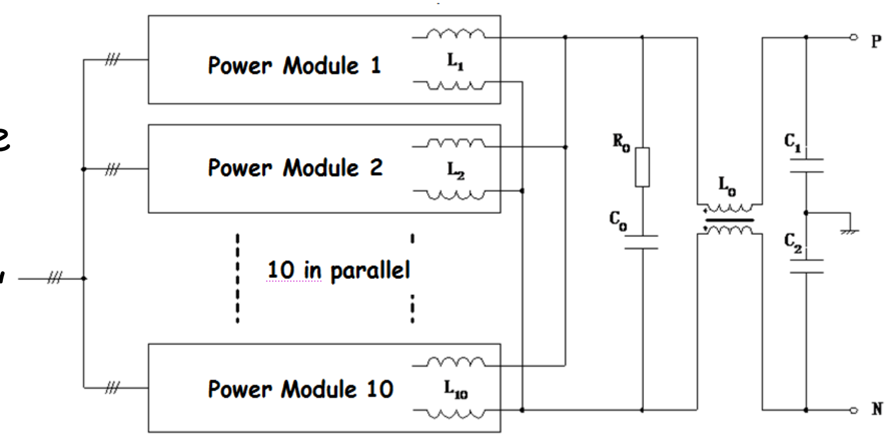
Basic structure : Diode rectifier + Booster + PWM H-Bridge

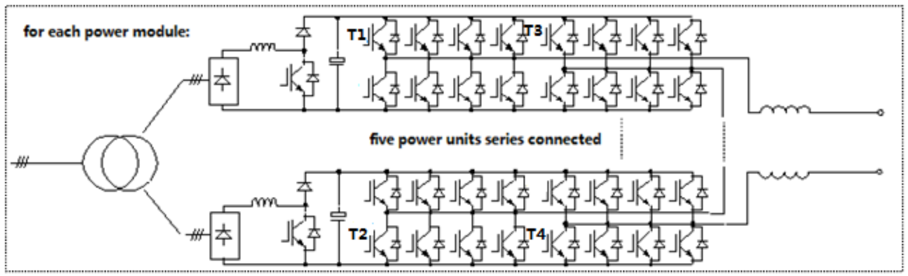
- modular approach

- Four IGBTs in parallel forming one arm of a H-bridge

- Five H-bridge units in series comprising one "Power Module" reaching Vpeak 3150V and 2000A per unit

-Ten identical 'Power Modules' connected in parallel reaching Irate 18000A





Topologies

SMPC : CSNS painting magnet PC

Significantly speed up the response time of the entire power system and greatly reduce the size of output filter.

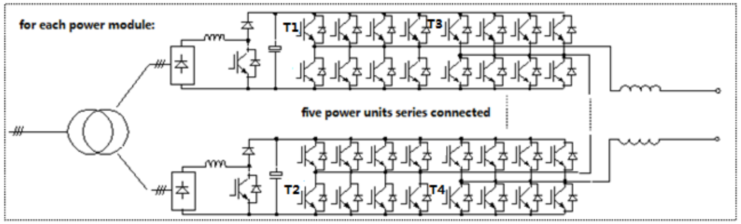
- PWM multi phase-shifting

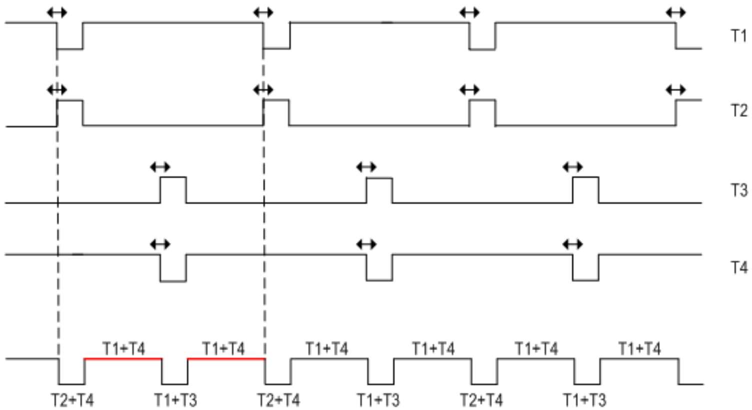
- H-Bridge:
  double the basic switching frequency (f0)

- five power units:
  ten times of f0

- ten power modules
  one hundred times of the f0

**Selecting f0 = 18.432KHz,
the equivalent operation switching frequency up to 1.8432 MHz !**



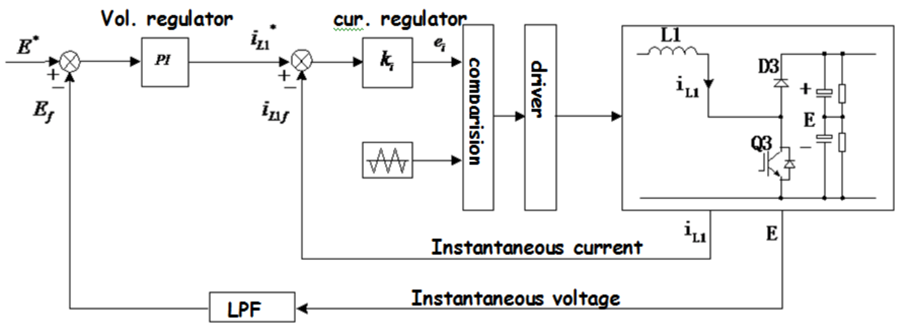


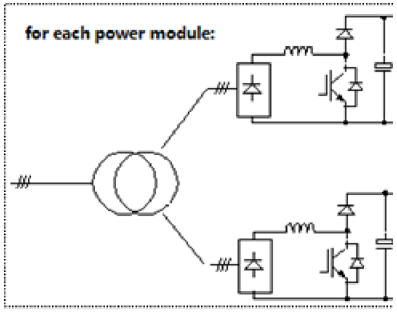
Topologies

SMPC : CSNS painting magnet PC

A booster circuit is employed at each diode rectifier output stage.

- Combined with the capacitor-storage system, the huge power variation is disposed of inside the power converter, and much smaller power fluctuation is seen from the grid.
- The BOOSTER circuitry fixes on the input current constant control, so the BOOSTER converter is preferable to depress fluctuation of input power.

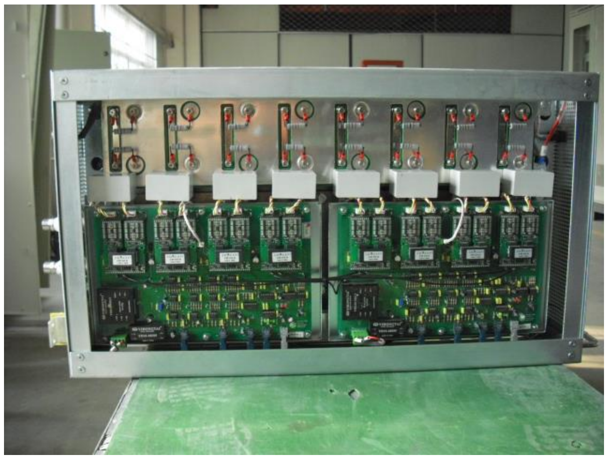


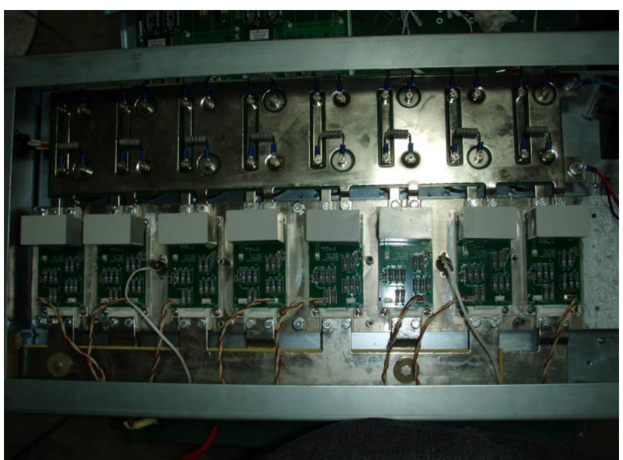


Topologies

- SMPC : CSNS painting magnet PC

some pictures





Topologies

SMPC : SLS Booster Bending Magnet PC

capacitative energy storage system with switch mode control for:
small and medium-sized systems, with medium repetition rates

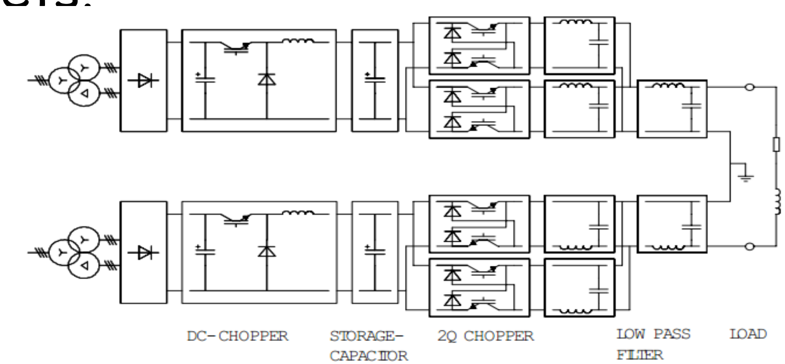
- fast switching inverter bridges giving waveform control
- capacitor energy storage
- the implementation was pioneered at SLS
- similar schemes are also used or proposed for booster synchrotrons of ANKA, ALS, DIAMOND, SOLEIL, CANDLE, SESAME, SSRF and etc.

