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Low level control upgrade to the ISOLDE High Resolution Separator magnet

HIE-ISOLDE WORKSHOP, 28-29 November 2013

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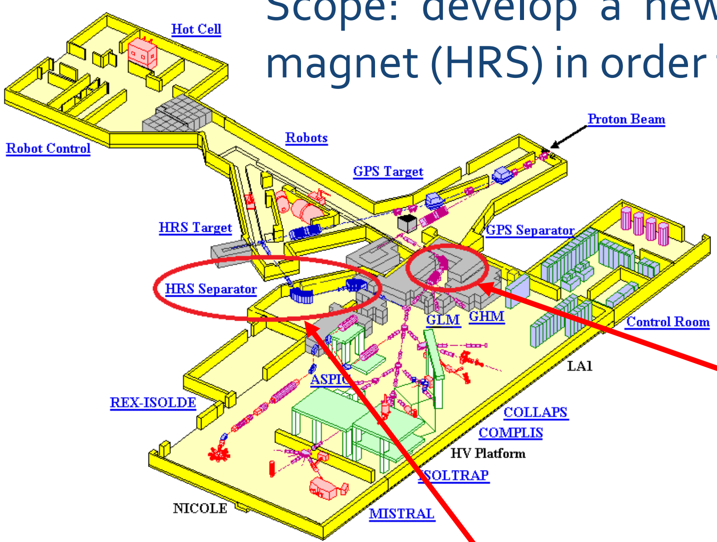
Outline

- Introduction
- Front end system architecture (FESA)
- Control system
- Matlab simulation
- Conclusion and future steps

Introduction: system overview



Scope: develop a new control system for the High Resolution Separator magnet (HRS) in order to achieve better performances for HIE-ISOLDE.

What is the HRS?

Isolde has two mass separators and they are used to separate the ions generated in the facility, according to their mass.

HRS= High Resolution Separator (90° and 60° magnet)

GPS= General Purpose Separator (70° magnet)

Introduction: HRS migration plan

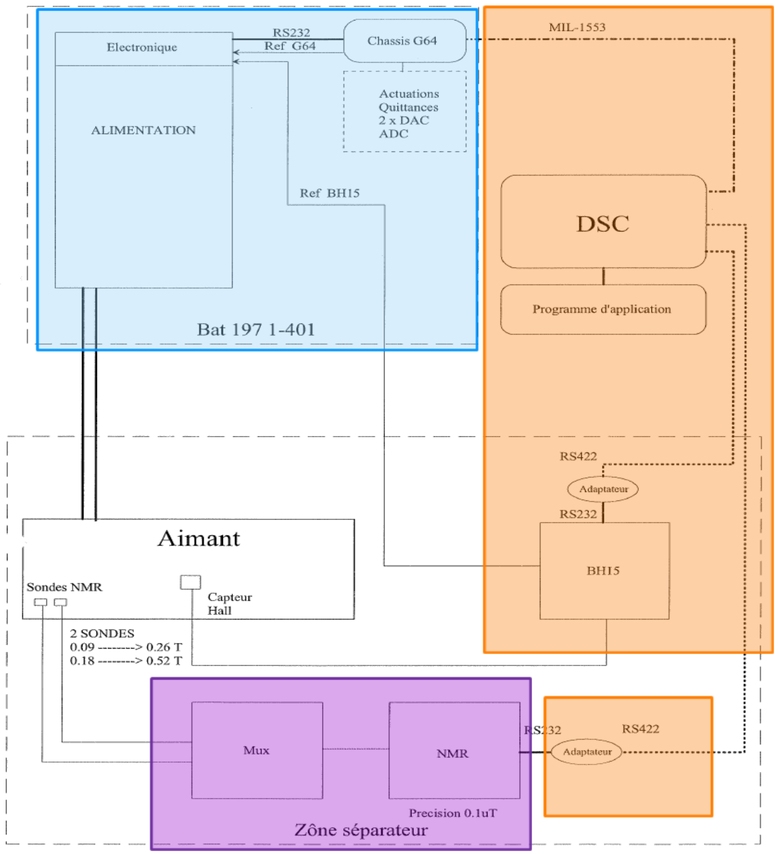
In 2016

Power supply and $G64$ crate substituted by $FGC3$

When available

$PT2025$ replaced by $PT2026$

NO destructive upgrade!



