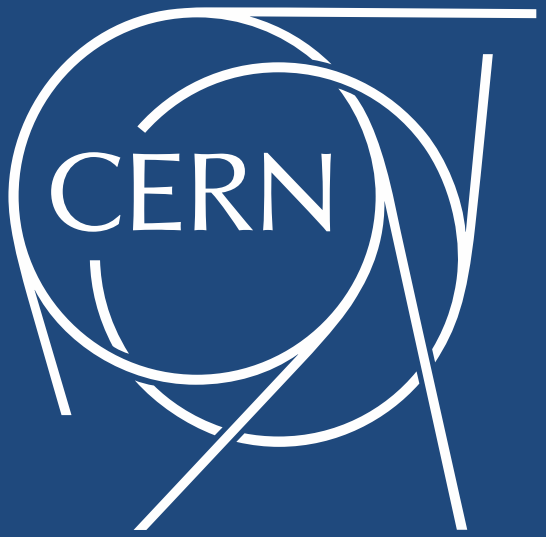
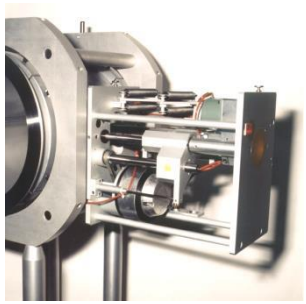
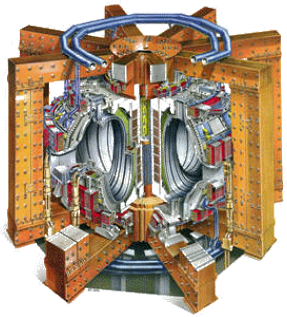

CERN

Controls and Interfaces

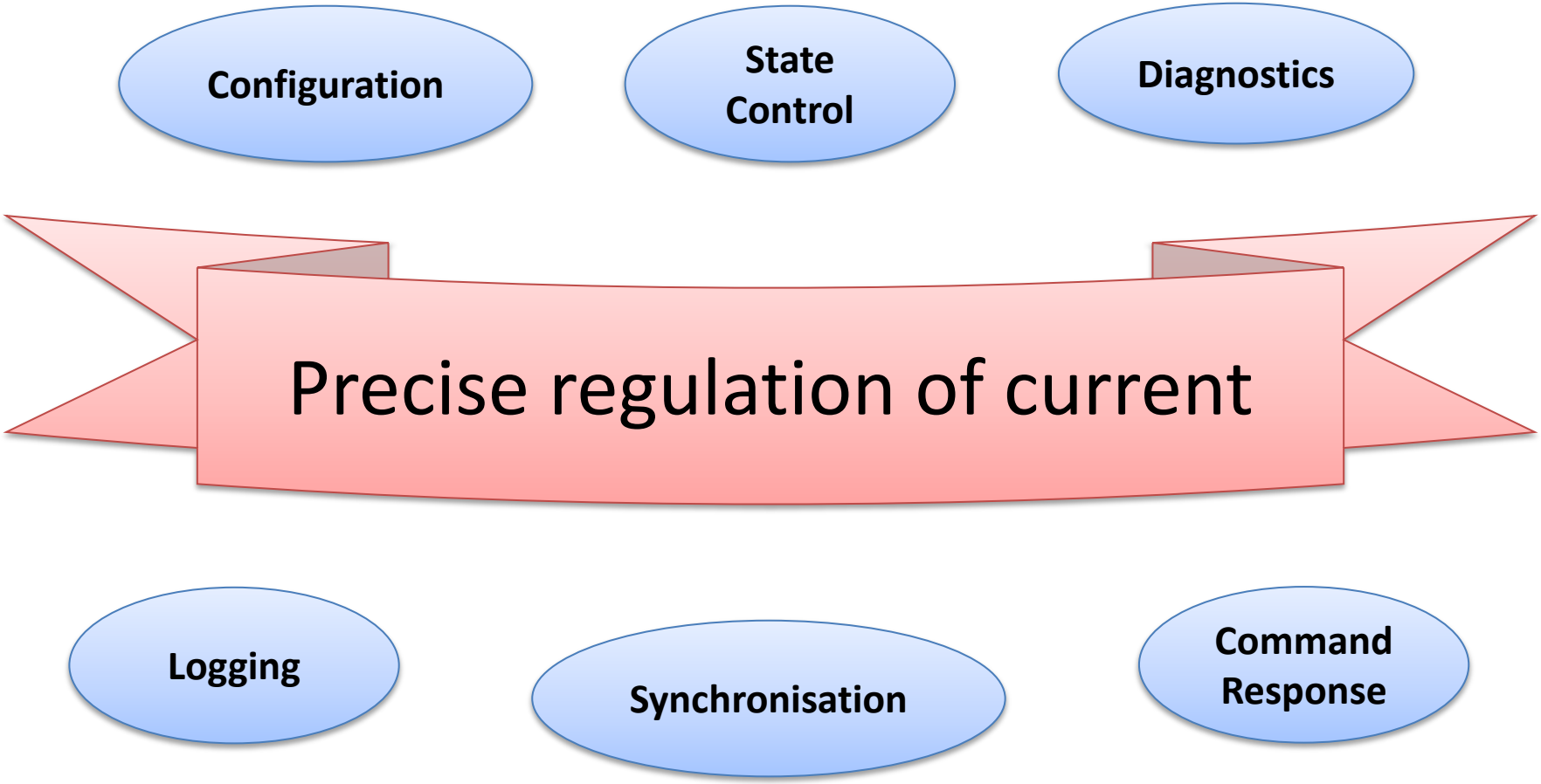
CERN Accelerator School, Baden, 2014

- Quentin King
  - Physicist by training
  - 1987-89 : Beam instrumentation at CERN
  - 1991-97 : Control systems at the JET project
  - 1998- : Power converter controls at CERN