Topologies

SMPC : SLS Booster Bending Magnet PC

capacitative energy storage system with switch mode control.

- a delta/star transformer (30deg phase shifting),
- a diode rectifier which provides a d.c. power source
- a one-quadrant chopper, which is used to keep the level of the storage-capacitor voltage constant.
- the main energy storage-capacitor
- two parallel-connected 2-quadrant choppers, which is capable of transferring energy into the magnet, allowing the load to invert the energy flow and recharge the storage-capacitor from the energy stored in the magnets.
- LC output filter

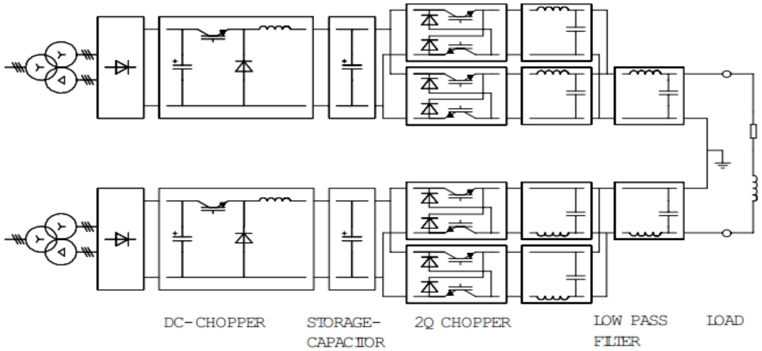


Topologies

- SMPC : SLS Booster Bending Magnet PC

capacitative energy storage system with switch mode control.

- During the conduction mode, energy transfers from the storage-capacitor through the 2Q choppers to the load.
- During the inversion mode, current through the magnets finds its way through the diodes of the 2Q choppers and charges the storage-capacitor bank.
- The high frequency inverter chopper controls both the direction and the flow rate of energy between the capacitor and magnet.
- At present it is only possible in the repetition rate of a few herts for reasons of limited capacitor and IGBT voltage ratings.
- For higher cycling frequency, the inductive storage systems are still commonly used.



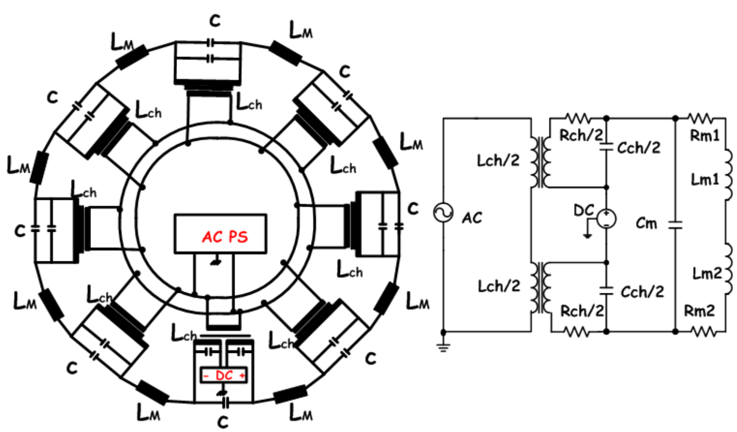
Topologies

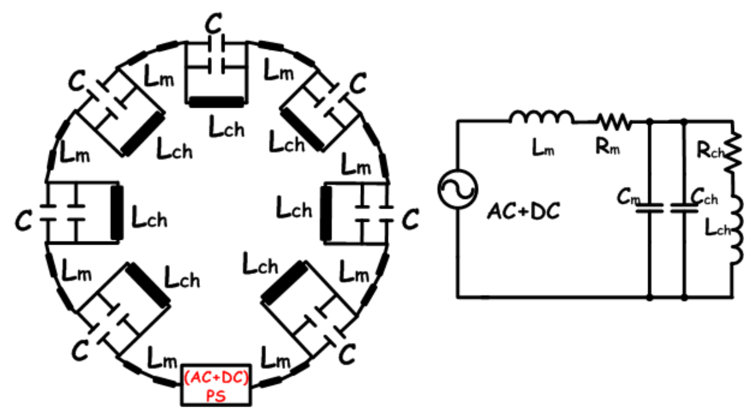
SMPC : CSNS RCS BMPC

standard circuit named 'White Circuit' for: medium to large fast cycling systems

- inflexible in waveform control
- but high capital and operational costs

serial-resonant with one combined DC and AC PC





parallel-resonant with separated DC PC and AC PC

Topologies

- SMPC : CSNS RCS BMPC

For the RCS main magnets: totally six families' power converters, one for bending magnets, and five for quadruple magnets.

	RCSBPS	RCSQPS1	RCSQPS2	RCSQPS3	RCSQPS4	RCSQPS5
Idc	1350	900	990	900	950	910
Iac.peak	970	640	700	640	670	650
Vpeak	6000	1000	4000	1000	1000	1000
Pavg	2400	212	1280	212	320	330
Power Module	3par.* 10ser.	2par.* 2ser.	2par.* 8ser.	2par.* 2ser.	2par.* 2ser.	2par.* 2ser.
SwitchingFreq.	2kHz	4kHz	2kHz	4kHz	4kHz	4kHz
EquivalentSF	40kHz	16kHz	32kHz	16kHz	16kHz	16kHz
Switchingdevice	IGBT (FF1400R12IP4, 1200V/1400A)					

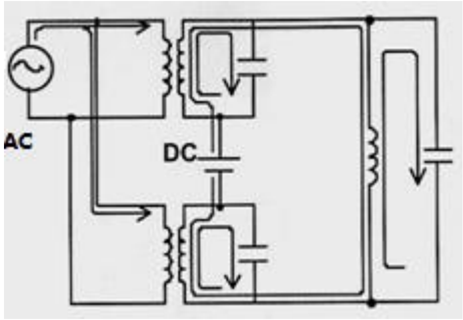
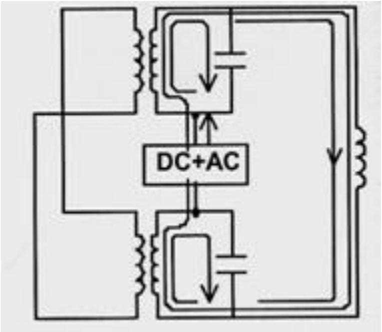
requirements

Topologies

- SMPC : CSNS RCS BMPC

comparison of separated or combined PC

- combined: easy to control the AC phase, easy to design the choke

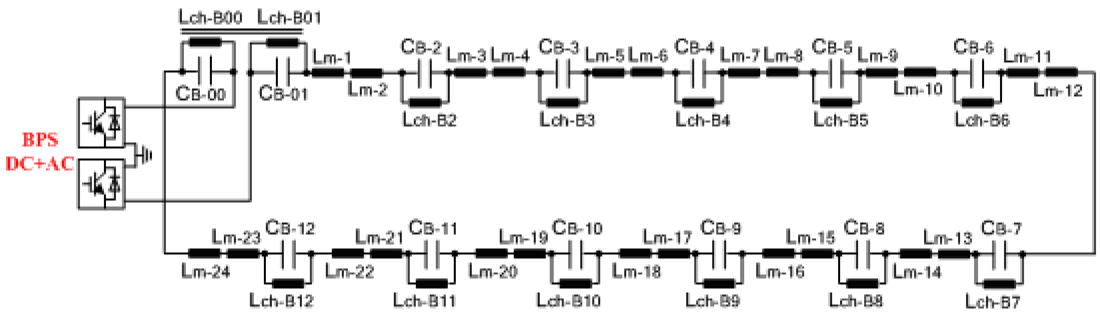
	SEPERATED DC AND AC	COMBINED DC AND AC
Principle circuit		
Number of PS	2	1
Peak power of PS	Small Pdc = Vdc * Idc , Pac = Vac * Iac	Large Ppeak = (Vdc + Vac) * (Idc + Iac)
JPARC-RCS	BMPS	QMPS
CSNS-RCS	No used	B and QMPS

Topologies

- SMPC : CSNS RCS BMPC

resonant network of BMPS

- There are totally 24 dipole magnets, no monitor magnet.
- The resonant network comprises of 12 resonant cells connected in series. Each resonant mesh consists of two magnets, one choke and one capacitor bank, and the energy is stored in the resonant network.
- the PC supplies the losses dissipated in the resistive part of the magnets, chokes and capacitors which are much lower than the cycling power needed.