HRS Hardware scheme

during LS1: hopefully April

The obsolete $VME\ MIL-1553$ bus master card replaced by new $PCI\ MIL-1553$ bus master card

Real time GM classes ($powvrt$ - $hrsmagrt$) replaced by FESA3 classes

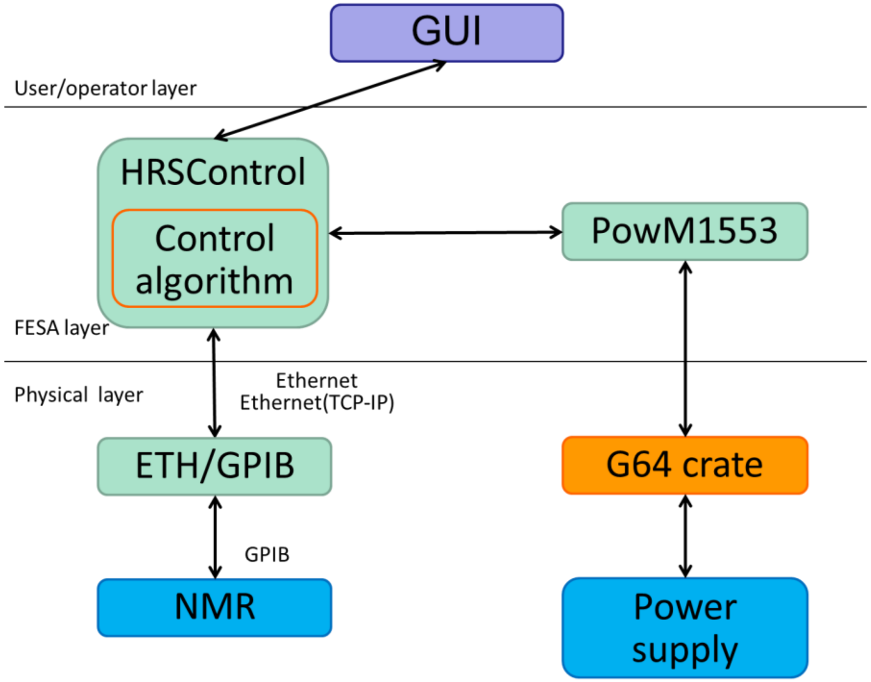
NMR communication protocol ($Rs232$) replaced by $gpib$ protocol

System upgrade

- Update currently used system to BE/CO standard:
  - converts the $hrsmagrt$ class to $FESA3$ (developing the NMR $gpib$ driver)
- Control algorithm:
  - develop a faster control algorithm for the HRS

FESA: system introduction

The FESA framework is a comprehensive environment for equipment-specialists to design, develop, test and deploy real-time control software for front-end computers



Communication system overview

- The HRSControl FESA class is instantiated on a Kontron industrial pc and it includes the current in use control algorithm as a Black Box.
- Interaction through BE/CO functions with:
  - GUI
  - $PowM1553\ FESA3$ class
  - After 2016 $FGC3$ gateway
- The new ethernet/gpib communication driver allows interact with:
  - NMR

Kontron industrial pc

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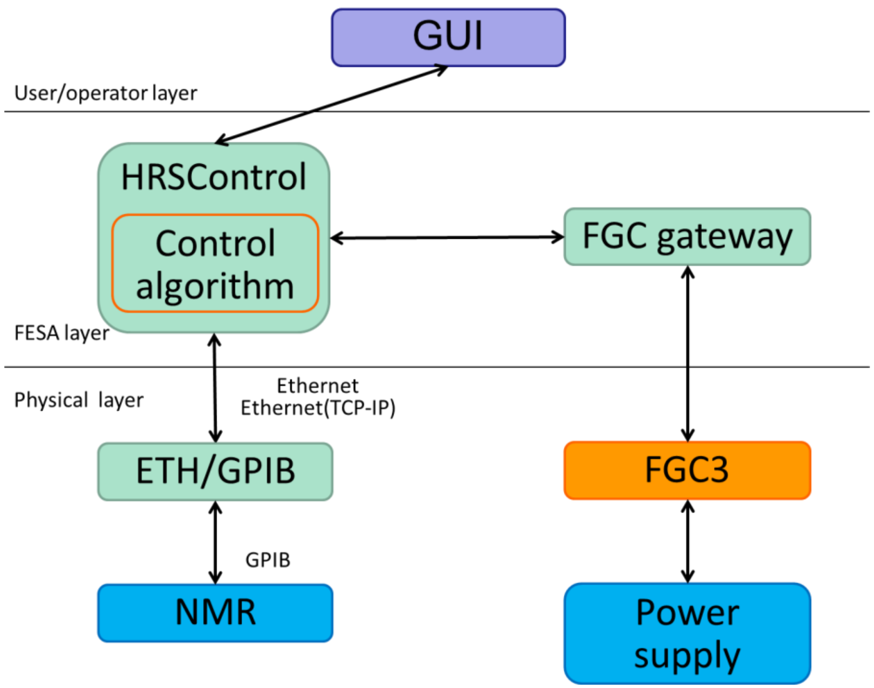