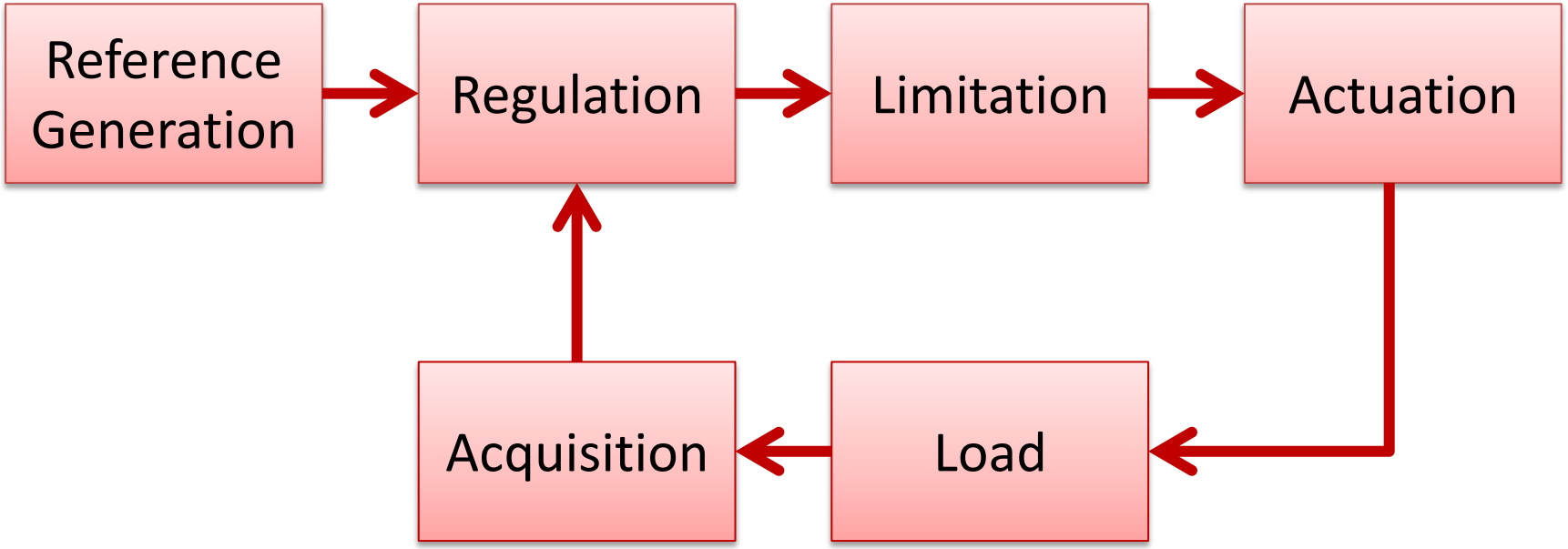




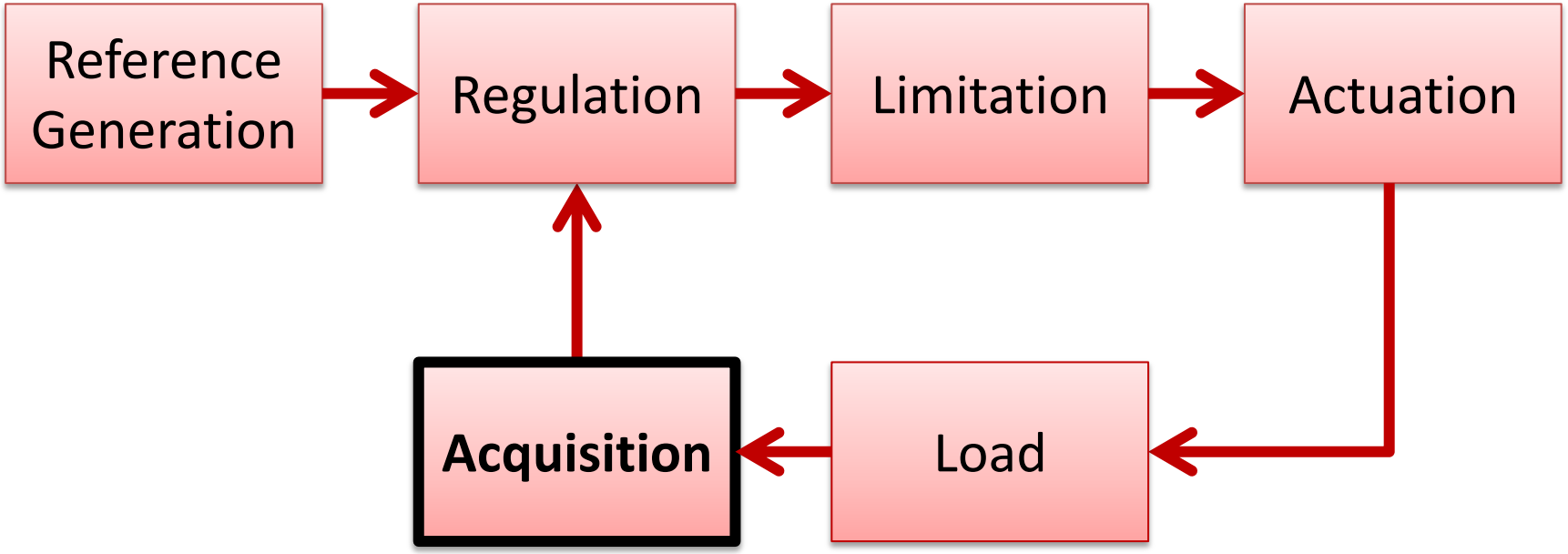
Controls and Interfaces



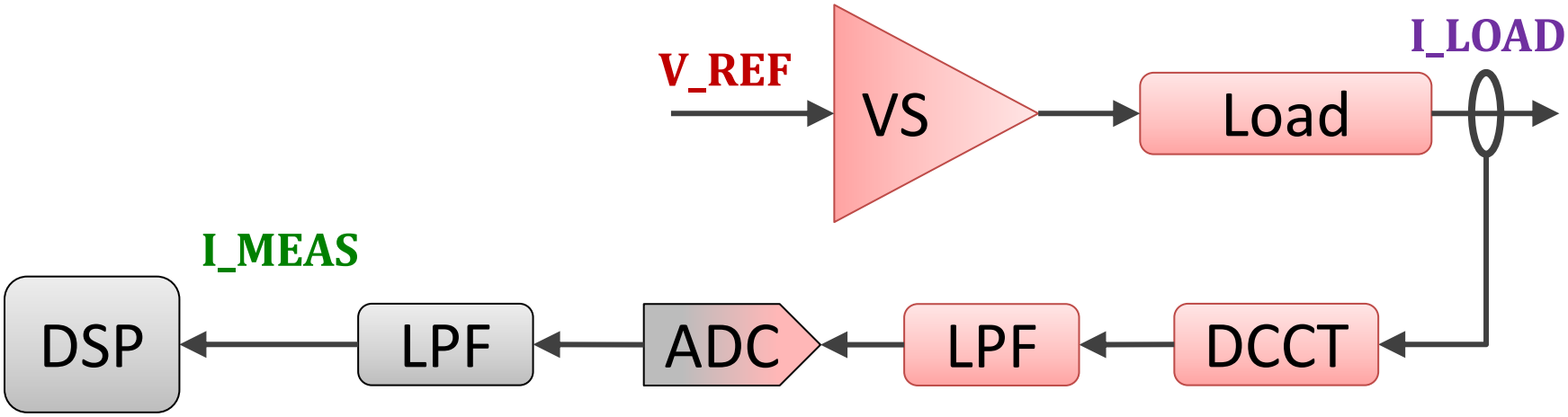
Outline



Case studies of converter controls at CERN


Reference Generation
Regulation
Limitation
Actuation
Acquisition
Load

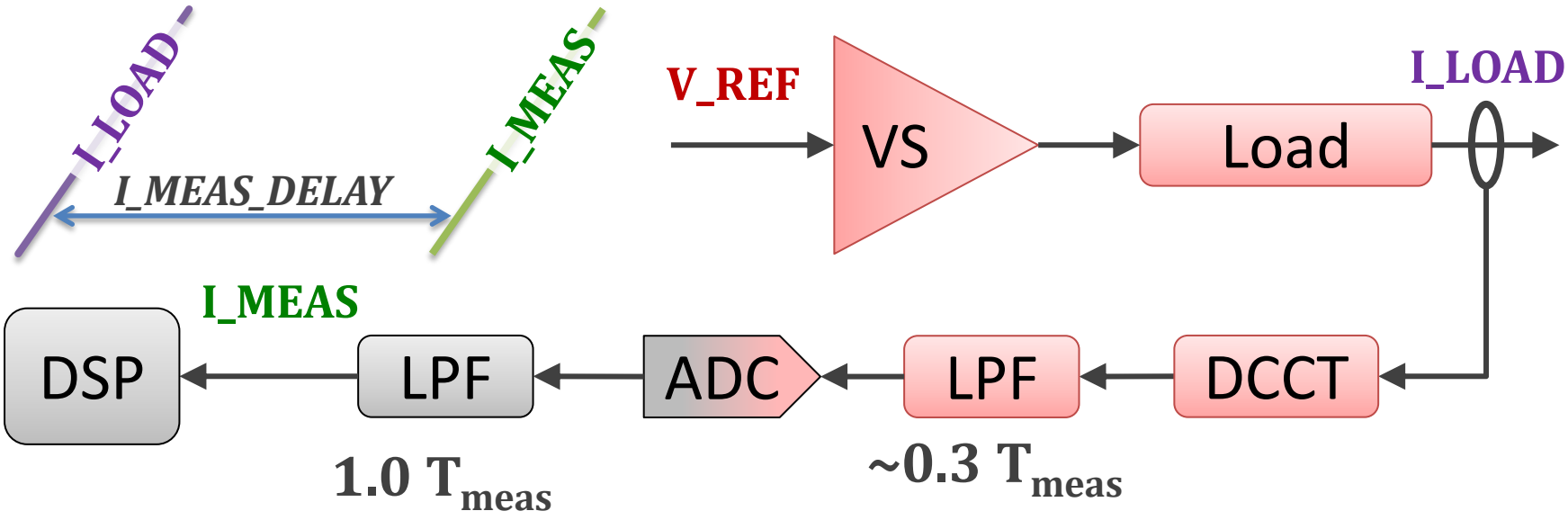
Acquisition – Key concepts as used at CERN



The DSP samples I_MEAS every iteration

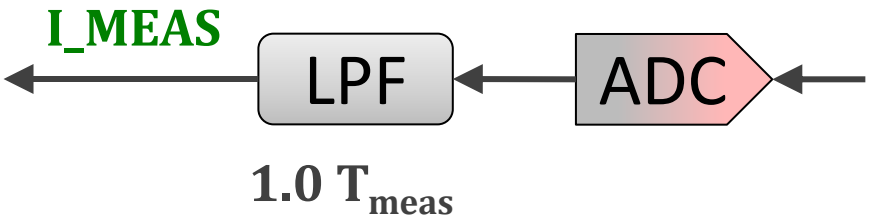
Iteration period = T_{meas}

Measurement delay

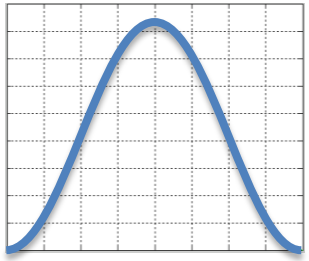


- Delay in I_MEAS is about 1.3 T_{meas}
- ~0.3 T_{meas} for analogue LPF – first order response
- 1.0 T_{meas} for digital LPF – pure delay for symmetric FIR

Measurement delay is very important

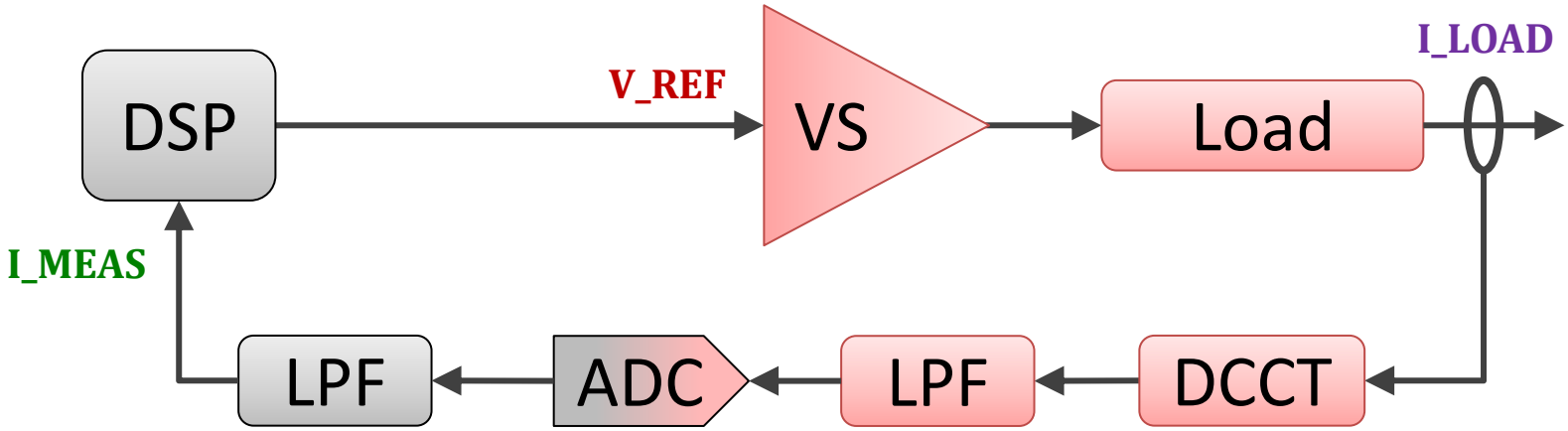


- All delays that affect the regulation loop must be considered
- The choice of filters can make a huge difference to the delay
- Many delta-sigma ADCs include a wide-band "brick wall" filter with delays as high as $40\ T_{meas}$ – they have amazing performance but are totally unsuitable for regulation
- Newer ΔΣ ADCs often have low latency filters, but these still commonly have delays of > $2T_{meas}$
- By implementing a cascaded sliding average filter in an FPGA we can produce a useable CIC filter with a delay of just $1.0\ T_{meas}$



4-stage CIC Filter coefficients

Regulation Period / Measurement Period

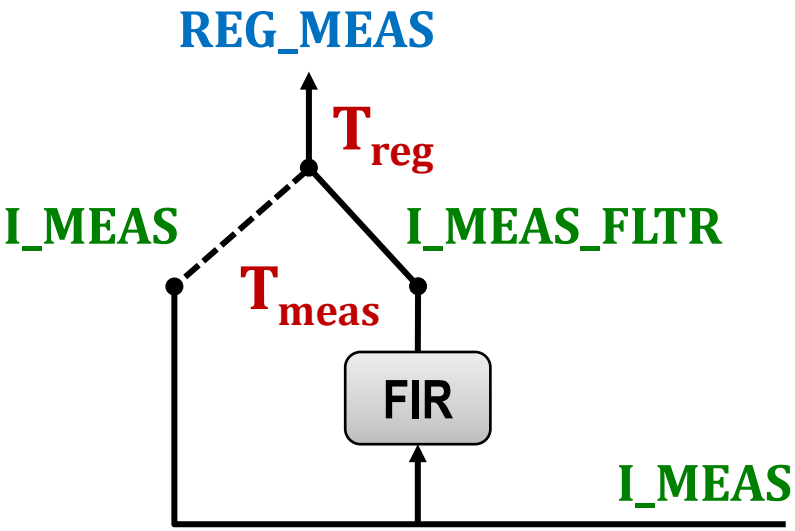


The current regulation period is typically greater than the measurement period:

Regulation period $T_{reg} = N\ T_{meas}$

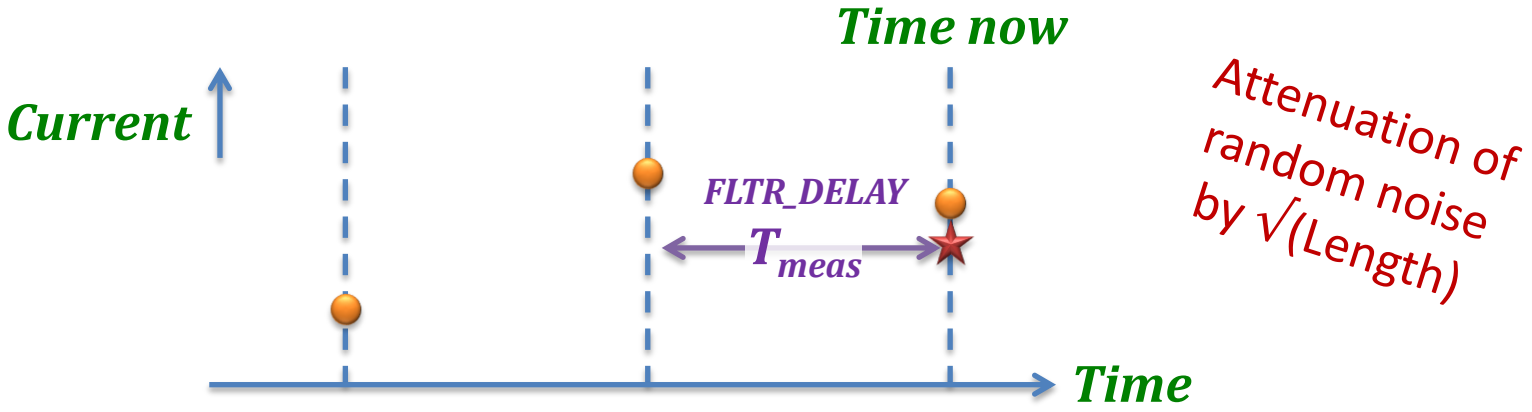
Measurement filter for regulation

Never filter more than necessary!



- To avoid noise being aliased into the regulation pass band, we may want to filter I_MEAS in the DSP
- The filter will run every iteration and is sampled for the regulation, every N^{th} iteration
- The simplest and fastest filter is a sliding average, which has a FIR and being symmetric, has a pure delay.

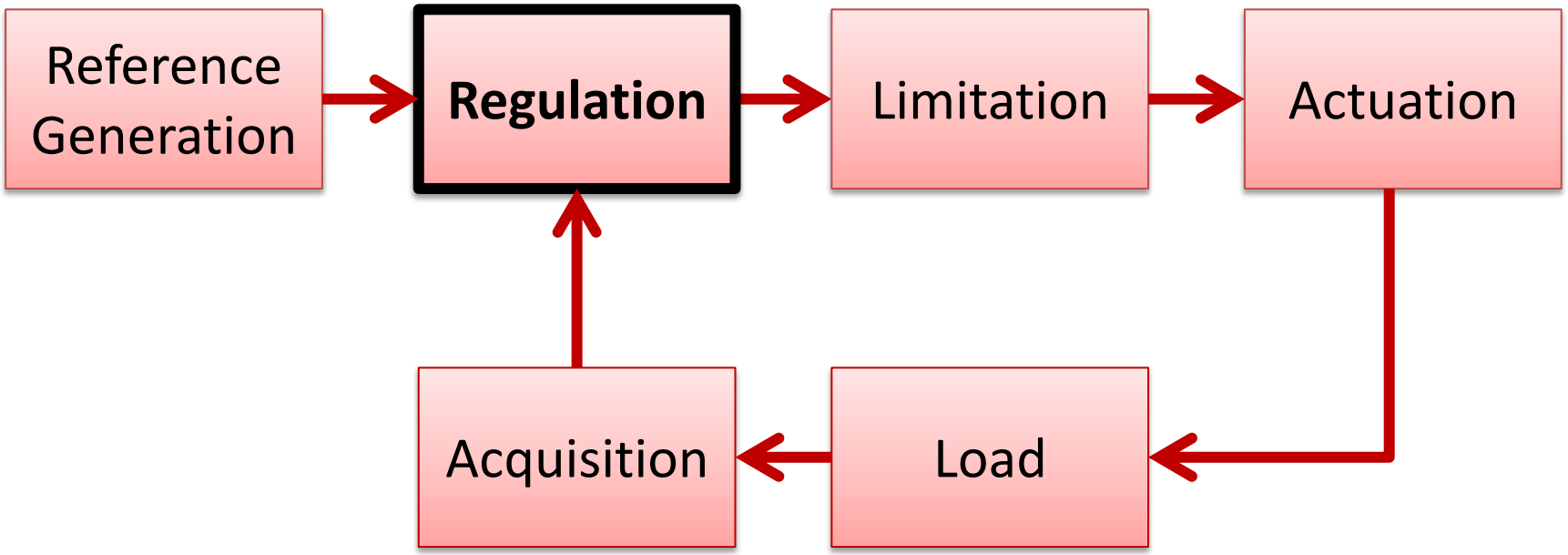
Measurement filter delay



- If the regulation period $T_{reg} = 3\ T_{meas}$ and we want the filter to be a sliding average of **3 samples** then the how **big is the delay**?
- In general, the delay for an FIR filter is the **Order/2** periods, where the order of the filter is the **length - 1**.
- If we cascade sliding average filters, we sum their delays

Delay = (L1 + L2 - 2) / 2

where L1 and L2 are the lengths of the two stages


Reference Generation
Regulation
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Acquisition

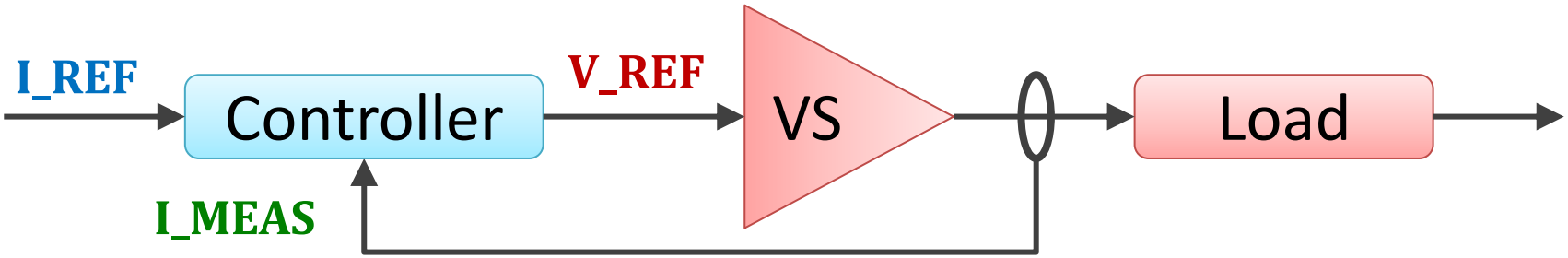
Regulation Variables

Regulation concerns three variables:

1. The **reference** – what you want
2. The **measurement** – what you have
3. The **actuation** – what you can control to make the measurement follow the reference

Regulation Variables

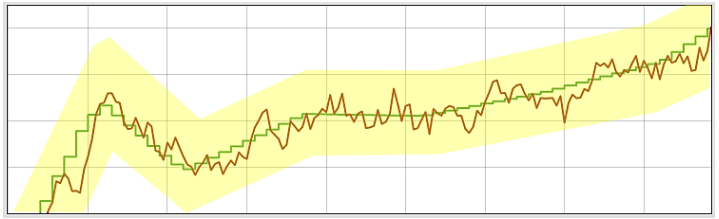
This presentation will refer to the CERN control model in which the reference and measurement concern the **circuit current** and the actuation is a **voltage reference.**



It is also possible for the actuation to be the firing reference for the PWM generators.