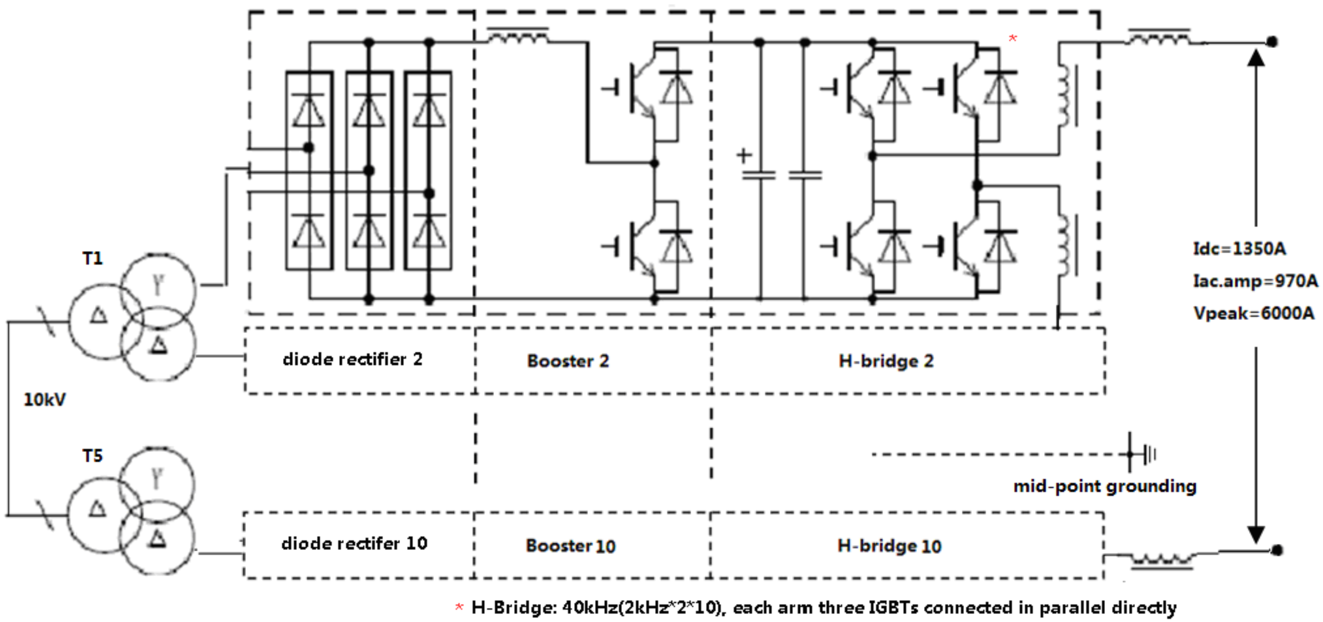


Topologies

- SMPC : CSNS RCS BMPC

circuit configuration of BMPC

- five step-down transformers
- ten diode rectifiers
- ten PWM H-bridge inverters connected in series.



Topologies

- How to control the output performance
  - how to control the tracking error of cycling currents?
  - how to get the ultra high accuracy and stability of steady or slow-ramping currents?

It is mostly determined by the control system of the power converter.

Control System

- evolving: analog

  The control system (regulation and tracking based on control theory, close-loop controllers) takes an very important role to promise the performance of a PC!

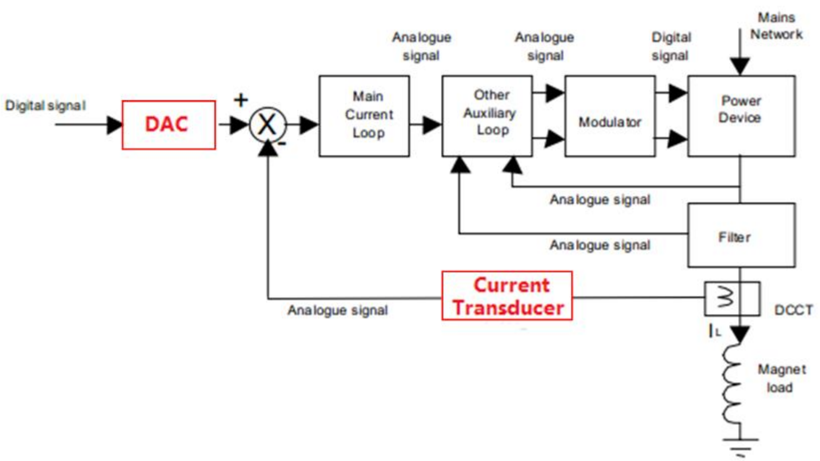
  - traditional analog control system based on PIDs
    - mature, used many years and extensively developed
    - if any changes of the PID parameters, manual hardware modification has to be done; if any major changes of the control system, the regulation hardware has to be redesigned
    - the performance of the regulation is mainly dependent on the DAC and the DCCT
    - not convenient for diagnostics

Control System

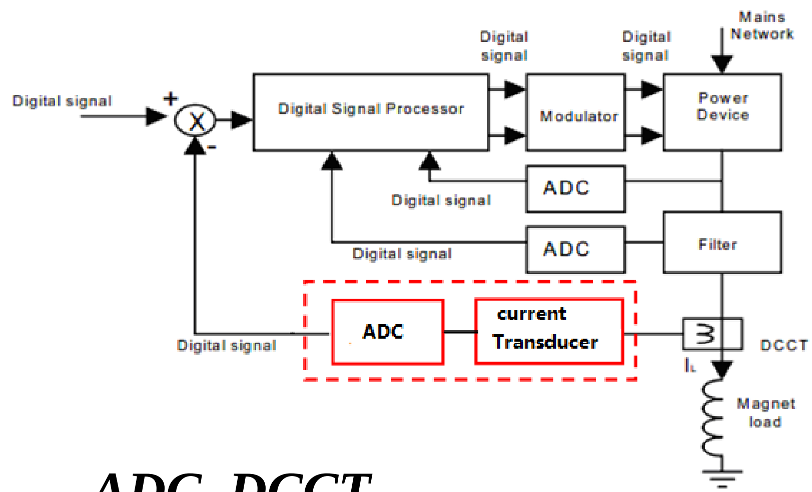
- evolving: fully-digital
  - popularity of using digital control in PCs
    - development of digital technology over last twenty years
    - increasing demands for higher performance and diagnostics
  - benefits of using digital control:
    - complex though fast control algorithms can be implemented and remains stable in relation with the process dynamics
    - flexible for different projects
    - no extra offset or drift, better noise immunity
    - parameters optimization and even changes of the control system can be done by software, no redesign required
    - friendly for debugging and diagnostics
    - easy to extend functionality

Control System

- analog vs. digital control system
  - block diagram of analog and digital control circuit



DAC, DCCT



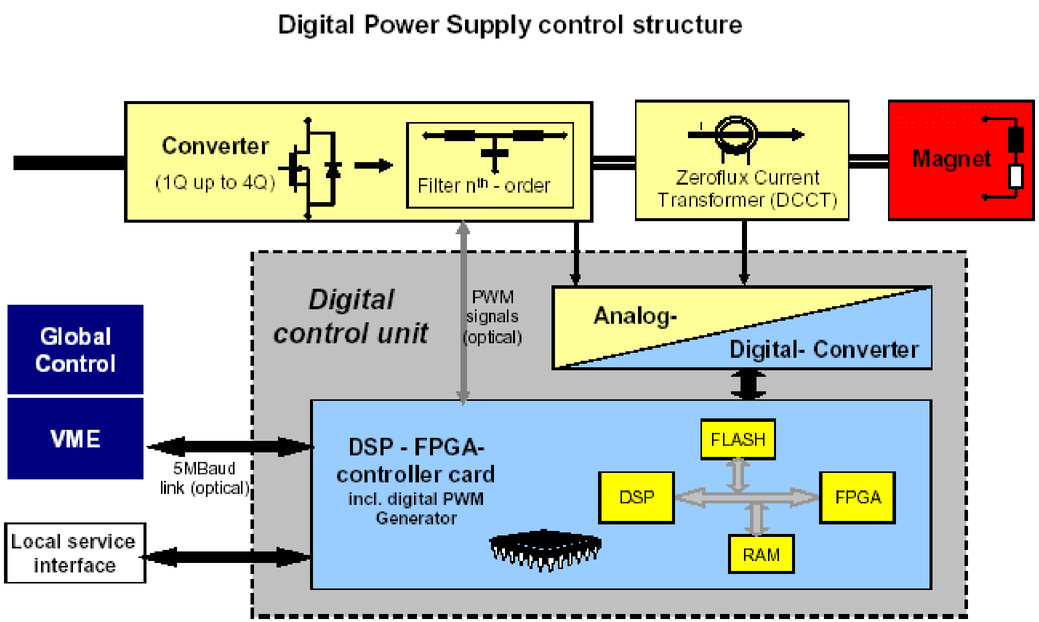
ADC, DCCT

Control System

- SLS: fully-digital

  Some modern accelerators like CERN (for the LHC project) and SLS have made major advances in the area of "digital controlled power converters".