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FGC3

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  - NMR

Kontron industrial pc

FESA: new classes

- The classes are going to be migrated to the new $FESA3$.
- Old user attributes unchanged
- New functionalities
  - Possibility to reset the NMR by software
  - Possibility to change the device connected (NMR,FGC, PowM1553 class) without stopping the class
  - A time stamp and measurement status have been added to the NMR value
- A test bench is almost set up to test the whole system

HRSControl

PROPERTIES

USER/EXPERT
- + UserSettings
- + PowMAcquisition
- + FgcAcquisition
- + NmrAcquisition

EXPERT ONLY
- + ExpertSettings
- + ExpertManControlSetting
- + PowMExpertSetting
- + FgcExpertSetting
- + NmrExpertSettin

METHODS
- + Real_time_action RunControl
- + Real_time_action CheckRbacToken

NMR

PROPERTIES

USER/EXPERT
- + fieldMeasure
- + fieldStatus
- + fieldTimestamp

EXPERT ONLY
- + reset

METHODS
- + Real_time_action Read
- + Real_time_action Reset

System upgrade: control algorithm

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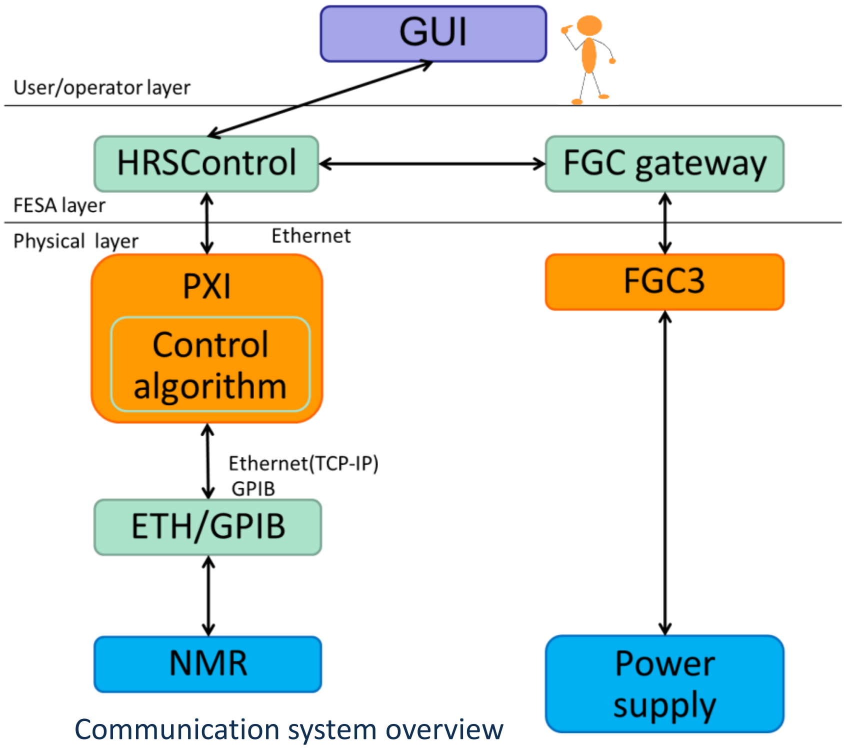
Control system: system introduction