Identifying the regulation requirements

- In general, the objective of the regulator is to ensure that the current is within the acceptable limits from the reference value, *when required*
  - DC operation
  - Cycling operation
  - Pulsed operation



- Reject perturbations with the appropriate bandwidth
- Track the reference with the appropriate bandwidth
- There are many different operational scenarios and many possible regulation solutions

Classical regulation versus RST

Two digital approaches are widely used in accelerators

1. Digital implementation of a classical PID

```
error = ref – meas;
act   = p->t_direct_gain * error +
        p->t_output_gain * p->t_state +
        p->i_output_gain * p->i_state;

/*--- Update integral state unless antiwindup active ---*/

if(p->antiwindup)
{
    p->i_state = p->i_state_last;
}
else
{
    p->i_state_last = p->i_state;
    p->i_state      = p->i_state_gain * p->i_state +
                      p->i_input_gain * error;
}

/*--- Update proportional + derivative state ---*/

p->t_state = p->t_state_gain * p->t_state +
             p->t_input_gain * error;
```

- History is stored in state variables
- Load model is NOT included
- Typically the actuation is the firing reference

Classical regulation versus RST

2. Digital implementation using RST algorithm

```
var_idx = vars->history_index;

act = pars->rst.t[0] * ref - pars->rst.r[0] * meas;

for(par_idx = 1 ; par_idx < REG_N_RST_COEFFS ; par_idx++)
{
    var_idx = (var_idx - 1) & REG_RST_HISTORY_MASK;

    act += pars->rst.t[par_idx] * vars->ref [var_idx] -
           pars->rst.r[par_idx] * vars->meas[var_idx] -
           pars->rst.s[par_idx] * vars->act [var_idx];
}

act = act * pars->inv_s0;

var_idx = vars->history_index;
vars->history_index = (vars->history_index + 1) &
                       REG_RST_HISTORY_MASK;

vars->ref [var_idx] = ref;
vars->meas[var_idx] = meas;
vars->act [var_idx] = act;
```

- History is stored in circular buffers
- Load model is included in RST parameters
- The actuation is voltage reference

Classical regulation verses RST

- The classical PID is simpler to tune as there are only a few parameters
  - By using a load model, it is possible to add feed-forward to improve the PID controller performance
  - Running the PID very fast can reduce the tracking delay
- The RST method offers more deterministic tracking
  - An algorithm can (must) calculate the RST coefficients for specific applications such as control of current in a magnet circuit
  - The RST method is wonderfully flexible

Example algorithm to calculate RST coefficients

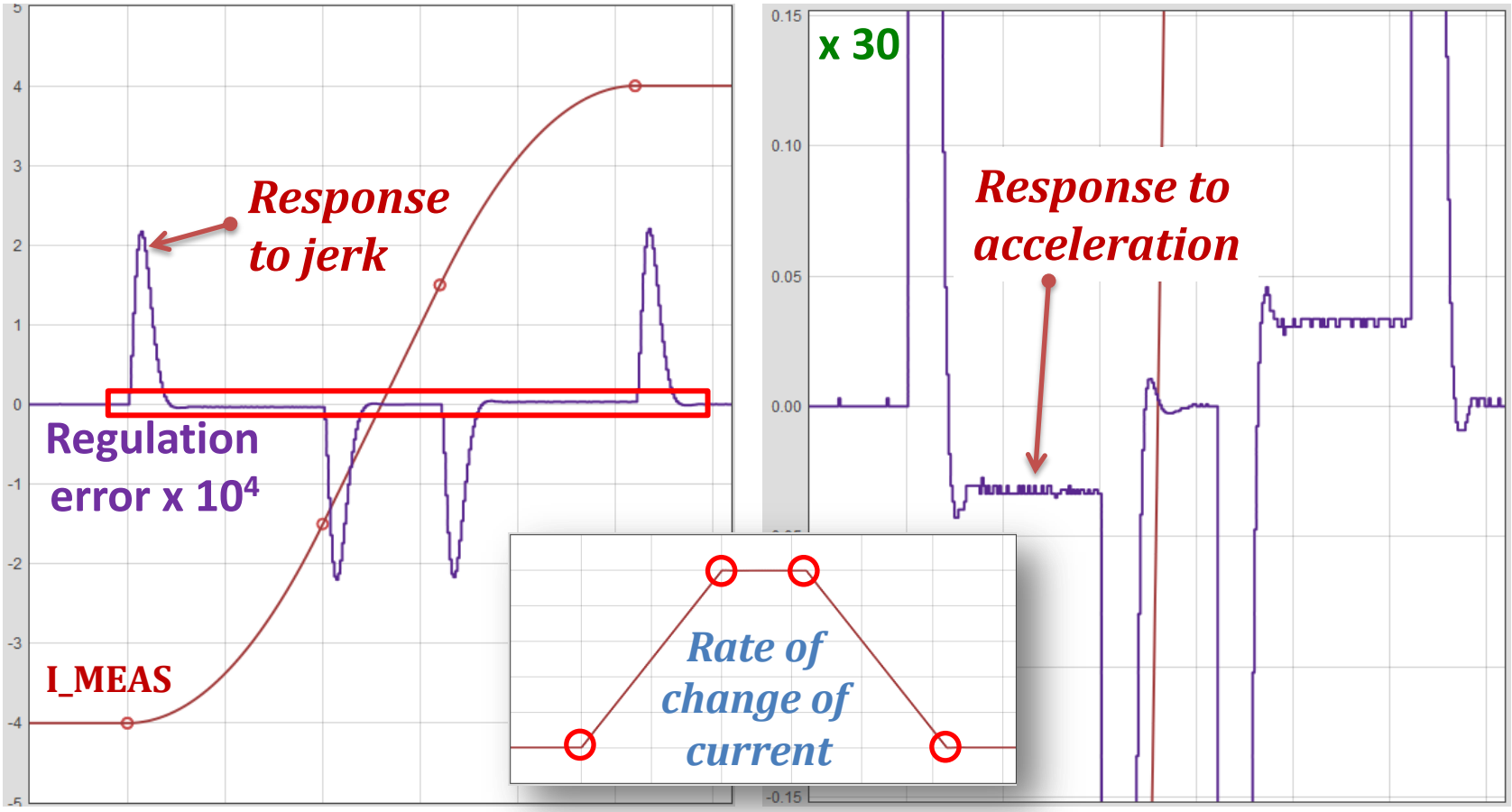
```
t1 = -pars->period / load->tc;
a1 = -exp(t1);
a2 = 1.0 + a1;

b0_b1 = 0.0;
b0_b1 = load->gain1 * a2;
b0 = b0_b1 * (2.0 - pars->pure_delay_periods);
b1 = b0_b1 * (pars->pure_delay_periods - 1.0);

c1 = -exp(-pars->period * TWO_PI * clbw);
q1 =  exp(-pars->period * TWO_PI * clbw2 * z);
d1 = -2.0 * q1 * cos(pars->period * TWO_PI * clbw2 * sqrt(1.0 - z * z));
d2 =  q1 * q1;
c2 = exp(-pars->period * TWO_PI * clbw3);

pars->rst.r[0] = (4*a1 + 2*c1 + 2*c2 + 2*d1 + d2 + 3*a1*c1 + 3*a1*c2 + 3*a1*d1 + 2*a1*d2 + c1*c2 + c1*d1 + c2*d1 + 2*a1*c1*c2 + 2*a1*c1*d1 + a1*c1*d2 + 2*a1*c2*d1 +
                  a1*c2*d2 - c1*c2*d2 + a1*c1*c2*d1 + 3)/(b0_b1*(a1 + 1)*(a1 + 1)) + (b1*(c1 + 1)*(c2 + 1)*(d1 + d2 + 1))/(b0_b1*b0_b1*(a1 + 1)) -
                  (a1*(a1 - c1)*(a1 - c2)*(a1*a1 - d1*a1 + d2))/((a1 + 1)*(a1 + 1)*(b1 - a1*b0));

pars->rst.r[1] = (c1*d2 - c2 - d1 - c1 + c2*d2 + 3*a1*a1*c1 + 3*a1*a1*c2 + 3*a1*a1*d1 + 2*a1*a1*d2 + 4*a1*a1 + c1*c2*d1 + 2*c1*c2*d2 + 2*a1*a1*c1*c2 + 2*a1*a1*c1*d1 +
                  a1*a1*c1*d2 + 2*a1*a1*c2*d1 + a1*a1*c2*d2 + a1*a1*c1*c2*d1 - 2)/(b0_b1*(a1 + 1)*(a1 + 1)) + (2*a1*(a1 - c1)*(a1 - c2)*(a1*a1 - d1*a1 + d2))/
                 ((a1 + 1)*(a1 + 1)*(b1 - a1*b0)) + (b1*(a1 - 1)*(c1 + 1)*(c2 + 1)*(d1 + d2 + 1))/(b0_b1*b0_b1*(a1 + 1));

pars->rst.r[2] = (a1*(2*a1 + a1*c1 + a1*c2 + a1*d1 - a1*a1 - c1*c2*d2)*b0*b0 + a1*(4*a1 - c1 - c2 - d1 + 2*a1*c1 + 2*a1*c2 + 2*a1*d1 + c1*d2 + c2*d2 - 2*a1*a1 +
                  c1*c2*d1 - 2)*b0*b1 - a1*(2*c1 - 2*a1 + 2*c2 + 2*d1 + d2 - a1*c1 - a1*c2 - a1*d1 + c1*c2 + c1*d1 + c2*d1 + a1*a1 + 3)*b1*b1)/(b0_b1*b0_b1*(b1 - a1*b0));

q1 = 2.0 - a1 + c1 + c2 + d1;
q2 = (b1*(c1 + c2 + d1 - c1*d2 - c2*d2 - c1*c2*d1 - 2*c1*c2*d2 + 2) +
       a1*b1*(2*c1 + 2*c2 + 2*d1 + d2 + c1*c2 + c1*d1 + c2*d1 - c1*c2*d2 + 3))/(b0_b1*(a1 + 1)*(a1 + 1)) +
      (b1*b1*(c1 + 1)*(c2 + 1)*(d1 + d2 + 1))/(b0_b1*b0_b1*(a1 + 1)) +
      (b1*(a1 - c1)*(a1 - c2)*(a1*a1 - d1*a1 + d2))/((a1 + 1)*(a1 + 1)*(b1 - a1*b0));

pars->rst.s[0] = 1.0;
pars->rst.s[1] = q1 - 2.0;
pars->rst.s[2] = q2 - 2.0*q1 + 1.0;
pars->rst.s[3] = q1 - 2.0*q2;
pars->rst.s[4] = q2;

pars->rst.t[0] = 1.0 / b0_b1;
pars->rst.t[1] = (c1 + c2 + d1) / b0_b1;
pars->rst.t[2] = (d2 + c1*c2 + c1*d1 + c2*d1) / b0_b1;
pars->rst.t[3] = (c1*d2 + c2*d2 + c1*c2*d1) / b0_b1;
pars->rst.t[4] = c1*c2*d2 / b0_b1;
```

Types of controller

Type of controller	Steady state	Linear ramp	Parabolic ramp
P	Error	Error	Error
PI	No error	Error	Error
PII	No error	No error	Error
PIII	No error	No error	No error

- The RST algorithm can implement any of these algorithms (and many others) just by the choice of coefficients.
- Experiments with the PIII didn't reveal any advantage over the PII because the tracking error during a parabolic ramp is very small compared to the response to the jerks at the start and end of the parabolas.