  - SLS: system structure



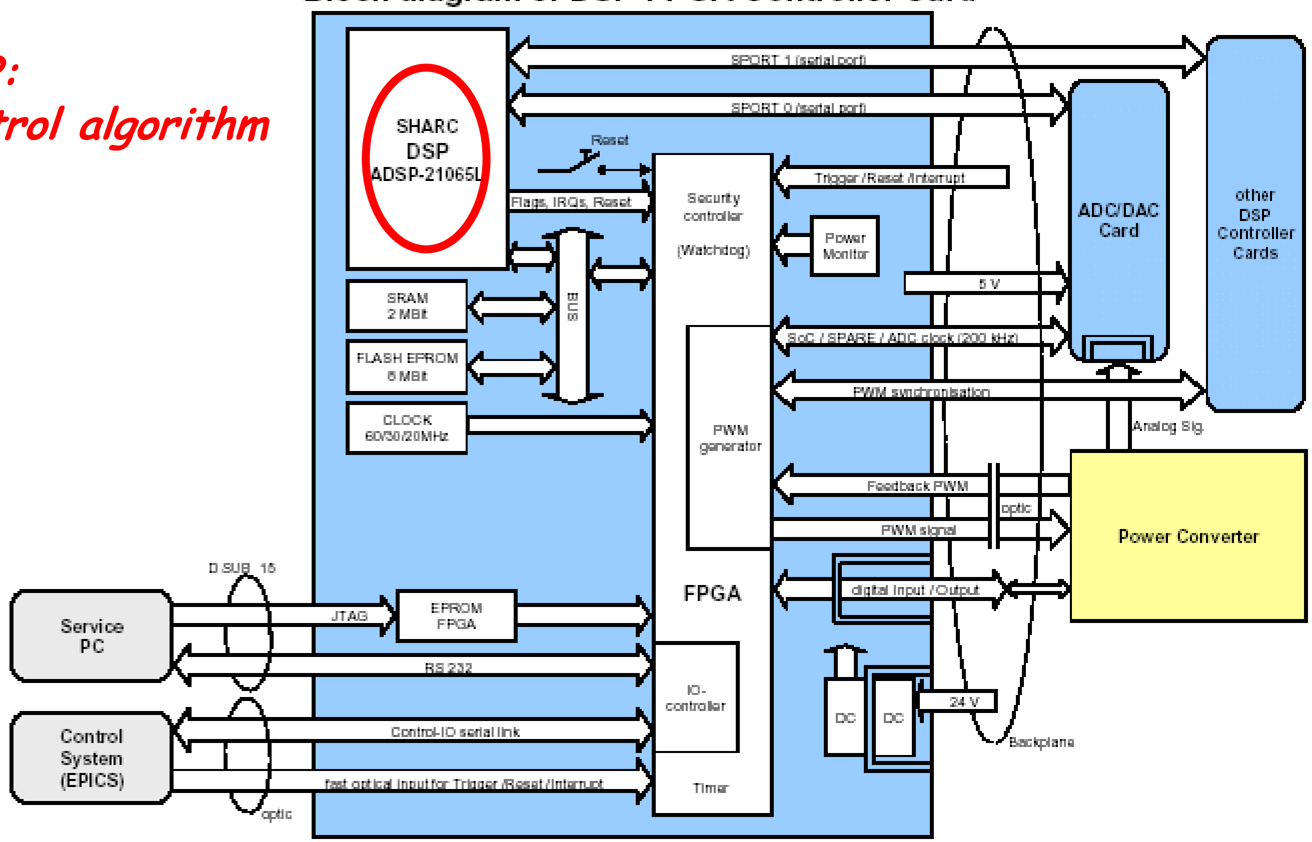
a) memory control
b) IO control
c) PWM generator
d) Local and remote interface
e) analog to digital control
f) close-loop control

Control System

- SLS: fully-digital
  - SLS: system structure

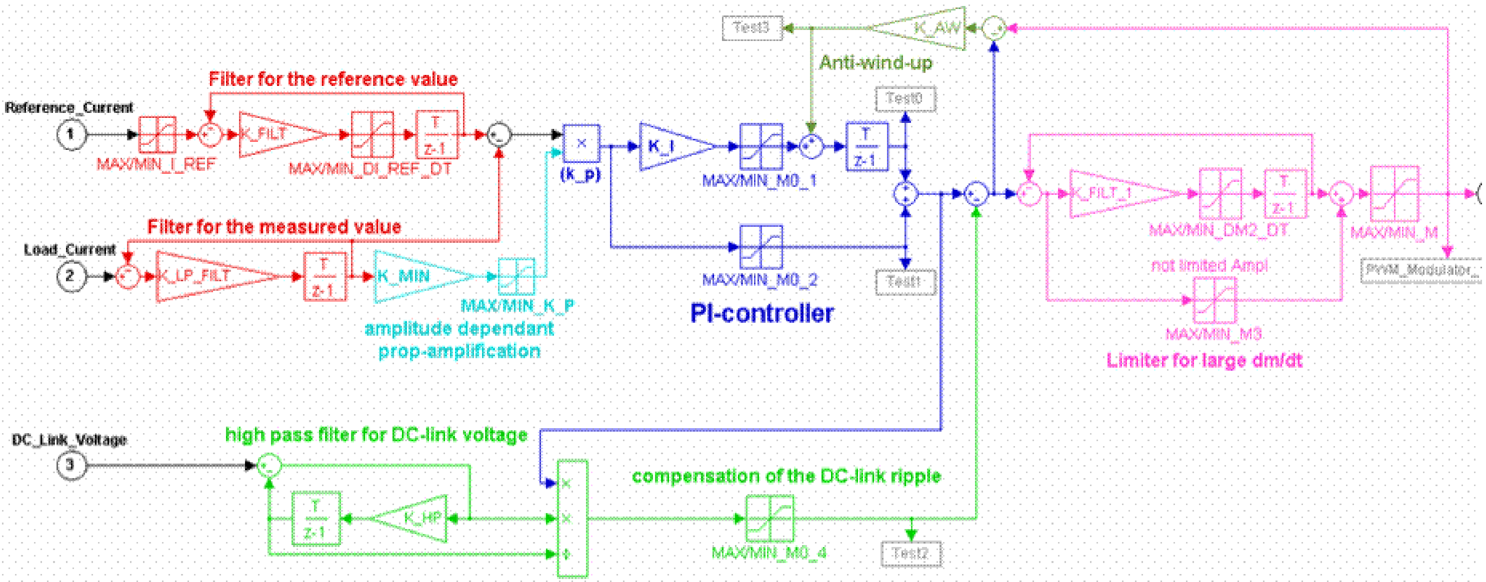
DSP:
control algorithm

Block diagram of DSP-FPGA Controller Card



Control System

- SLS: fully-digital
  - SLS: control structure



- Ziegler-Nichols principles for PI tuning
- Feed forward for DC link ripple compensation
- Integrator Anti-windup

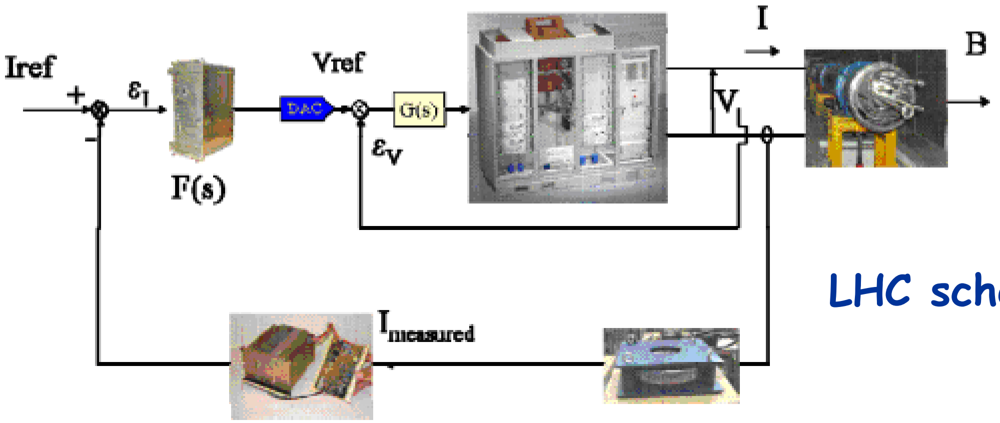
All PCs at SLS are fully-digital controlled based on this system.