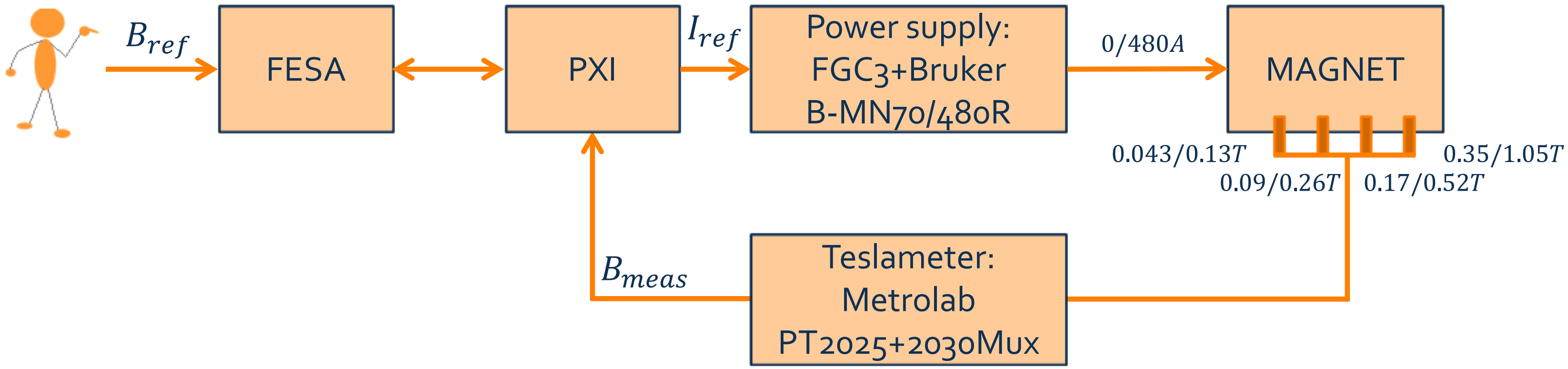
Communication system overview

PXI platform

- The control algorithm is developed with Labview Real Time on a PXI platform.
- The GUI will be the same as HRSControl thanks to the FESA class instantiated on a Kontron industrial pc.
- The FESA class allows:
  - exchanges of data with the user interface through standard BE/CO functions
  - sends the current reference calculated by the algorithm to the $FGC3$ gateway

Control system: overview

Physical overview of the control system

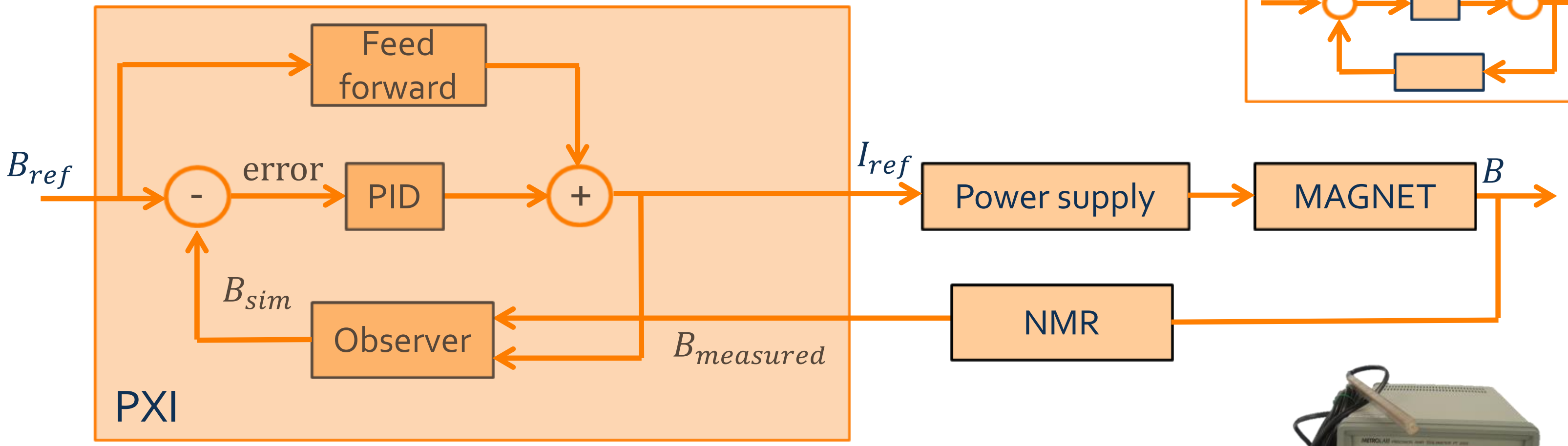


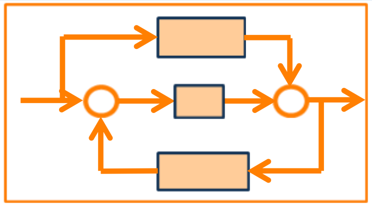
BASIC IDEA:

- The control system compares the measured value with the desired one.
- The magnetic field is measured with a Nuclear Magnetic Resonance (NMR) sensor.
- It calculates the reference current to feed the magnet.
- New current set point is sent to the power supply each cycle.