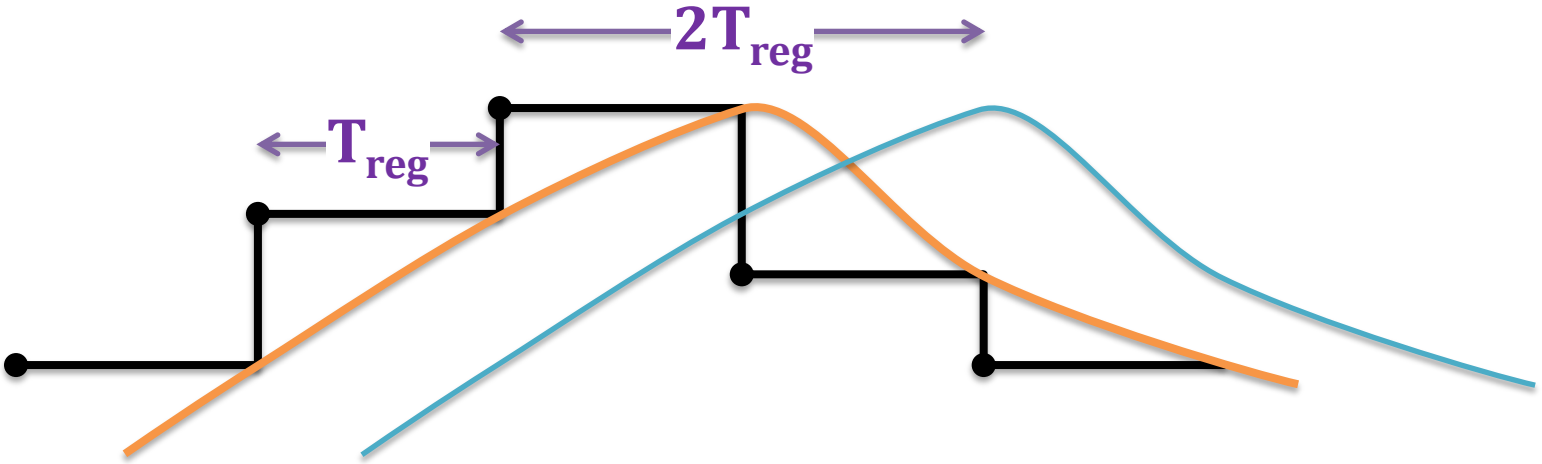
Example of PII controller regulation error



In this example, the peak error due to the jerk in acceleration is over 50 times greater than the error due to the acceleration itself.

Dead-beat control

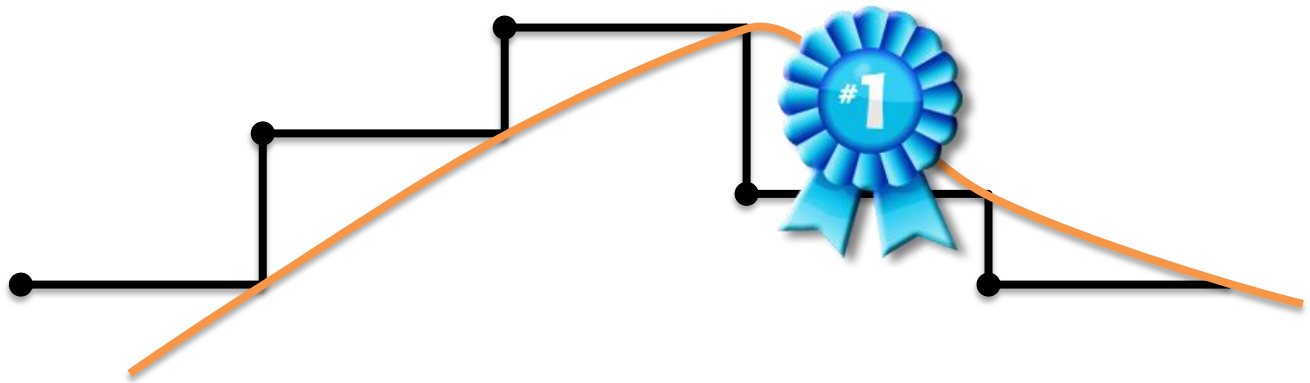
- A dead-beat controller will drive the system so that the measurement equals the reference after an **integer number of regulation periods**.



- A dead-beat controller with a track delay of 1 period is the gold standard – you cannot do better.

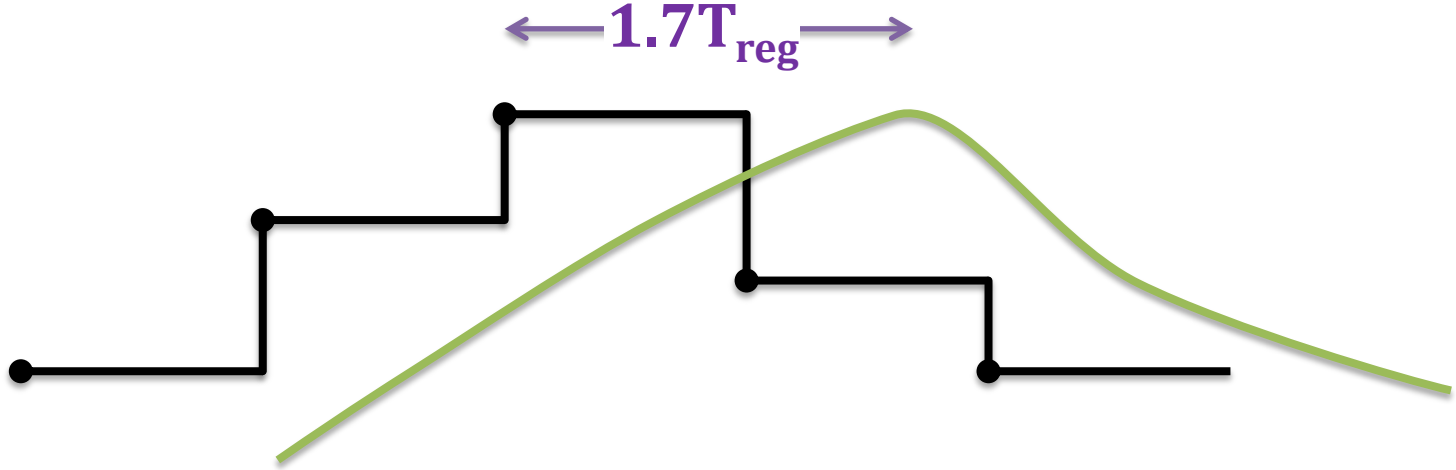
Dead-beat control

- The system must be linear and very well modelled for the bandwidth of interest
- The poles of the closed-loop transfer function must be at the origin on the z-plane
- A dead-beat controller will be more sensitive to noise on the measurement than a non-dead-beat controller



Non-dead-beat control

- With a PII regulator, it is possible to have a non-dead-beat controller that still has a **constant** but **non-integer** tracking delay during ramps



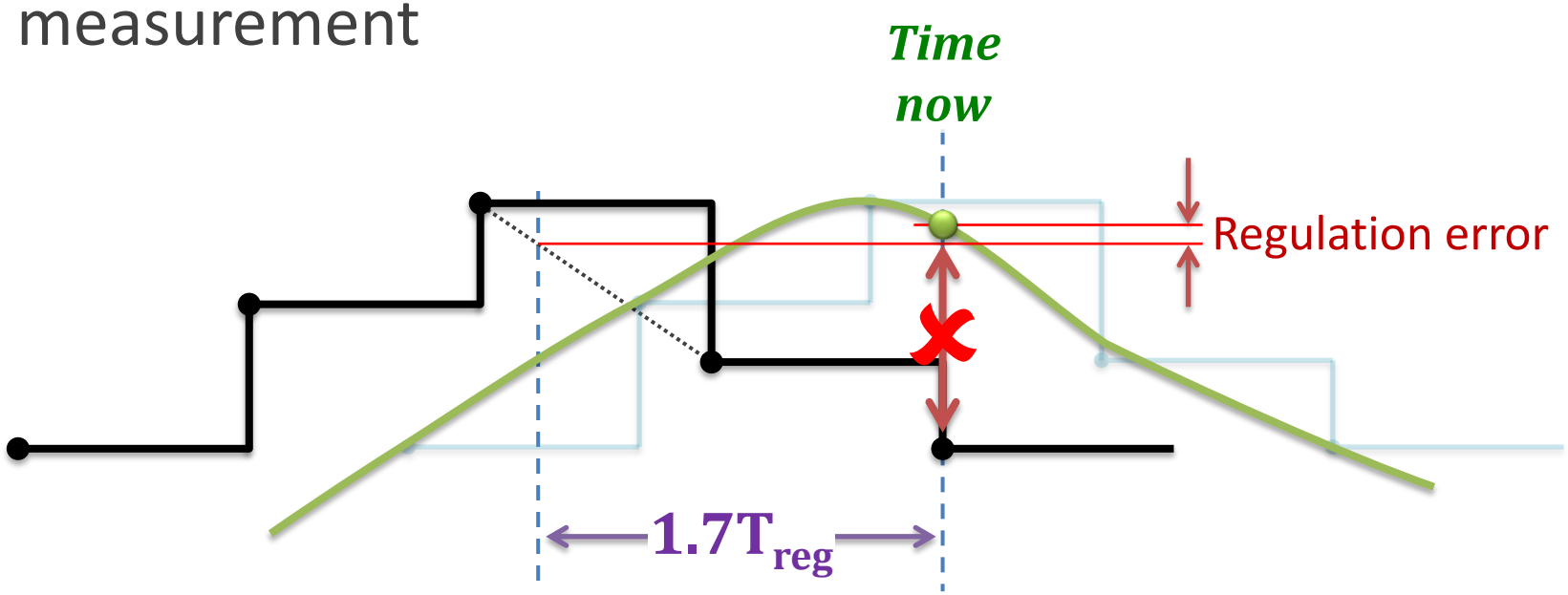
- When implemented using an RST algorithm, a non-dead-beat controller is less sensitive to noise

Does the Tracking Delay matter?

- If the reference is pre-defined then no – the reference function can be played in advance so that the response follows the user's reference
- If the reference is not pre-defined, then the tracking delay may need to be minimised
- If the converter is an actuator for beam orbit or tune feedback, then our current regulation tracking delay is going to affect the bandwidth of this outer beam feedback loop

Regulation Error

- The regulation error is not the difference between the reference and measurement!
- The regulation error is the difference between the reference ***shifted by the tracking delay*** and the measurement

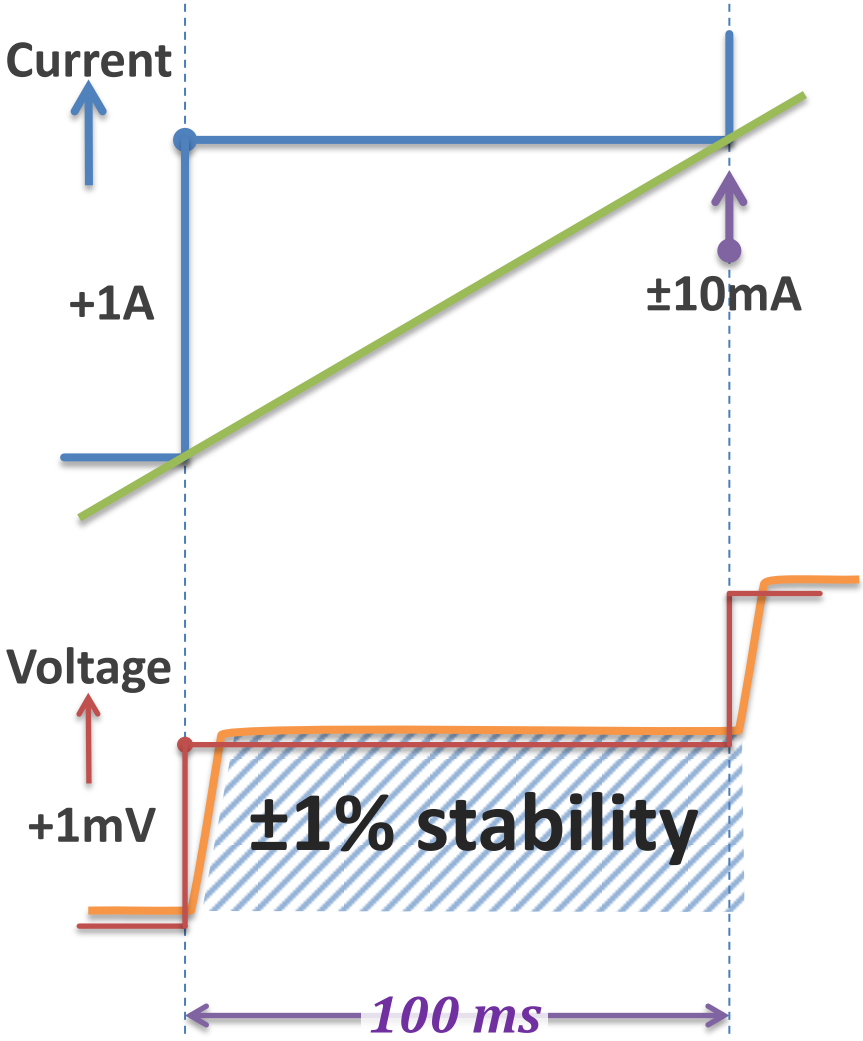


Regulation Error

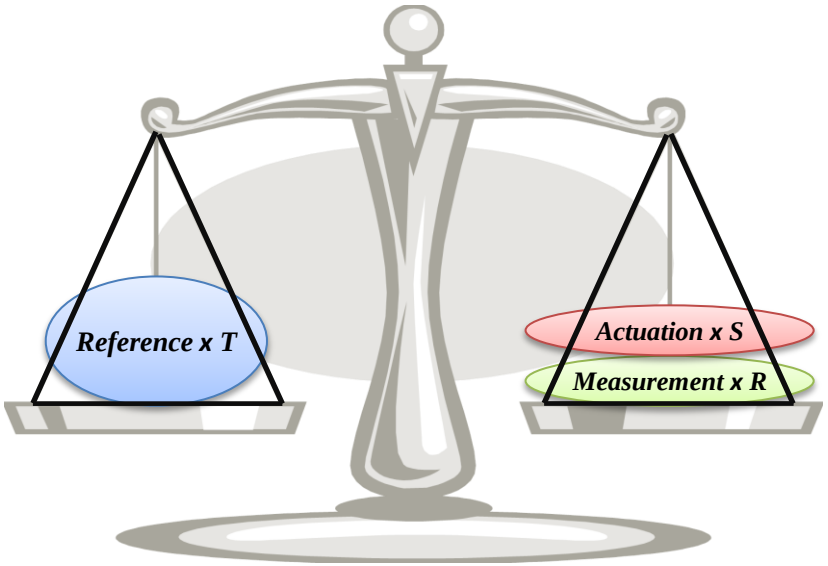
- The regulation error can be calculated at the regulation period or the measurement period if tighter surveillance is necessary
- Once the regulation error is known, warning and fault limits can be checked and potentially the converter can be stopped if the regulation is unstable

Requirements for the Voltage Loop

- In the LHC, the main super-conducting circuits are very slow:
  - L = 15 H, R = 1 mΩ, τ_m= ~4 Hours.
- The bandwidth for the rejection of perturbations is 1 Hz:
  - Regulation period is 100 ms.
- The p-p regulation error is less than 2 ppm of nominal:
  - ±10mA on 11kA
- Voltage source stability must be around 1% from period to period.