Control System

- LHC: mix of analog and digital

Most magnet PCs are current source.

- only apply their digital controller for current regulation
- a "universal" current controller: drive "a variety " of "standard voltage sources".
- voltage sources: vary between "switched mode power supplies" and "classical thyristor converters", all with internal voltage control.

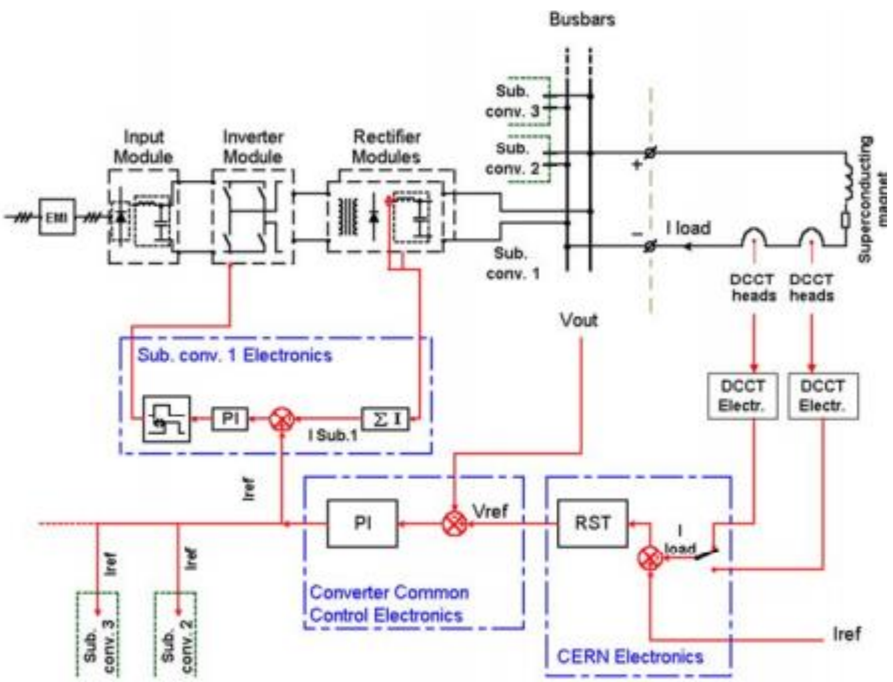


LHC schematic control loops

Control System

- LHC: mix of analog and digital

  for high-current power converters: except the outermost current loop, other loops are analog.



Control loops of the LHC high-current power converters

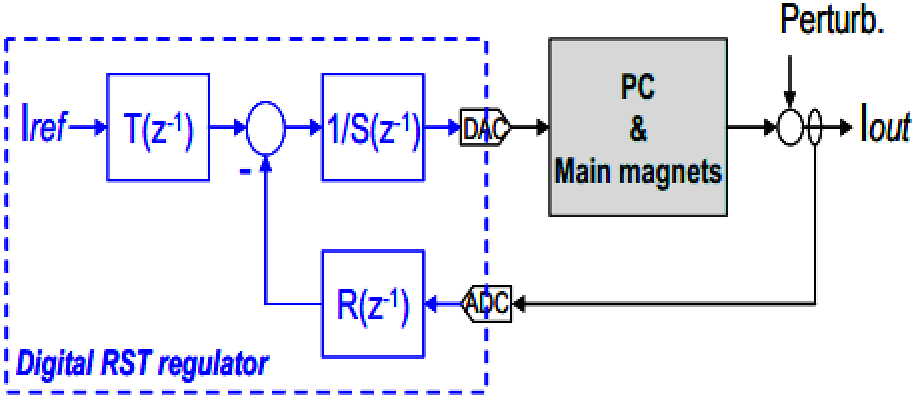
Control System

LHC: R-S-T

LHC: an order of magnitude improvement in accuracy and reproducibility over previous accelerators. The PCs must:

- follow a very precise acceleration curve with **absolutely no over or undershoot**!!
- almost impossible to realize an analog current loop with the high time constant of magnets.
- RST controller: tri-branched structure

performance: the regulation (R,S) tracking (T) can be independently optimized

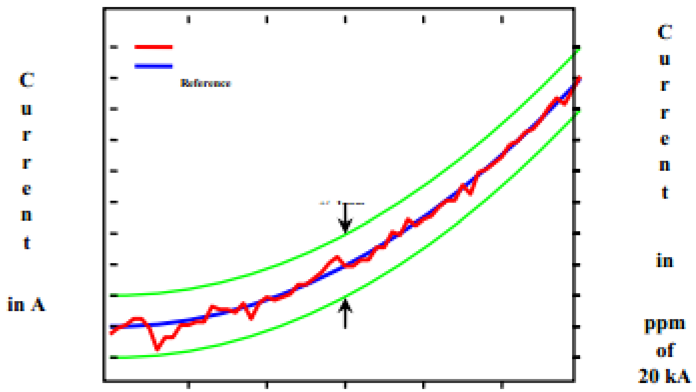


Control System

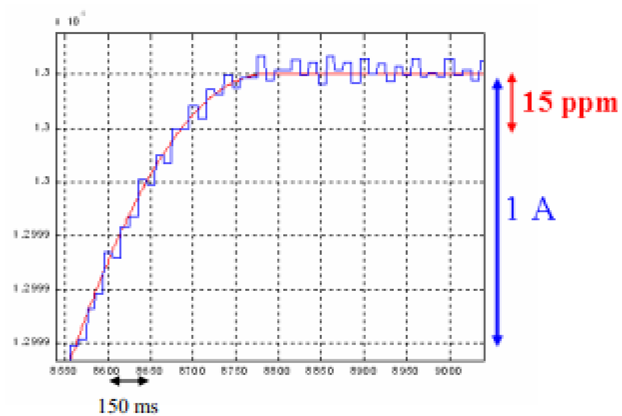
- LHC: R-S-T

With the RST:the desired tracking behavior (following the reference) is obtained independently of the desired regulation behavior (rejection of a disturbance). This method provides a good tracking of the reference with **no lagging or overshoot**.

- The current control loop is designed to make the complete system behave like **a "perfect" current source**, reaching a very high precision (a few ppm) even in the case of **very large time-constant of loads**.



The start of a short LHC ramp :great resolution and accuracy



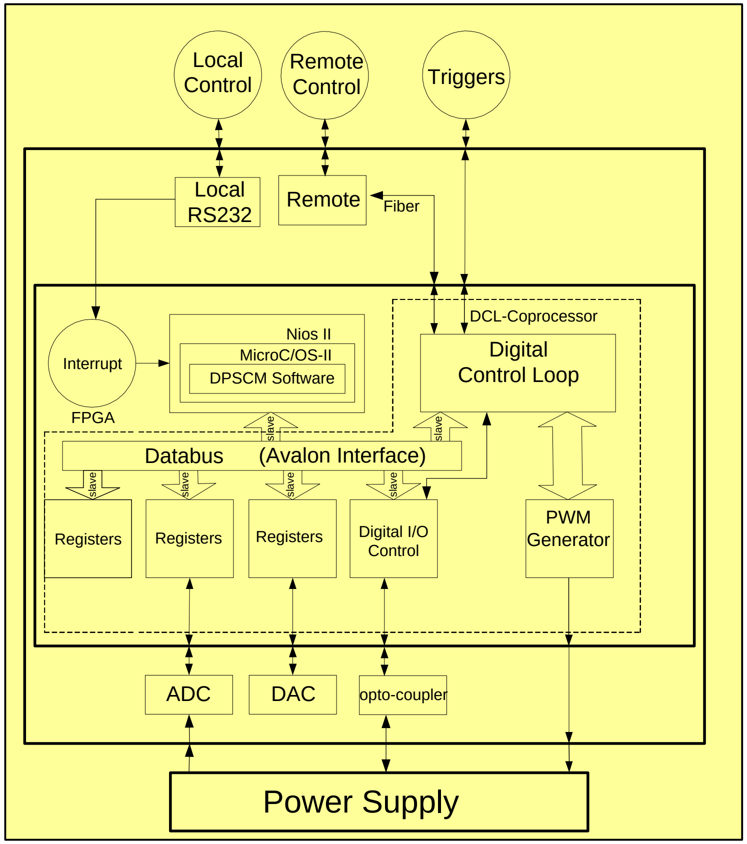
End of the ramp: from 12 999 A to 13 000 A
no under or overshoot