Control system: implementation

Implemented control system :



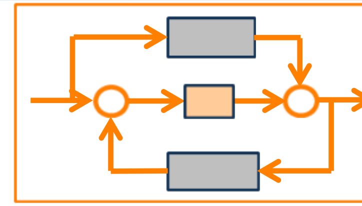


Teslameter PT2025

- The Proportional Integral Derivative (PID) feed back controller
- Observer combines measurements with model estimation
- Feed forward consists of the a priori knowledge of the system (magnet model + eddy current model)

Control system: PID controller

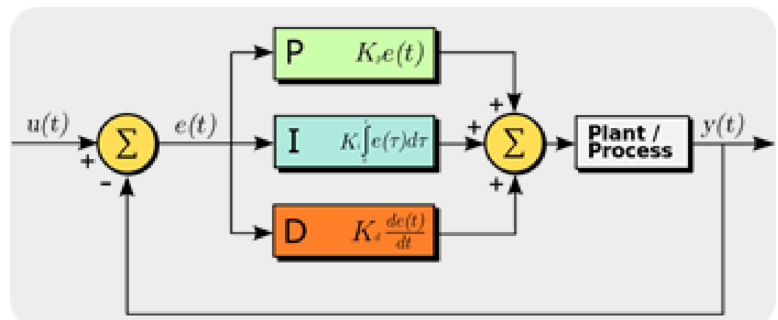
AIM: monitor and modify the system process variable to reduce the difference between desired value and the system output



+ PID controller

$$K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

$K_p = proportional\ gain;$
$K_i = integral\ gain;$
$K_d = differential\ gain.$

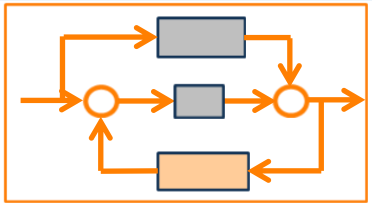


$u(t) = B_{ref}$ and $y(t) = B_{meas}$ by NMR

+ Other elements:
  - anti-windup: excludes the error integration if the output variable is saturating ⟶ fast reaction of the control system;
  - bump-less strategies: limits the switching noise provoked by auto and manual control switching (pre-cycle – manual control);

+ Tuning strategy: Loop shaping control according to the stability constraints

Control system: observer model



AIM: estimates the magnetic field value

- High frequency magnetic field flux evaluation
- Avoid holes in measurements (NMR blindness)

Dynamic + Static

System model

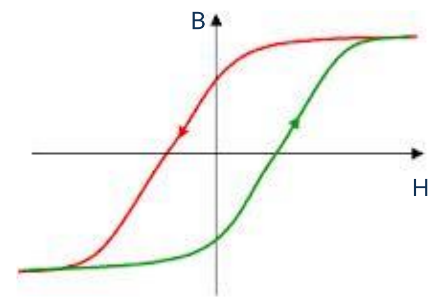
HOW:

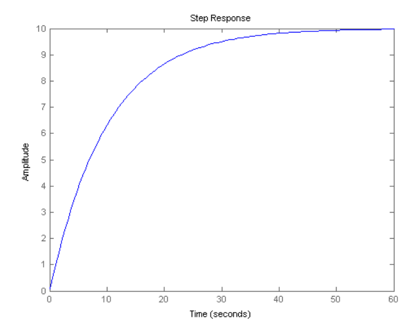
- Static
  - Coleman-Hodgdon hysteresis model (modified Duhem model)
- Dynamic
  - First order model of the system delay:

$$G(s) = \frac{k}{1 + \tau s}$$

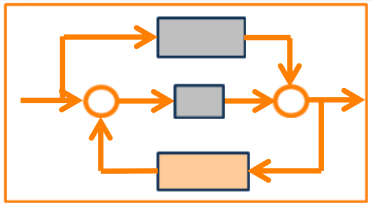
Where: k = system gain
τ = system time constant

  - Eddy current model on study in collaboration with the magnetic measurements section
  - Device (FGC3) dynamics are negligible compared to those of the system





Control system: observer model



COLEMAN-HODGDON MODEL

$$\dot{B} = C_\alpha|\dot{H}|[f(H) - B] + \dot{H}g(H)$$

Where: B = magnetic flux   f(H) = odd, monotone increasing, real valued function
H = magnetic field   g(H) = even, real-valued function

- Ordinary differential equation hysteresis model
- Physical model
- Unidirectional
- Large variety of hysteresis shapes according to f(H) and g(H)
- Rate independent
- Counterclockwise