The RST is all about balance



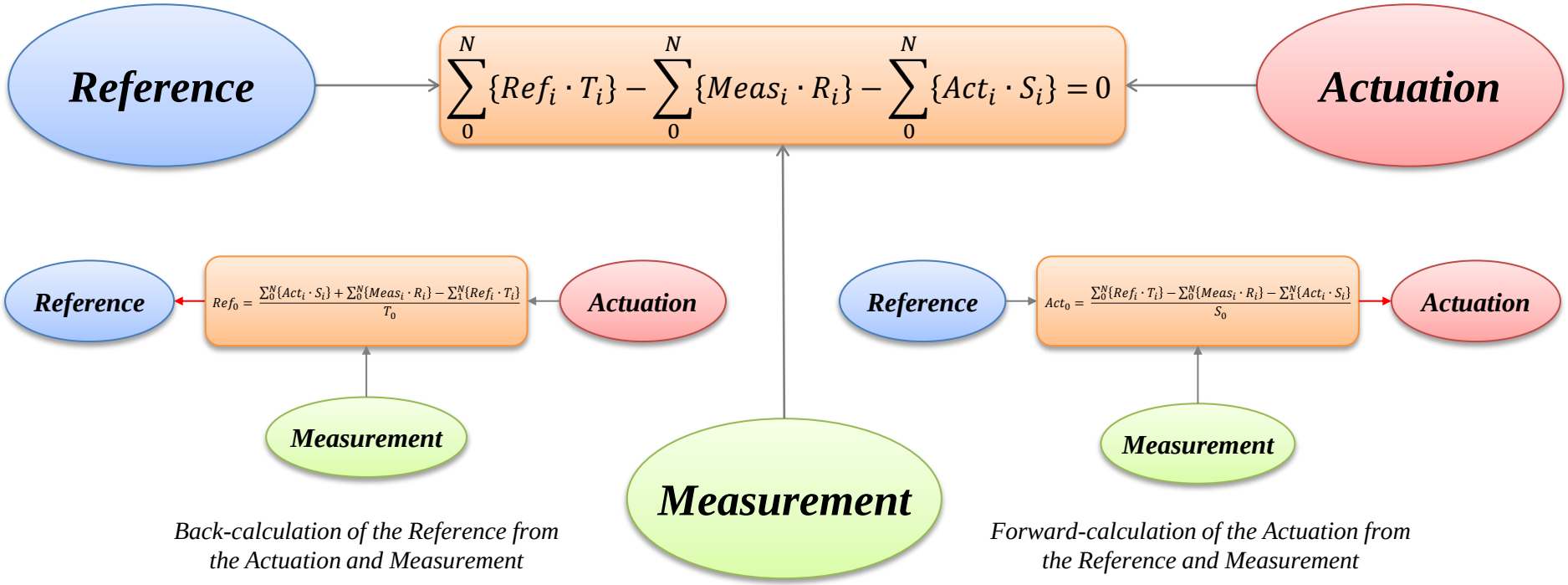
Reference

$$\sum_{0}^{N}\{Ref_i \cdot T_i\} - \sum_{0}^{N}\{Meas_i \cdot R_i\} - \sum_{0}^{N}\{Act_i \cdot S_i\} = 0$$

Actuation

Measurement

Using the RST algorithm

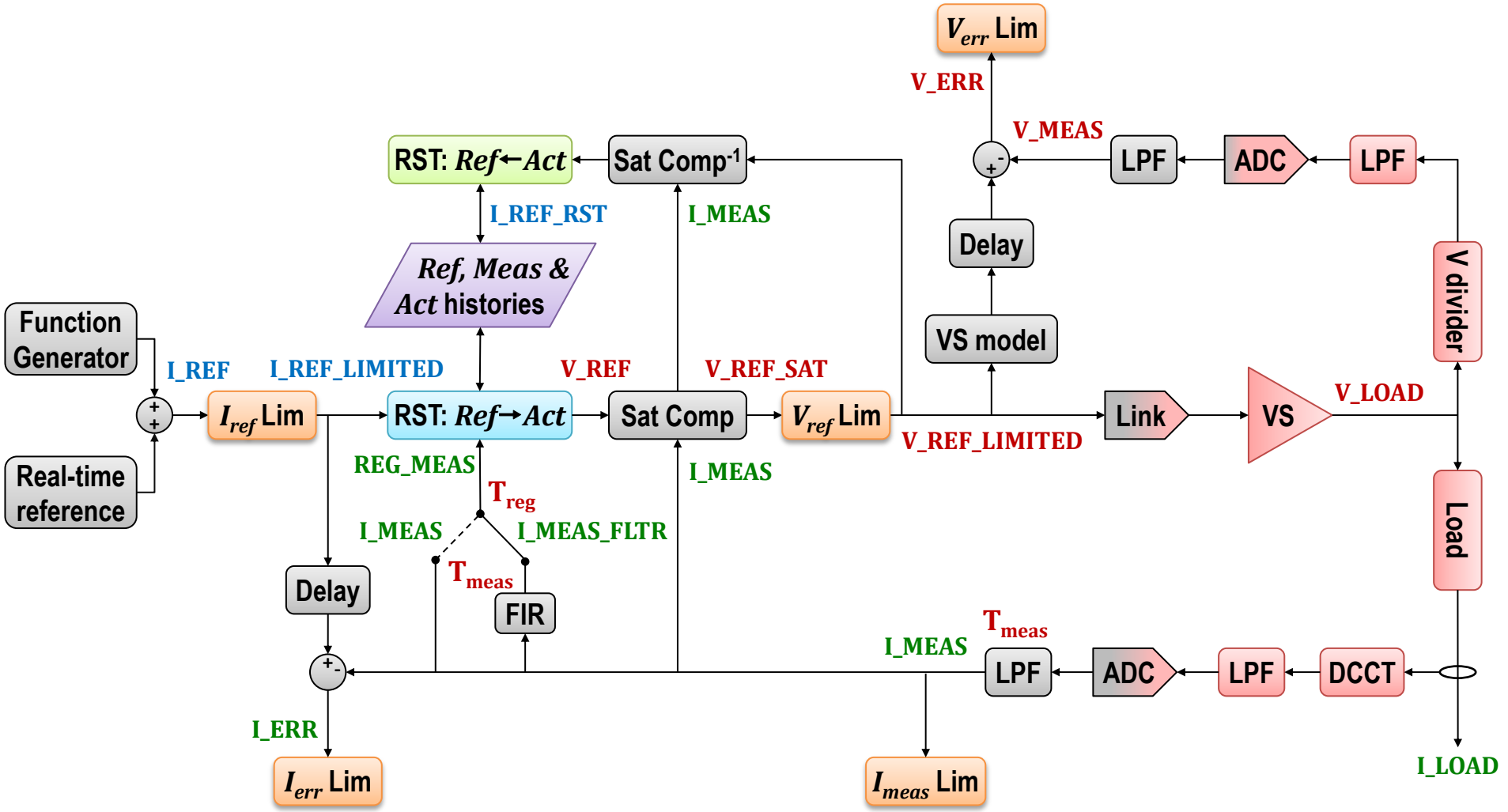


Back-calculation of the Reference from the Actuation and Measurement

Forward-calculation of the Actuation from the Reference and Measurement

Back-calculation of the reference provides a simple way to implement anti-windup behaviour.

Example of Current Regulation using the RST algorithm



Magnet Saturation

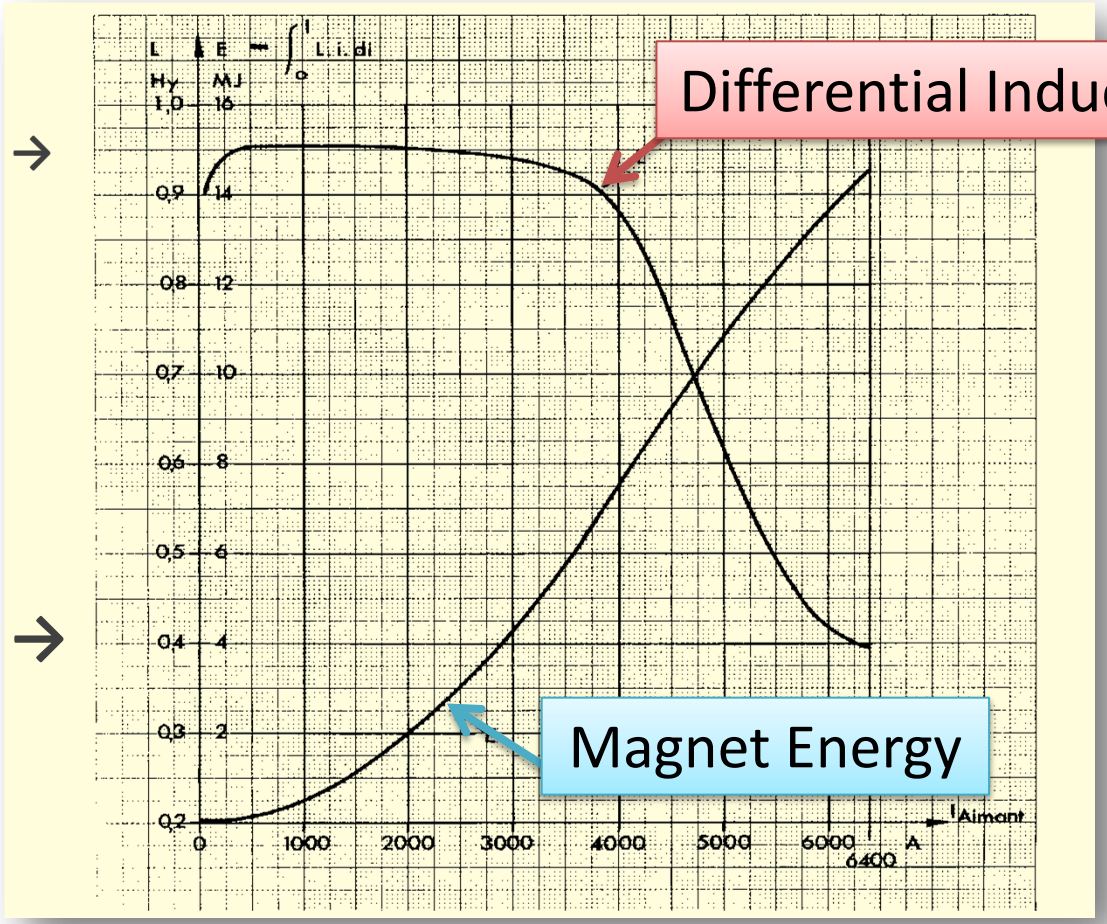
- Our governing equation is:

$$V = IR + L\frac{dI}{dt}$$

  where L is the differential inductance.
- What to do when the inductor's iron starts to saturate (B > 1T)?
- The differential inductance will fall which can lead to instability
- Solution 1: reduce the bandwidth and accept poor performance
- Solution 2: change the controller parameters as a function of current
- Solution 3: hide the change in inductance from the controller

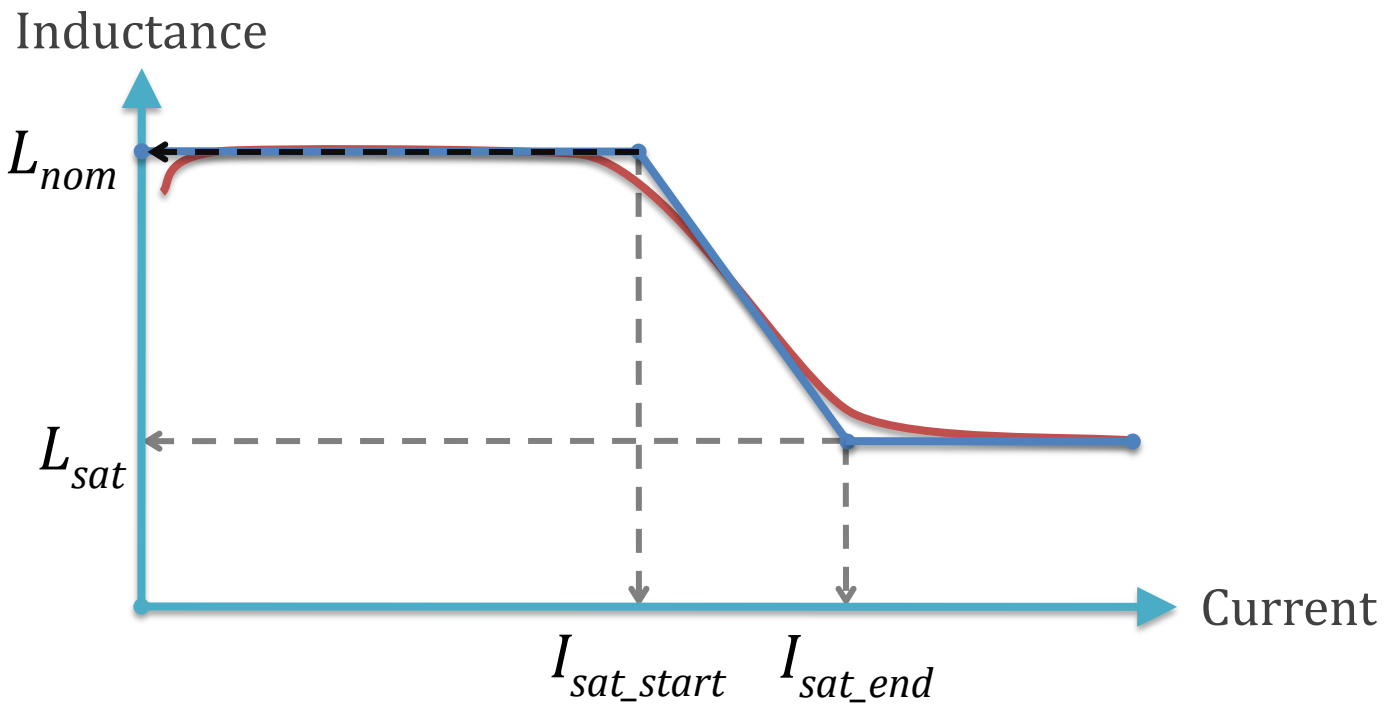
Magnet Saturation : CERN PS Main Magnets

Differential Inductance drops by 60%



O. Bayard, "La nouvelle alimentation de l'aimant du synchroton à protons du CERN, Fascicule 2: description des composants", CERN 71-20, September 1971.