Control System

- CSNS: Digital Power Supply Control Module (DPSCM)

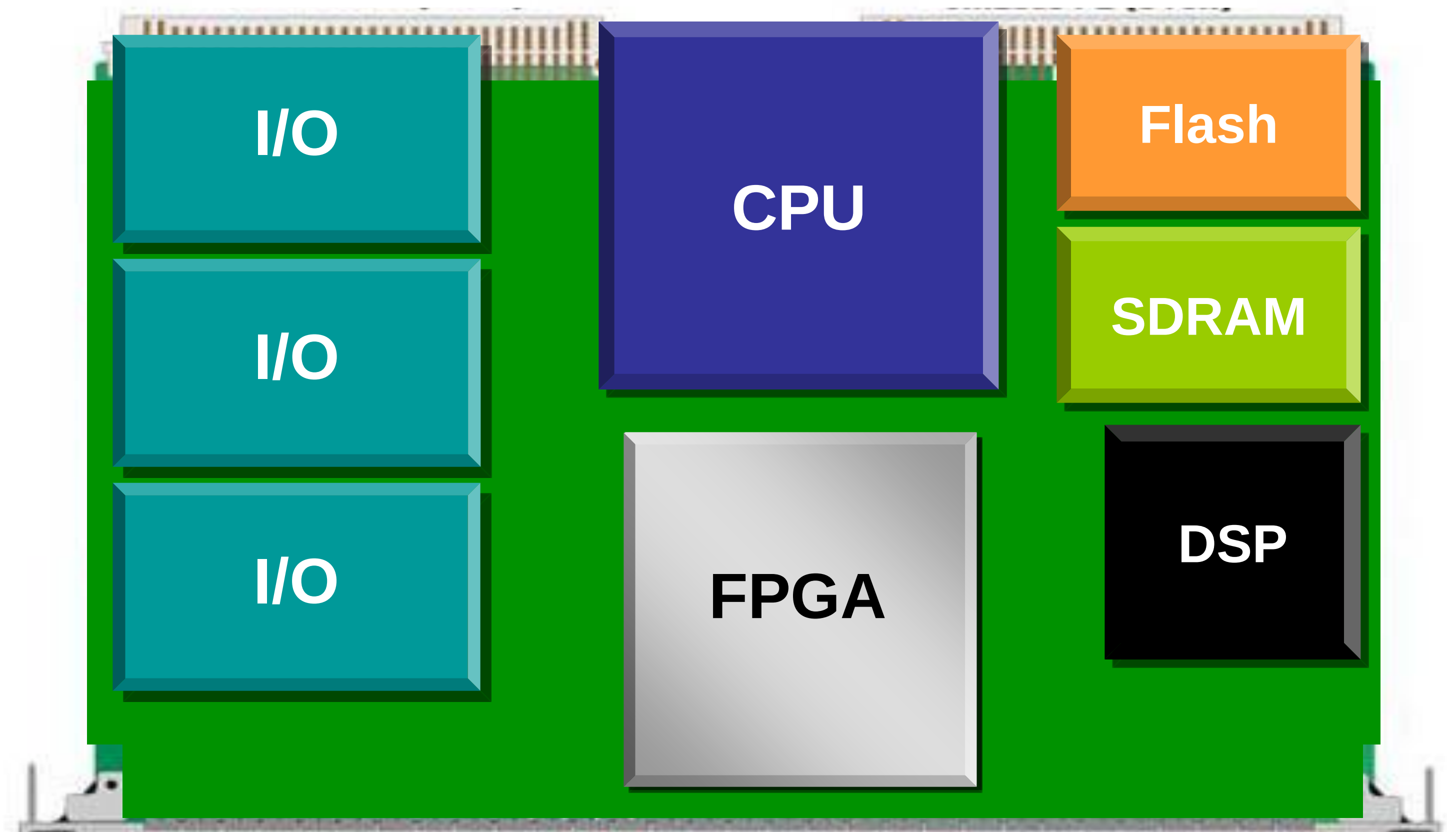
  fully-digital controller based on a FPGA.

  - All algorithms and peripherals control entirely implemented in a FPGA.



Control System

the principles of FPGA-based design: SOPC (System On a Programmable Chip)



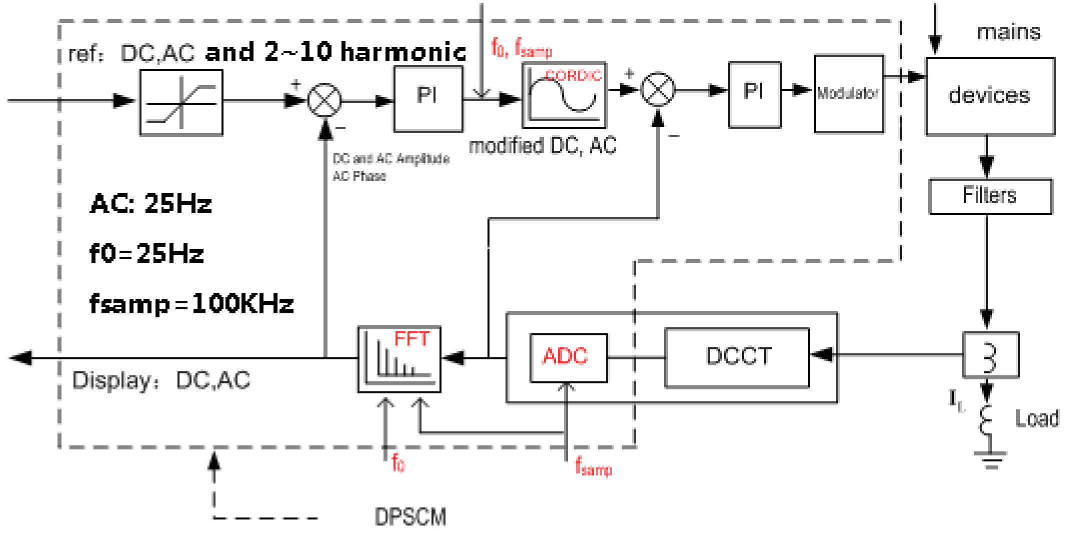
Solution: Replace External Devices with Programmable Logic

Control System

- **CSNS: DPSCM**

  for RCS resonant PCs: DC + AC (25Hz)

  - difficult to promise the tracking error while current cycling
  - three additional PIs: for DC, 25Hz AC amplitude and 25Hz AC phase, to promise the tracking errors as small as possible
    - sina wave generator
    - FFT
    - PIs



Control System

CSNS: DPSCM

for RCS resonant PCs: DC + AC (25Hz)

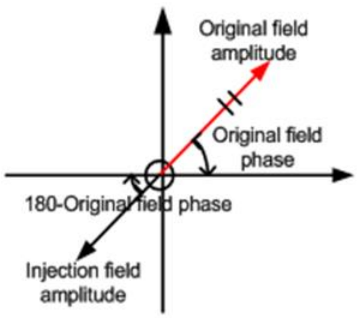
- difficult to promise high order harmonic magnetic field as small as possible under the case of magnetic field saturation (for dipole magnet prototype, non-linearity of dynamic inductance up to 15%)
- harmonic vector-injection implemented in DSPCM

desired dc+25HzAC

2~10th harmonic currents: added manually
to create 2~10th harmonic magnetic fields

•the same amplitudes
•but phases reversed

(compared to the fields produced by the 25Hz ac current)



settings

readback

harmonic injected specially

Control System

Current (before injection)		
	Current-B	Current-Q
1^{st}(25)	100%	100%
2^{nd}(50)	1.301%	1.061%
3^{rd}(75)	0.527%	0.327%
4^{th}(100)	0.202%	0.054%
5^{th}(125)	0.114%	0.025%
6^{th}(150)	0.047%	0.021%
7^{th}(175)	0.021%	0.020%