Soft ferromagnetic model

$$f(\mathrm{H}) = \begin{cases} Ca[H + H^*] - bH^* & for\ H < -H^* \\ bH & for\ H < -H^*\ and\ H > H^* \\ Ca[H - H^*] + bH^* & for\ H > H^* \end{cases}$$

$$g(H) = \begin{cases} u & for\ -H^* \le H \le H^* \\ Ca & for\ H < -H^*\ and\ H > H^* \end{cases}$$

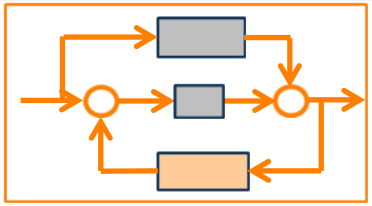
Model constraints:

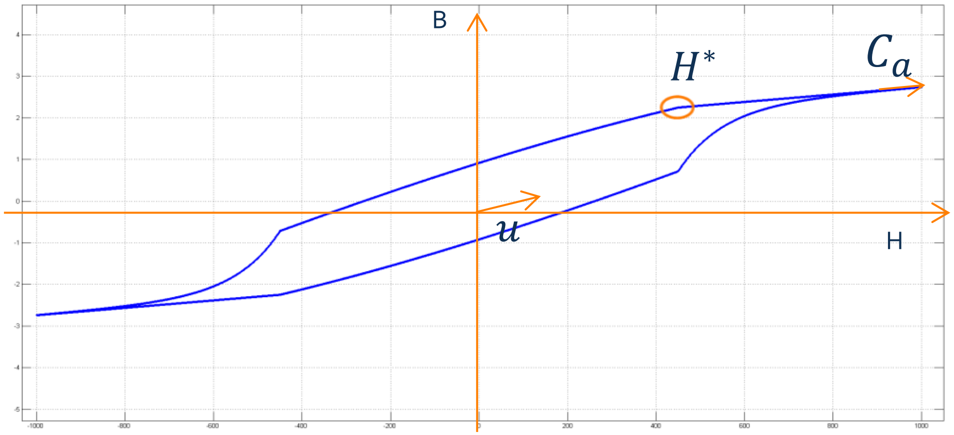
- $C_\propto, C_a, b, u, H^* > 0;$
- $b > u$
- $b - u < u[1 - e^{-2C_\propto H^*}]$
- $b - u < C_a[1 - e^{-2C_\propto H^*}]$

Observer update according to: $B = \hat{B}_{sim} + k * (B_{nmr} - \hat{B}_{sim})$

Control system: observer model

- Off-line hysteresis parameter estimation:
  - low frequency signal input to avoid dynamics;
  - detection of the parameters from main loop;
  - non linear fitting (trust region to respect constraints);
  - average parameter values;
- Off-line dynamics parameter estimation
  - high frequency signals
  - eddy current parameters estimation

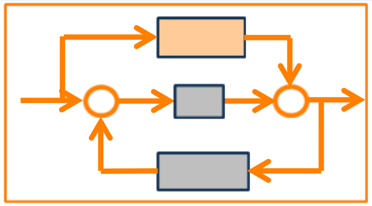




Simulated hysteresis

H^* is the value of the saturation starting point
u is the slope value of the hysteresis at $H = 0$
C_a is the limiting slope for large H

Control system: feed forward



- AIM: improves the control of the magnetic field in open loop using a priori system information
- Ideal case: it predicts the process input variable behaviour to obtain the desired output (perfect tracking)
- Real case: the idea is to invert the magnet model in order to avoid the non linearity of the system
  - Inversion of the Coleman-Hodgdon model using the lambert function (calculated by numerical integration on-line)

Control system: stability

- The PID feedback loop with differential hysteresis is asymptotically stable:

Where: d_1 = input noise
d_2 = measurements noise
r = reference signals

- Stability condition hypothesis
  1) If the input is continuous ⟶ output continuous
  2) The hysteresis is monotone ⟶ (ferromagnetic hysteresis)
  3) The hysteresis operator is Lipschitz
  4) The hysteresis is multi-bracket continuous
  5) The output is bounded (saturation)

The PI limiting condition ($k_d = 0$) ⟶ $0 < k_i < \frac{k_p k_i}{m_1} < \frac{k^2{}_1}{\lambda m_1}$

The PID limiting condition ⟶ $0 < k_i < \frac{k_p k_1}{m_1} < \frac{k_p k_1}{\lambda k_d}$ $\quad 0 < k_p < \frac{m_1 k_i}{k_1} + \frac{k_1}{\lambda}$ $\quad 0 < k_d < \frac{m_1(k_p k_1 - m_1 k_i)}{k^2{}_1}$

"H. logemann B. Jayawardhana and E. P. Ryan. Pid control of second order systems with hysteresis. International Journal of Control, 2008."