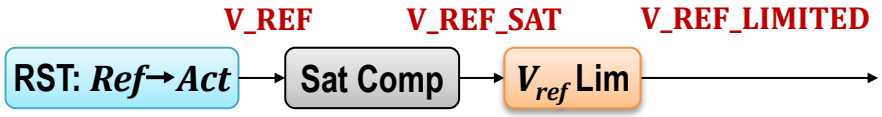
Magnet Saturation



- Simple 3-segment linear model: $L(I)=f(I).L_{nom}$
- Defined by four parameters: L_{nom} L_{sat} I_{sat_start} I_{sat_end}

Magnet Saturation

- Controller actuation pathway:

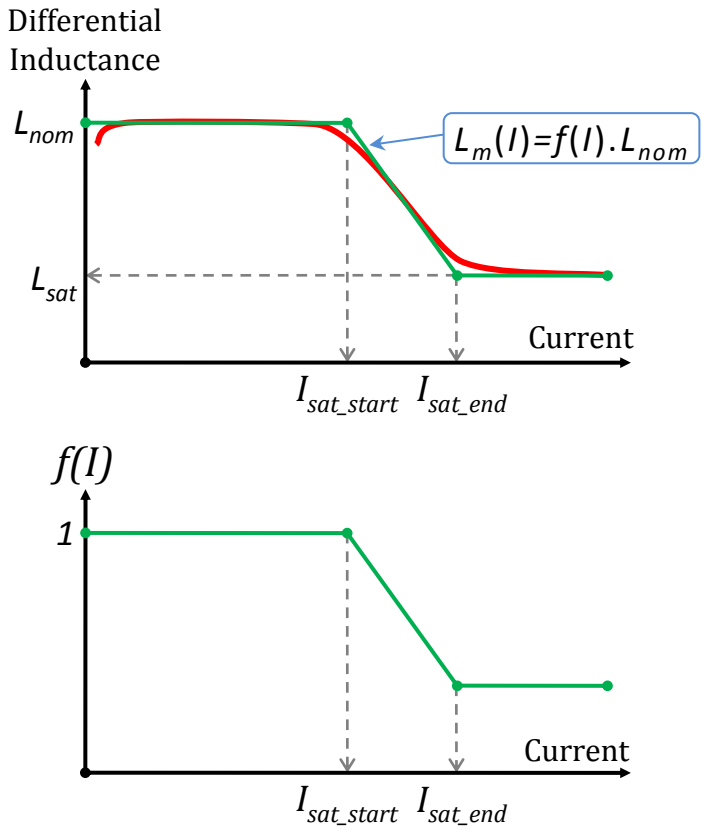


- To calculate V_REF_SAT:

$$V_{ref} = IR + L_{nom}\frac{dI}{dt}$$

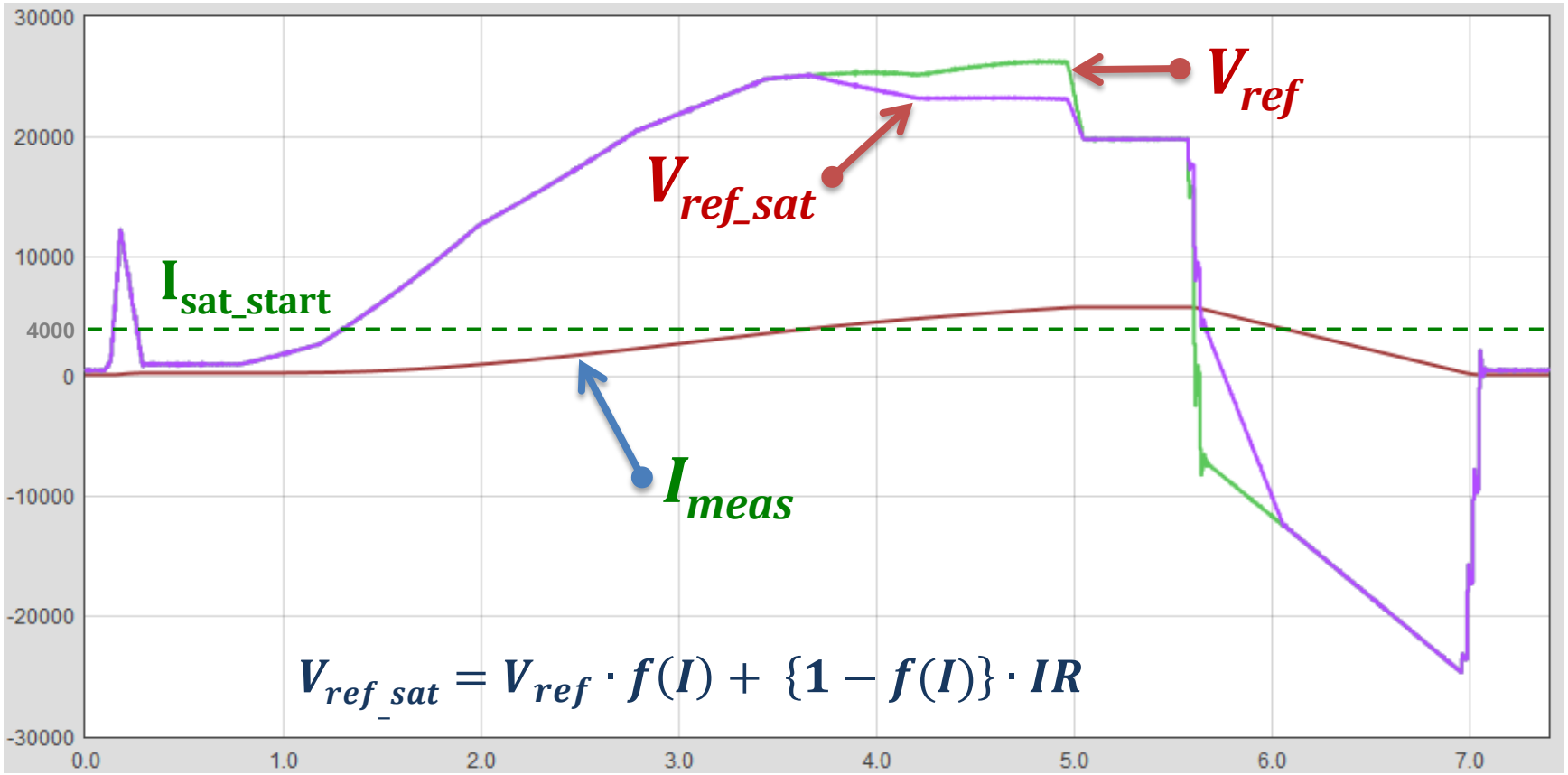
$$V_{ref\_sat} = IR + f(I)\cdot L_{nom}\frac{dI}{dt}$$

$$V_{ref\_sat} = IR + f(I)\cdot\{V_{ref} - IR\}$$



$$V_{ref\_sat} = V_{ref}\cdot f(I) + \{1 - f(I)\}\cdot IR$$

Example of Saturation Compensation



Calculating the RST coefficients

- The RST algorithm can implement any linear regulator up to the order defined by the number of coefficients minus 1
- Simply changing the coefficients can change the type of regulator (PI, PID, PII, …) and/or the load model
- No code needs to change! ☺

The challenge is to calculate the coefficients!

Calculating the RST coefficients

- For an arbitrary load, a control theory expert must perform an analysis to define the load model and the appropriate controller
- Then they must calculate the RST coefficients (generally using Matlab) for each instance of that type of load

- This is not practical for an accelerator with lots of circuits!

Calculating the RST coefficients

- For a standard first order magnet load, the control theory experts were able to create an algorithm that could be implemented in C, which calculates the coefficients for any instance of that type of load.

- So far, this was only possible by ignoring the dynamics of the voltage source and measurement filtering.
- This limits the bandwidth possible with the resulting controller to about 10% of the regulation frequency

Regulation Loop Delays

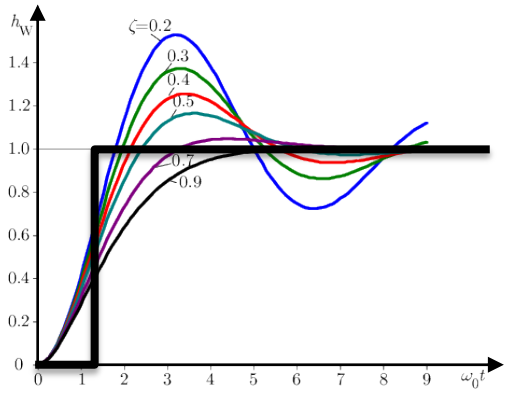
- At the moment, we have five variants of the RST coefficient calculation algorithm, which work with different ranges of **pure loop delay.**

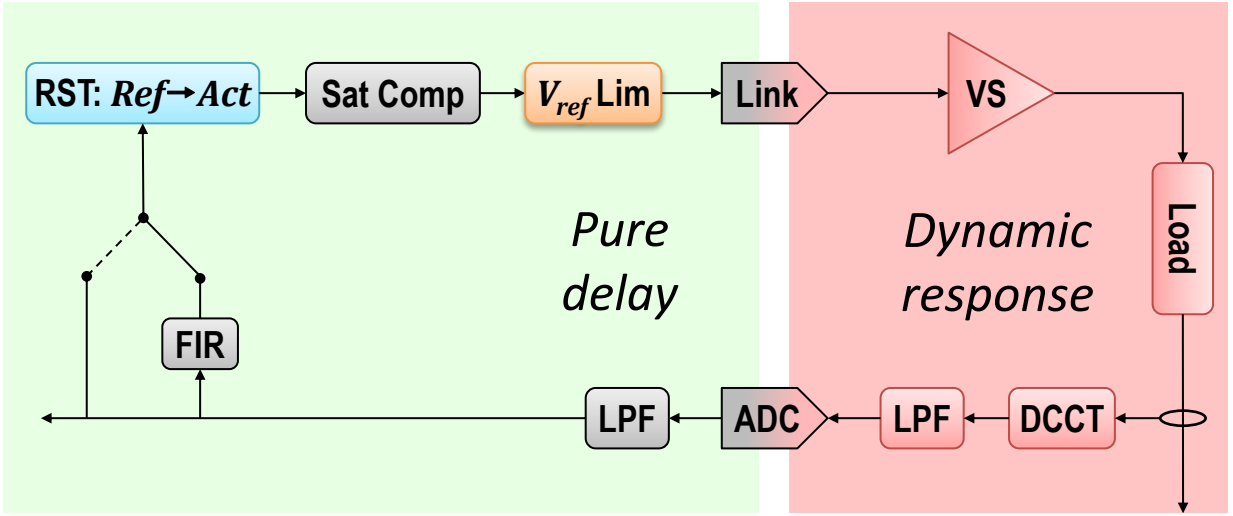
- What is the **pure loop delay**?

- The **pure loop delay** is the sum of the **approximate** delays of all elements in the regulation loop which are not included in the load model

Contributions to Pure Delay

Some delays really are “pure”, while others are really a dynamic response that we have to approximate by a step response:





Only **symmetric** digital FIR filters have a really pure delay.
More exotic digital filters will have a non-linear phase response.