Field (before injection)		
	B(BL)	Q(GL)
1^{st}(25)	100%	100%
2^{nd}(50)	0.524%	0.713%
3^{rd}(75)	0.112%	0.135%
4^{th}(100)	0.042%	0.094%
5^{th}(125)	0.015%	0.0365
6^{th}(150)	0.010%	0.006%
7^{th}(175)	0.003%	0.015%

Current (after injection)		
	Current-B	Current-Q
1^{st}(25)	100%	100%
2^{nd}(50)	0.882%	0.583%
3^{rd}(75)	0.513%	0.324%
4^{th}(100)	0.224%	0.133%
5^{th}(125)	0.106%	0.058%
6^{th}(150)	0.038%	0.016%
7^{th}(175)	0.022%	0.008%

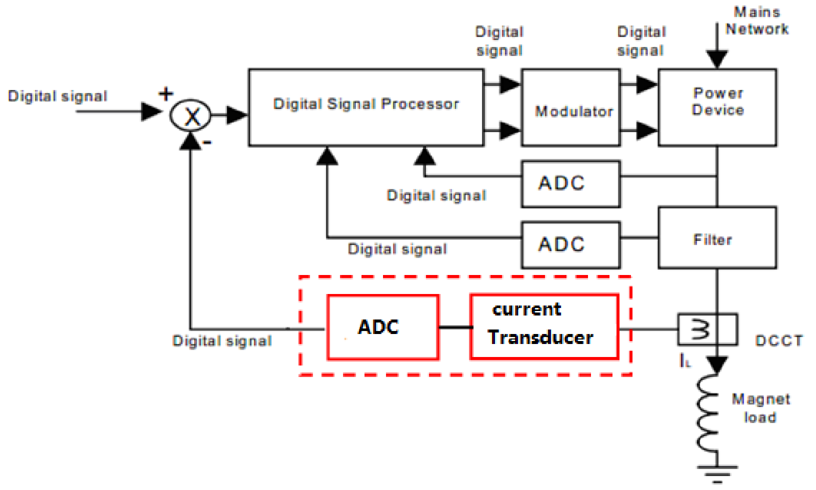
Field (after injection)		
	B(BL)	Q(GL)
1^{st}(25)	100%	100%
2^{nd}(50)	0.003%	0.005%
3^{rd}(75)	0.005%	0.002%
4^{th}(100)	0.002%	0.006%
5^{th}(125)	0.002%	0.008%
6^{th}(150)	0.001%	0.002%
7^{th}(175)	0.003%	0.001%

Considerations: digital control

- fully digital control system:

  It is already a trend in magnet PCs for accelerators, and the performance is significantly determined by the ADC and DCCT.

  - implementation of variety of algorithms
  - architecture of the controller
  - digital DCCT
  - communication system
  - ADC options
  - synchronization
  - ……



Considerations: digital control

IPAC14

- digital DCCT

If a "digital" DCCT could be designed with the same speed and accuracy as the analog counterpart, this would provide far greater flexibility and convenience in the control system of a PC.

It's difficult to assign a value to the meaningful contributions of students at the laboratory, but faculty members at one university recently gave top marks on a student's Accelerator Division project.

The project was the development of the world's first digital direct-current current transformer, or DCCT, which measures particle beam intensities. The development of this new Fermilab component is thanks to Silvia Zorzetti, former Fermilab intern and recent guest scientist in the Beam Instrumentation Department.

Feature

Accelerator Division graduate student helps develop world's first digital DCCT

From March to November last year, graduate student Silvia Zorzetti worked with a team in the Accelerator Division to develop a digital DCCT for measuring beam intensities. She graduated in December with a master's in electronics engineering from the University of Pisa, and her thesis on the DCCT earned the maximum number of points. *Photo courtesy of Manfred Wendt, CERN*

Considerations: digital control

- digital DCCT

Digital Signal Processing and Generation for a DC Current Transformer for Particle Accelerators by Silvia Zorzetti

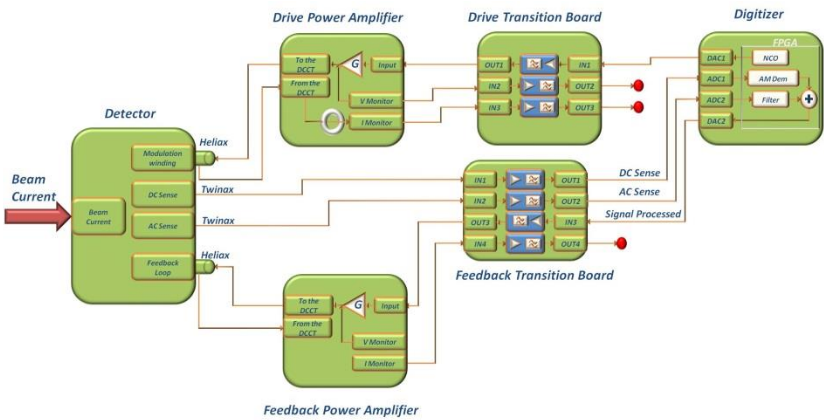
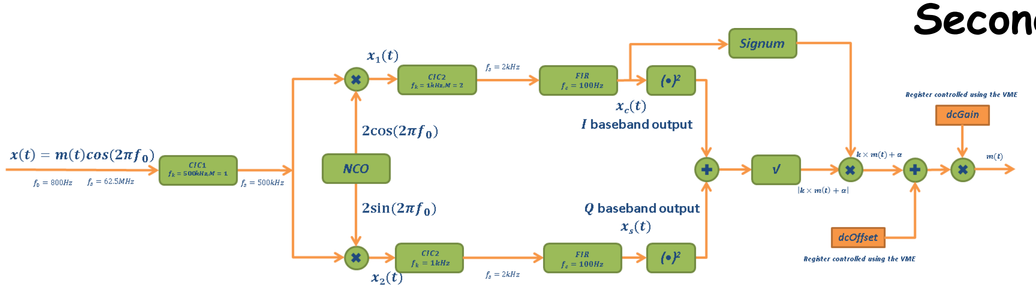


diagram of the complete system

Second harmonic detector



Although the requirement of DCCT for beam instrumentation and for PC is different, the principle is almost the same. The news gives us some enlightenment ……

Considerations: digital control

- communication system:

  It is now an integral part of the digital controller.

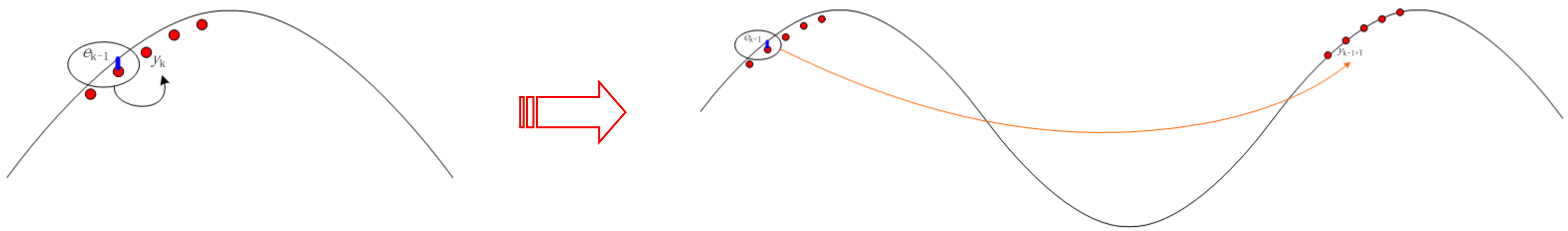
  - more close relation with the accelerator control people
  - solutions easy to develop, easy to interface, simple architecture, reliable, advanced in the future
  - interface with timing system to accept gloabal timing/event triggers
  - strong integration in the particle orbit feedback system
    - a deterministic(!!) communication between systems
  - fiber connection recommended to reduce EMI affect for the low voltage electronics circuits……

Considerations: digital control

- control algorithms:

  It is the soul of a digital system: a lot of algorithms can be implemented to achieve better performance.

  - optimized PID controllers
  - repetitive controller, very useful for cycling output
    - ***Not only the present but also the former error will act on the plant. The error is active repeatedly, after a few cycles, the tracking error will be greatly improved.***



Considerations: digital control

- control algorithms:
  - harmonic analyzers

    applying modern signal processing methods

    - digital filters, wavelet analysis, and etc, useful for active filters, dedicated frequency ripples suppression…
  - adaptive state controller (integration in PIDs), optimizing parameters during operation
  - Artificial Intelligence (AI) technology for example expert systems embedded into the digital controller for better diagnostics, faults prediction, analysis and location
  - any creative ideas

Powerful "brain" constructed by electronics in a digital PC!