Matlab simulation: system

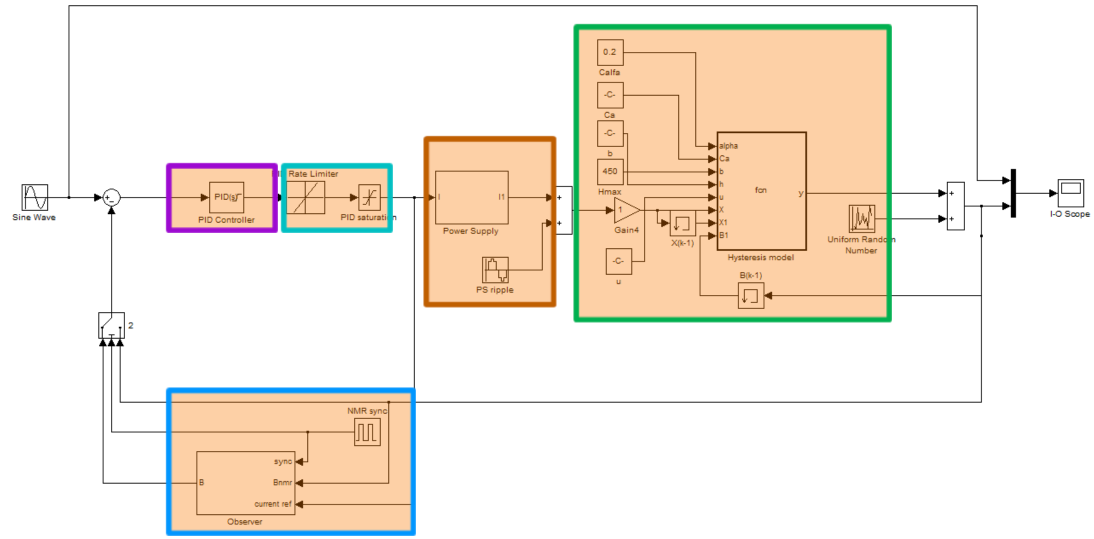
Model simulation:

C-H param	system	model
u	0.2	0.02
b	0.0009	0.009
C_a	0.0014	0.014
H^*	450	410
C_α	0.0024	0.002

Hysteresis parameters table

Dynamic param	system	model
τ	30	40
k	1	1

Dynamics parameters table



PI constant	value
k_p	$180\ /500$
k_i	$6\ /30$

PID parameters table

saturation	value
Maximum	500
Minimum	0
slope	$5A/step$

Saturations parameters table

Observer model error:

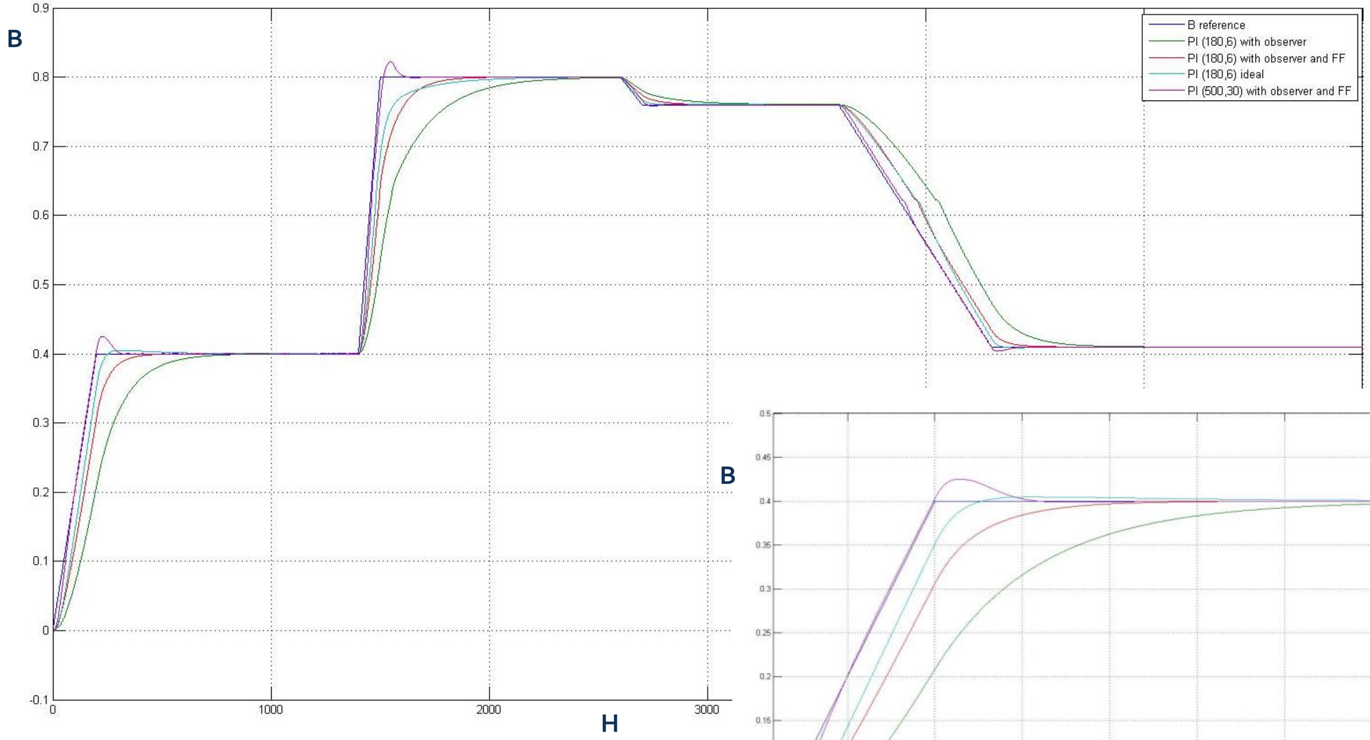
- maximum = 2.3%
- average = 0.1%

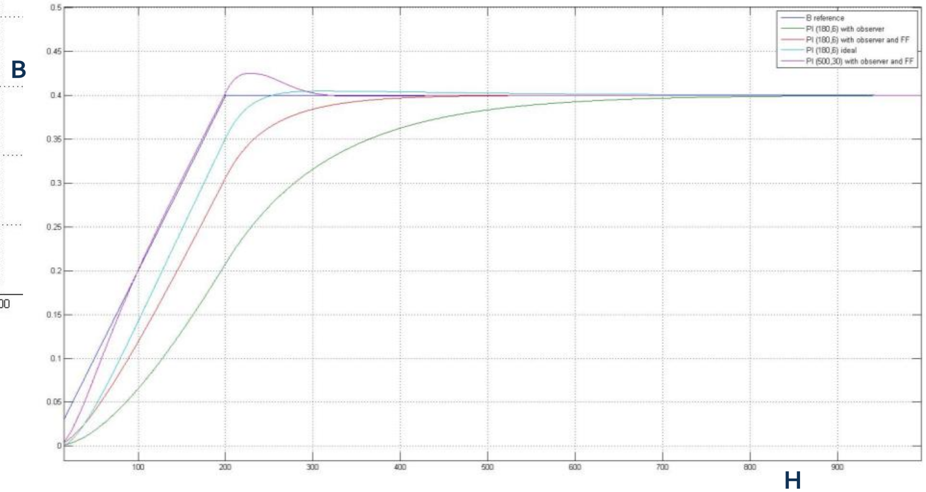
Noise:

- PS: sinusoidal ripple + 3% offset error
- NMR: $WN(0{,}5e^{-6})$

Matlab simulation: results

Improved control performance achievable with PID tuning





Conclusions and future steps

- Updating system → the $FESA2.10$ classes have been developed
  → the $gpib$ driver for the NMR has been realised
  - Migration to $FESA3$ (on going)
  - Test the system on a test bench
- Control algorithm → a feed back control system has been presented
  - Hysteresis inversion
  - Parameters tuning on the HRS (Hysteresis, controller, Magnet model)
  - Eddy current model
- Labview real time → the system architecture has been developed
  → the control algorithm has been implemented
  - The $FESA3$ class has to be developed
  - The feed forward element has to be added

Thank you for your attention

Back up

Back up: lambert function

The $LambertW$ $function\ is\ the\ inverse\ of$

$$W \rightarrow z = We^{W}$$

It has to be solved (approximated) with numerical integration algorithm
Ex. Fritsch method, Newton method

With Fritsch method in tranche $x > -\frac{1}{e}$
After 1 step -> $accuracy\ = 10^{-5}$
After 2 step -> $accuracy\ = 10^{-16}$

Test are on going