Contributions to Pure Delay

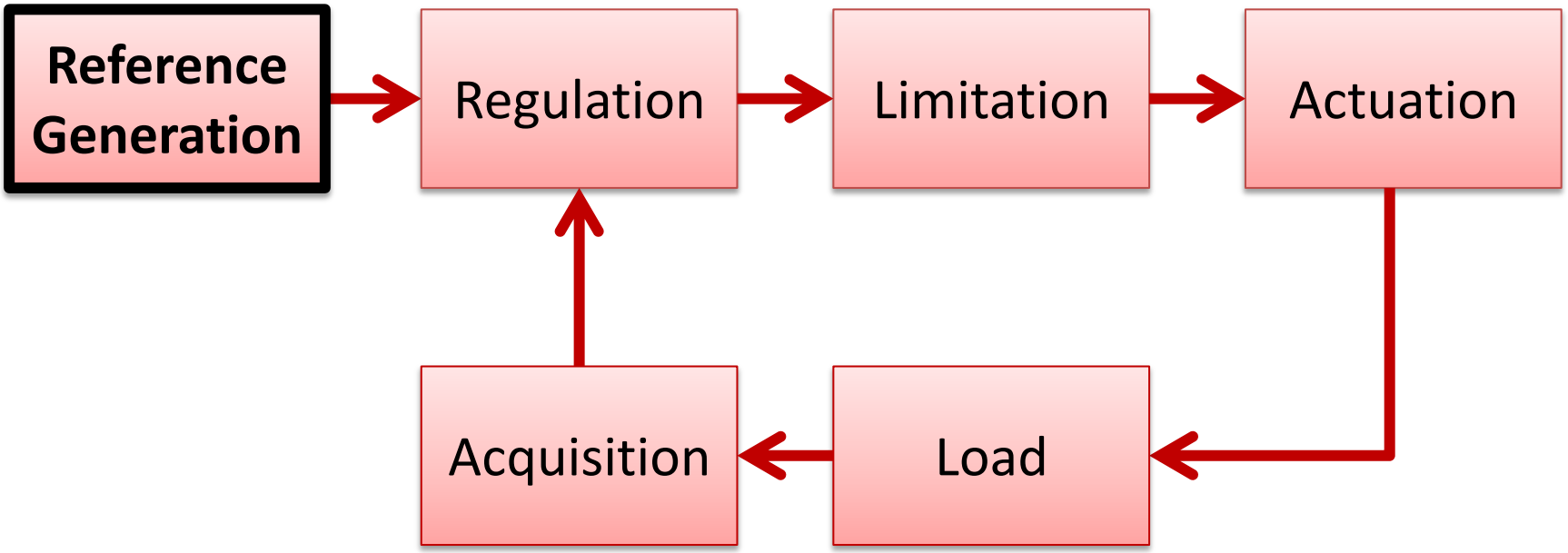
Loop element	Response	Contribution to PURE DELAY	Comments
DSP algorithm	Pure delay	V_REF_DELAY	Rounded up to worst case
DAC	First order		High bandwidth so insignificant
Voltage source	Second order	VS_STEP_RSP_TIME	Calculated from model
DCCT	First order	I_MEAS_DELAY	High bandwidth so insignificant
Analogue LPF	First order		Typically a third of one iteration
ADC conversion	Pure delay		Insignificant for Delta-Sigma ADC
FPGA FIR	Pure delay		Typically one iteration
DSP FIR	Pure delay	FLTR_DELAY	(Order - 1) / 2

PURE_DELAY = V_REF_DELAY + VS_STEP_RSP_TIME + I_MEAS_DELAY + FLTR_DELAY

Pure Delay and Tracking Delay

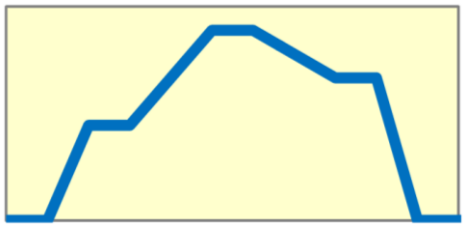
- At the moment, we have five different algorithms to calculate the RST coefficients
- Each algorithm works with a range of pure delay

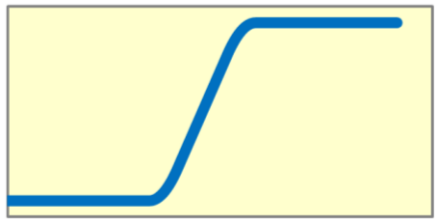
Algorithm	Pure delay	Dead-beat	Tracking delay
1	0.0 – 0.4 T	Yes	1.0
2	0.4 – 0.99 T	No	1 + PURE_DELAY
3	1.0 – 1.4 T	Yes	2.0
4	1.4 – 1.99 T	No	1 + PURE_DELAY
5	2.0 – 2.4 T	Yes	3.0


Reference Generation
Regulation
Limitation
Actuation
Load
Acquisition

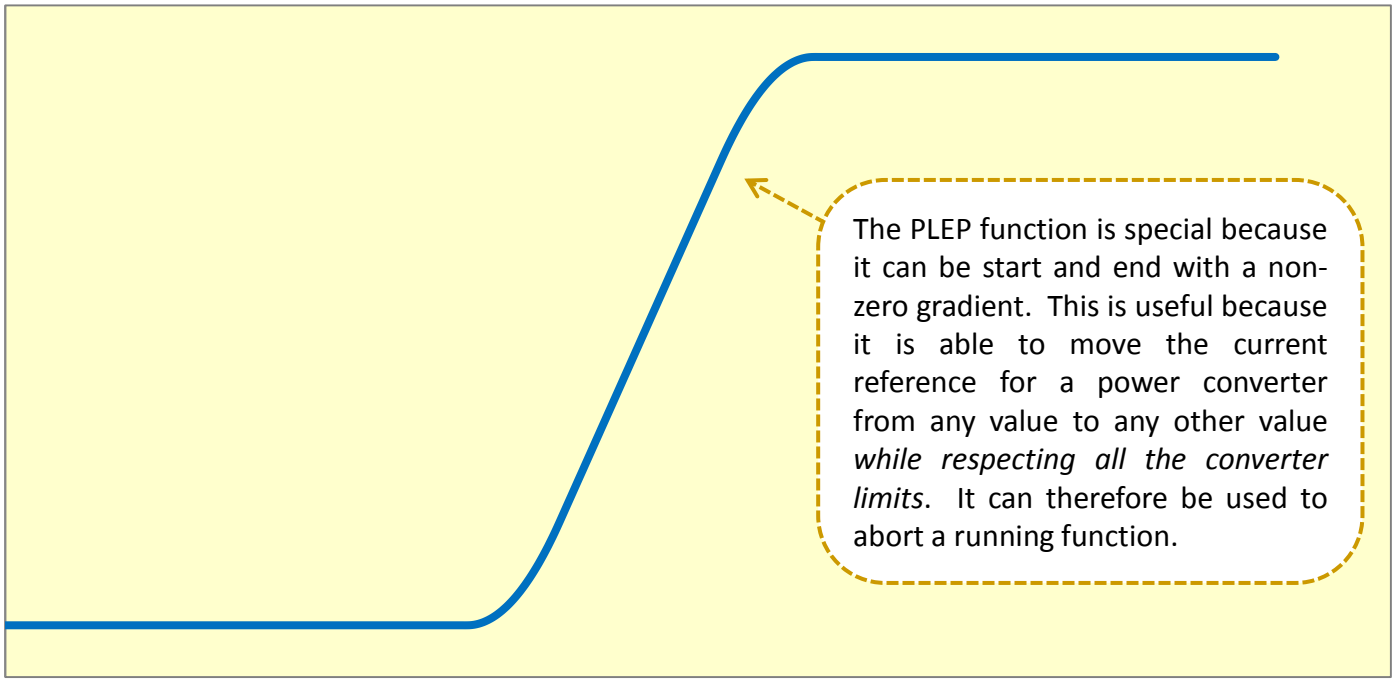
Reference Generation

- There are many operational scenarios requiring different types of reference generation:
  - DC set point
  - Cycling operation with just one reference function
  - Cycling operation with different reference functions
  - Ramping operation with no persistent functions
- The standard function is a linearly interpolated table
- Parametric functions can also be useful

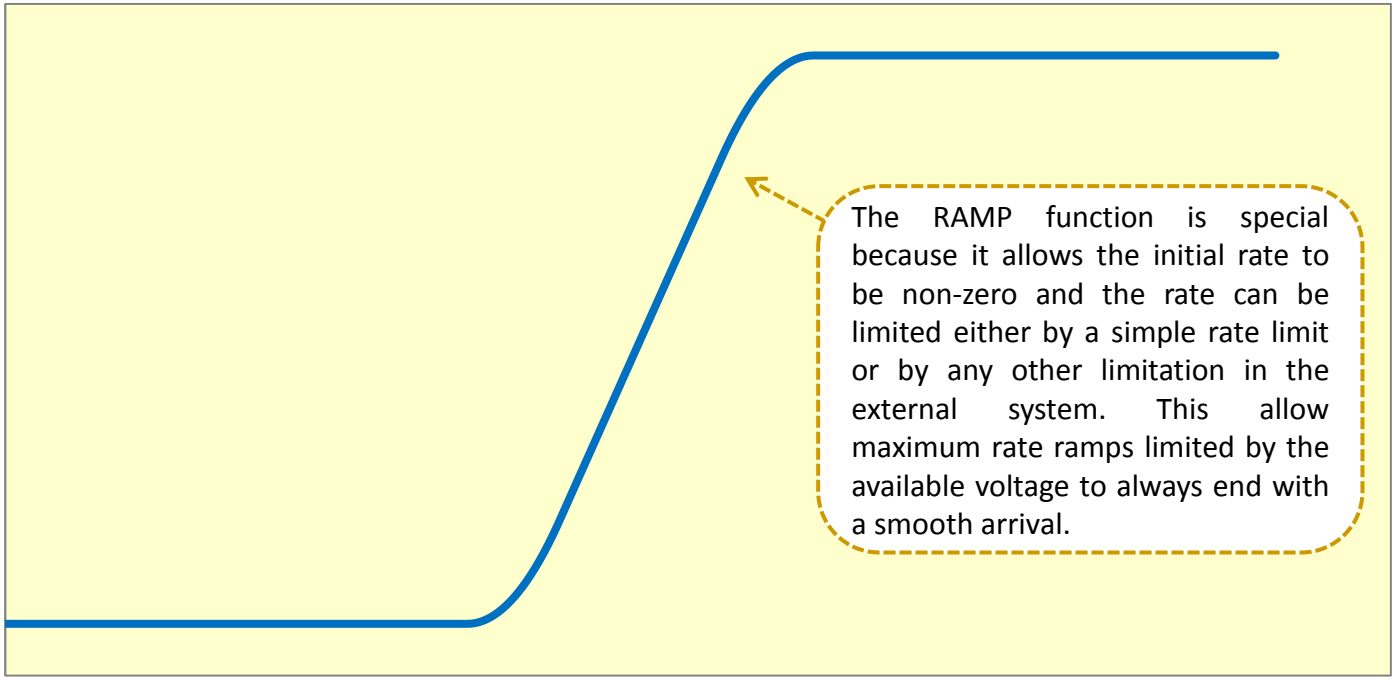




PLEP


The PLEP function is special because it can be start and end with a non-zero gradient. This is useful because it is able to move the current reference for a power converter from any value to any other value *while respecting all the converter limits*. It can therefore be used to abort a running function.

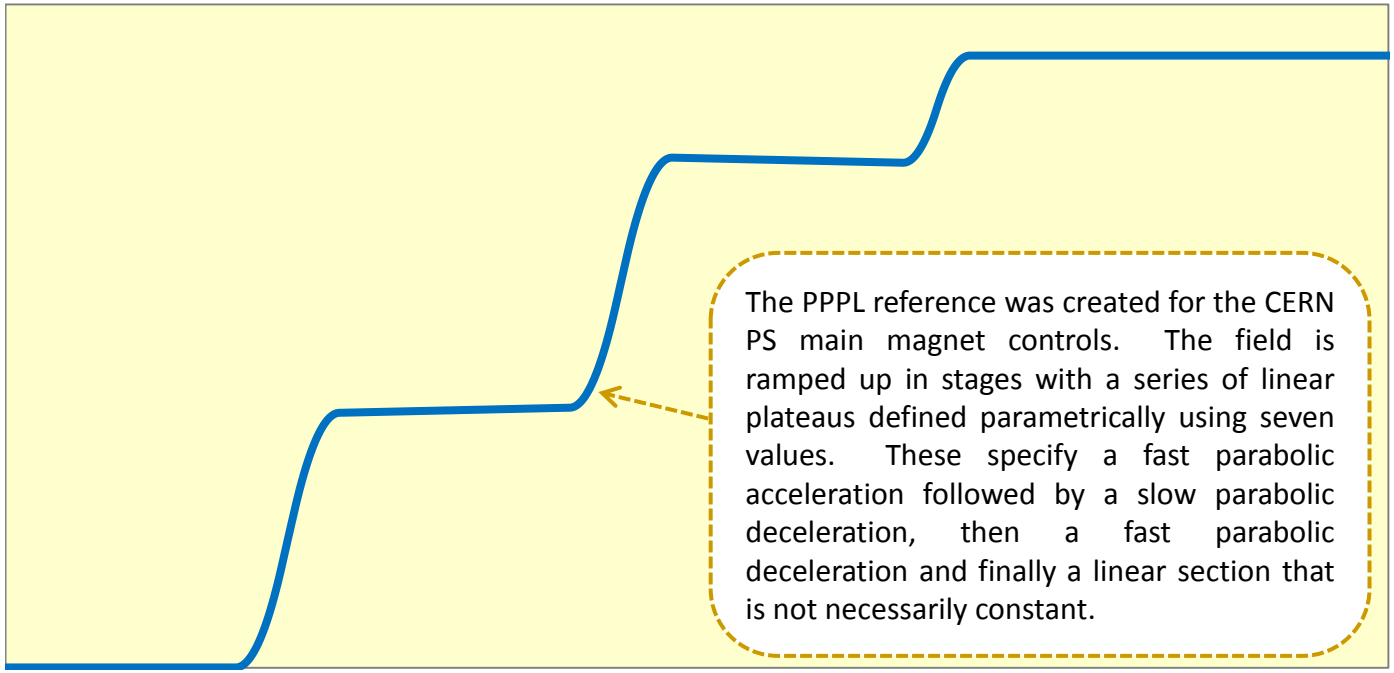
RAMP


The RAMP function is special because it allows the initial rate to be non-zero and the rate can be limited either by a simple rate limit or by any other limitation in the external system. This allow maximum rate ramps limited by the available voltage to always end with a smooth arrival.