Considerations: digital control

- system architecture:

  DSP + FPGA

  It is popular that the processing core of a power supply digital controller is based on the DSP, where the DSP is responsible for the algorithms and an auxiliary FPGA responsible for the logic operation.

  or FPGA only?

  With a more powerful ability of computation and excellent timing control of FPGA, it is likely to use one single FPGA to fulfill all functionality of the digital controller.

  a popularity of using non device-specific code

  deterministic controlling with hardware-based design

Considerations: digital control

- application of ADCs:
  - The ADC is a most important and temperature-sensitive component for a digital control system.
  - For the ongoing requirements of higher and higher beam positional stability and precise control, current precison:
    - 100ppm is common
    - 10ppm normal for many applications
    - 1ppm or higher needed for ultra demanding facilities?

The choice and application for the ADC is very critical for the performance!

Considerations: digital control

- application of ADCs:
  - get a balance between the resolution, speed and cost
  - considerations on internal/external reference, linearity and latency etc
  - Never underestimate the difficulties in realizing the datasheet promises!

\ADC TYPE REQUIREMENT\	FLASH	PIPELINE	SAR	CHARGE BALANCE	SIGMA-DELTA
Throughput	excellent	v.good	good	poor	fair
Bandwidth	excellent	excellent	v.good	v.poor	fair
Resolution	poor	good	v.good	excellent	excellent
Latency/Hz	excellent	fair	v.good	Poor	fair
Multiplexing	excellent	poor	v.good	fair	poor
Linearity/bit	v.good	good	fair	v.good	v.good
Comments	power cost	v.fast clock	DNL stability	DC only	easy anti-alias

technology vs. requirements

A Review of ADCs & DACs and their Application by John PICKERING,CAS2014

Considerations: digital control

- synchronization:

  Anytime it is important for the design of a digital controller!

  - if the system is based on DSP+FPGA, clocks of the two processors…
  - digital mixed with analog…

In the J-PARC 3GeV synchrotron, the horizontal closed-orbit-distortion(COD) variation was observed at a period of about 140seconds. It was found that the horizontal COD was caused by the dipole magnet power converter.

The reason is the switching timing of the dipole magnet power converter that is determined by its inside oscillation (analog); but clock of the regulation system and current sampling is from the timing system (digital). Finally it has proved that the PWM generator synchronized with the timing system successfully suppressed the beam orbit variation.

Considerations: digital control

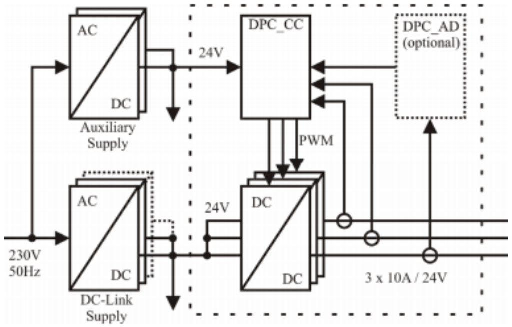
- compact and cost effective design

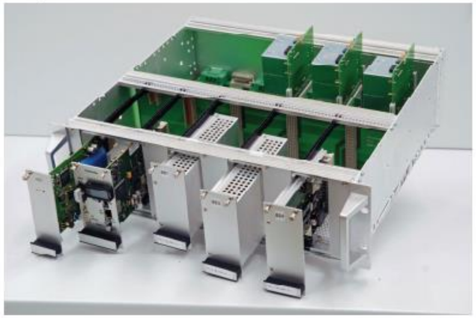
For ultra low power correction power converters:

- digital controller occupying a lot of space
- the costs are too high

use a compact design as SwissFEL does:

- compact and modular design
- one controller for 3 sets power converters
- AC/DC converters providing dc-link power should be common for several PS





3*10A power converter

Considerations: system reliability

- ongoing quest for high reliability

  short MTTR, long MTBF a few weeks generally, if installed underground a few months commonly, and even longer

  - yearly statistics on power converter reliability (from operations)
    - e.g., for APS, detailed records from Operations Groups, PSG
    - specific problems addressed such as control power supply board, noise, water cooling for partial components, loss of setpoints, regulation problems etc.
    - specialized diagnostic tools hunting for problematic converters
  - redundant design and 'hot' switching/repair (from equipments)
    - redundancy design: a power converter with a built-in redundancy by a modular approach. The power part is divided into n+ 1 module, n supplying nominal current, and one module will work in case of trip. Automatic 'hot' switching between modules are needed.

Considerations: system reliability

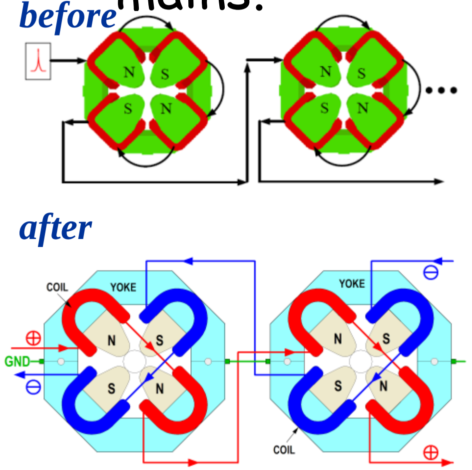
- ongoing quest for high reliability
  - redundant design and ‘hot’ switching/repair (from equipments)
    - ‘hot’ maintenance and repair
    - efficient monitor and diagnosis method to prejudge the problem appearance.
    - mains stability is required, the mains voltage sags correction devices and UPS might be needed.

Considerations: EMC

- EMC considerations:

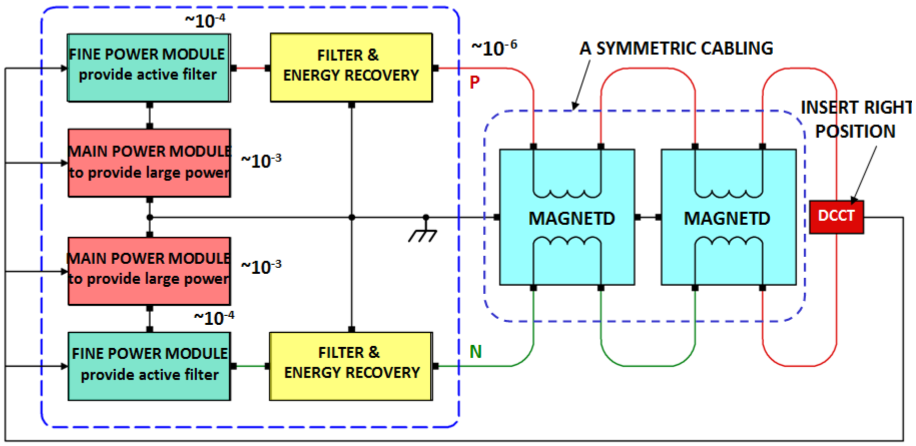
The power supply system EMC design should be conducted under the EMC principle of accelerator facility. The design work of PC EMC should be coordinated with:

- design of various equipments distribution,
- electricity mains distribution and grounding,
- design of overall facility grounding,
- design of cabling, especially the cabling for magnet loads and mains.



symmetric: power modules and cabling

reduce common mode noise



Considerations: EMC

- EMC considerations:

  - The PC equipment EMC design should be conducted at early stage, strengthen the EMC studies for converter prototype.

  - Converter topology design: Choose soft switch (ZCS/ZVS) for switch mode converter. Choose digital PS controller instead of analogue one. Use photo-fiber for signal long distance transmission. The decouple circuit among the DC-DC converters which are supplied by one common voltage converter.

Considerations: EMC

- EMC considerations:

  - The PC mechanical and electrical technology: prevent EM emission leakage, obstruct the EM coupling path, and strengthen the immunity of sensitive elements. The works include: elements distribution, PCB design, cabling, shielding design, grounding, filter and snubber design, installation etc.

  - Preventing any accidental connection between converter grounding bus and the power grid nature line to avoid mains current pass through PC grounding bus. The power parts and low level control parts should use separated low impedance cables to grounding bus.

Considerations: high power

- high current, high voltage and high power:
  - The switch-mode power converters will be more widely used for high power applications.
  - Several MW even a few tens MW can be achievable for this type converters.
  - High power semiconductors devices and new system topologies are continuously improving for achieving higher power, improved efficiency and reliability and better controllability.

Considerations: high power

- high current, high voltage and high power :

  solutions include:

  - modular approach: power modules in series and parallel to get the high voltage and high current requirements.
  - mutli phase-shift PWM: get a high equivalent frequency, then to reduce the size of output filters, and get a better regulation dynamics.
  - power semiconductor devices: the most important factor which determines the power converter technology in accelerators. There are a lot of developments ongoing in the near future which is possible to new and better semiconductors.

Thank you for your attention!