PULSE

PULSE is the standard reference used for transfer lines where the field must be correct only for the time when the beam is passing.

PPPL


The PPPL reference was created for the CERN PS main magnet controls. The field is ramped up in stages with a series of linear plateaus defined parametrically using seven values. These specify a fast parabolic acceleration followed by a slow parabolic deceleration, then a fast parabolic deceleration and finally a linear section that is not necessarily constant.

TABLE

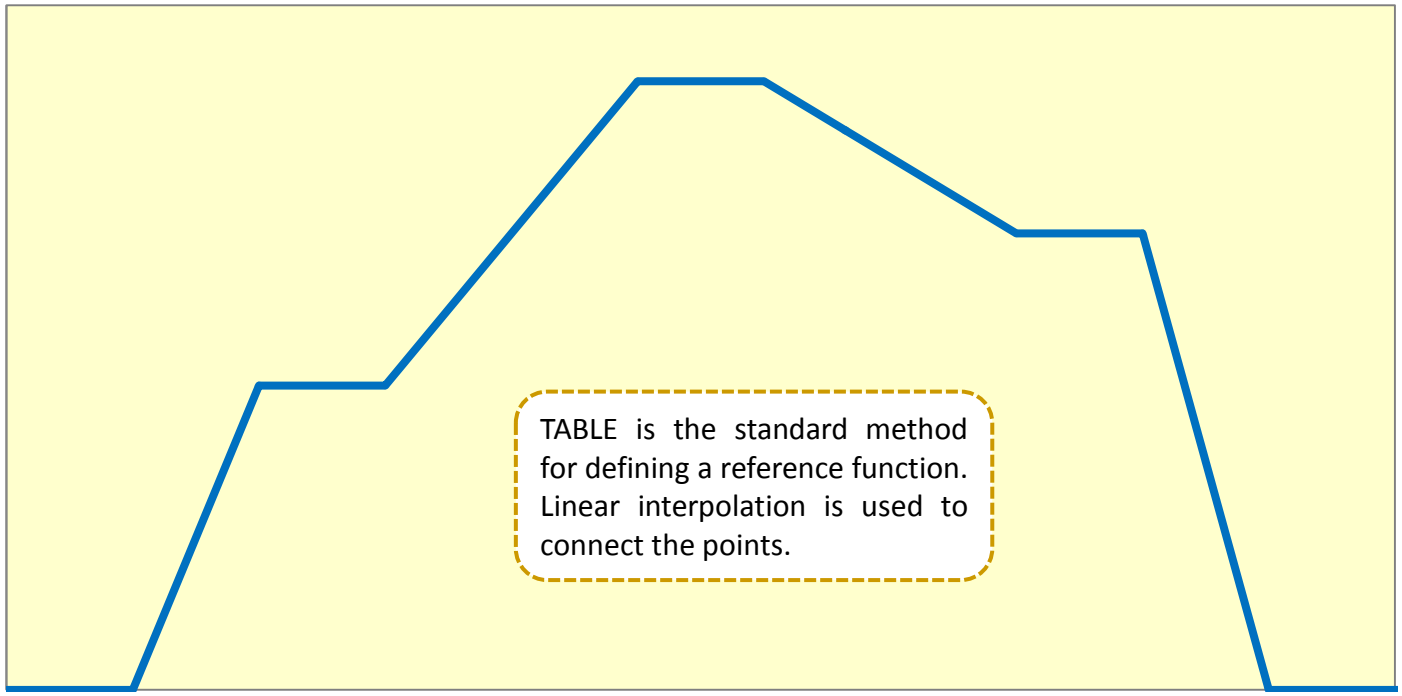
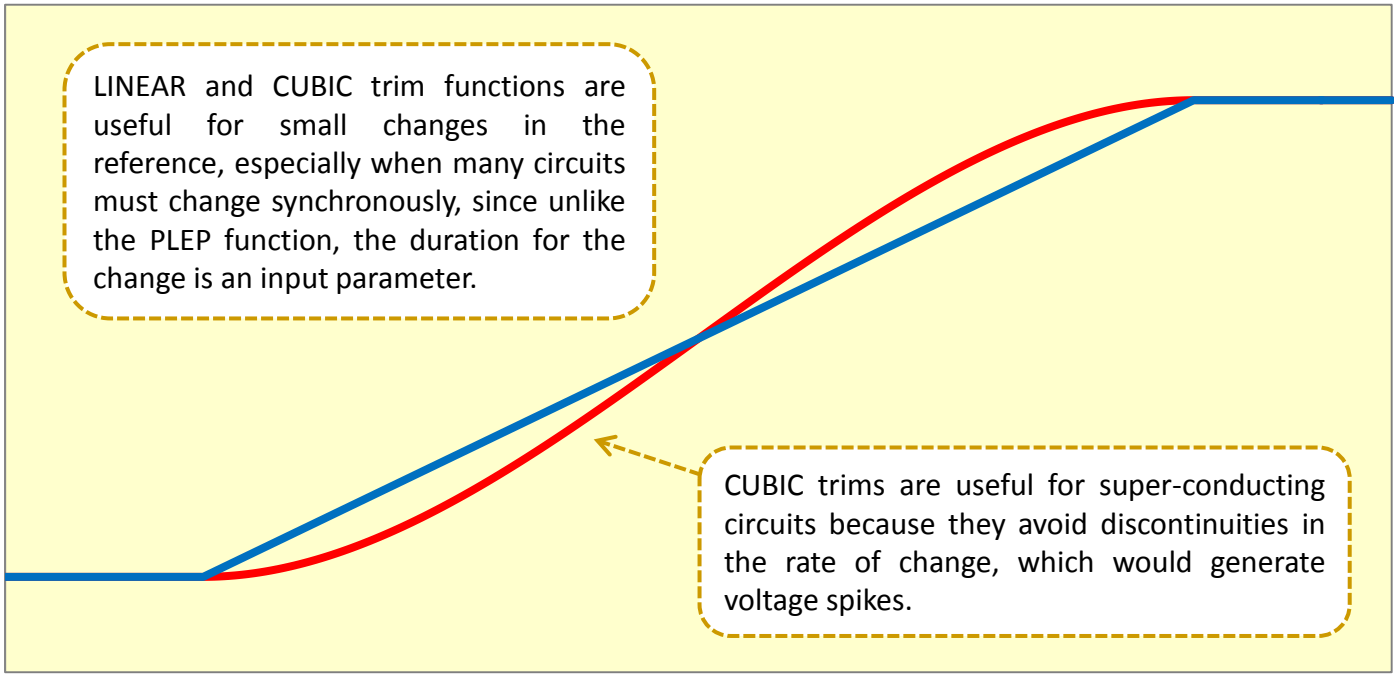
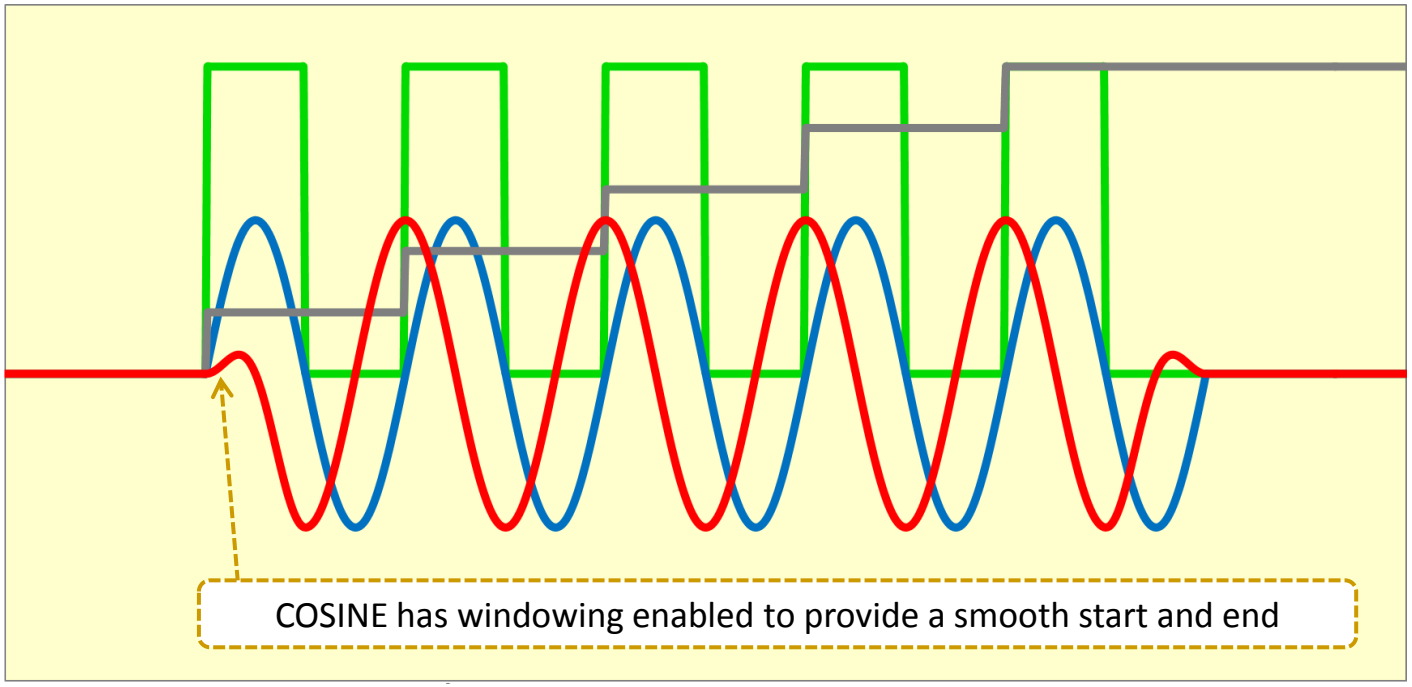


TABLE is the standard method for defining a reference function. Linear interpolation is used to connect the points.

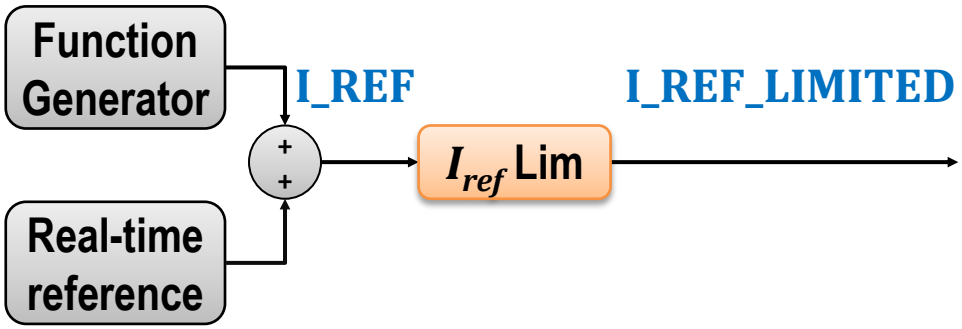
LINEAR and CUBIC



SINE, COSINE, SQUARE and STEPS

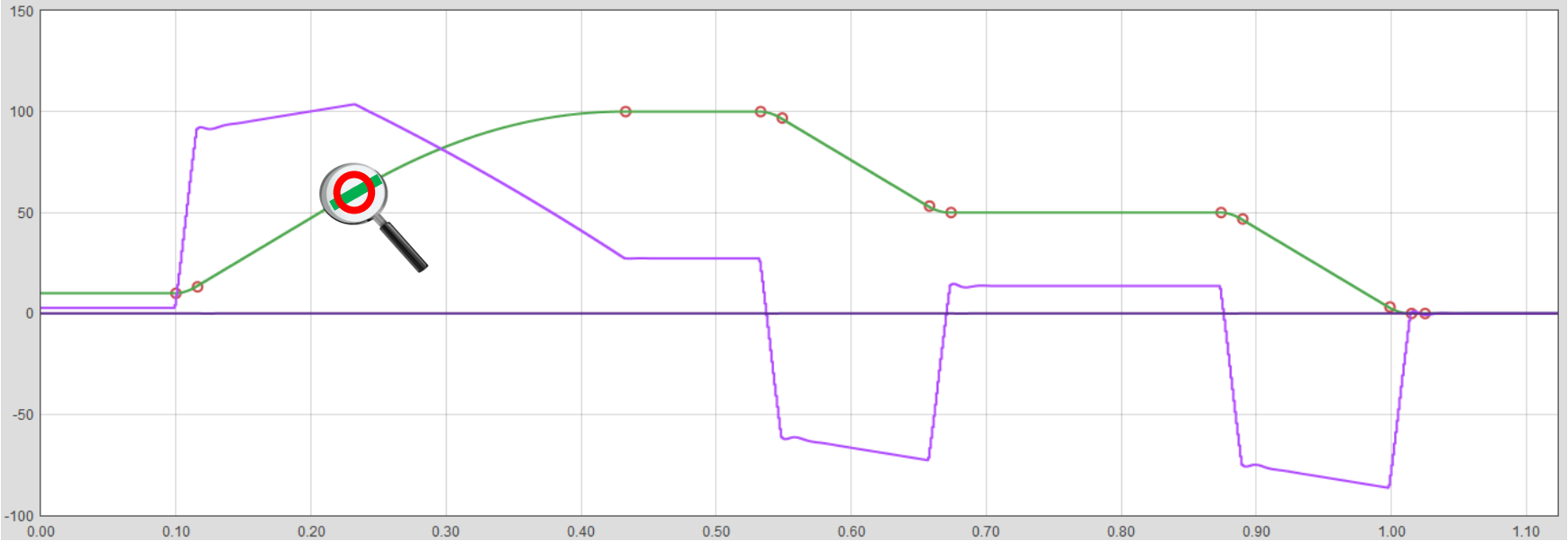


Real-Time Reference



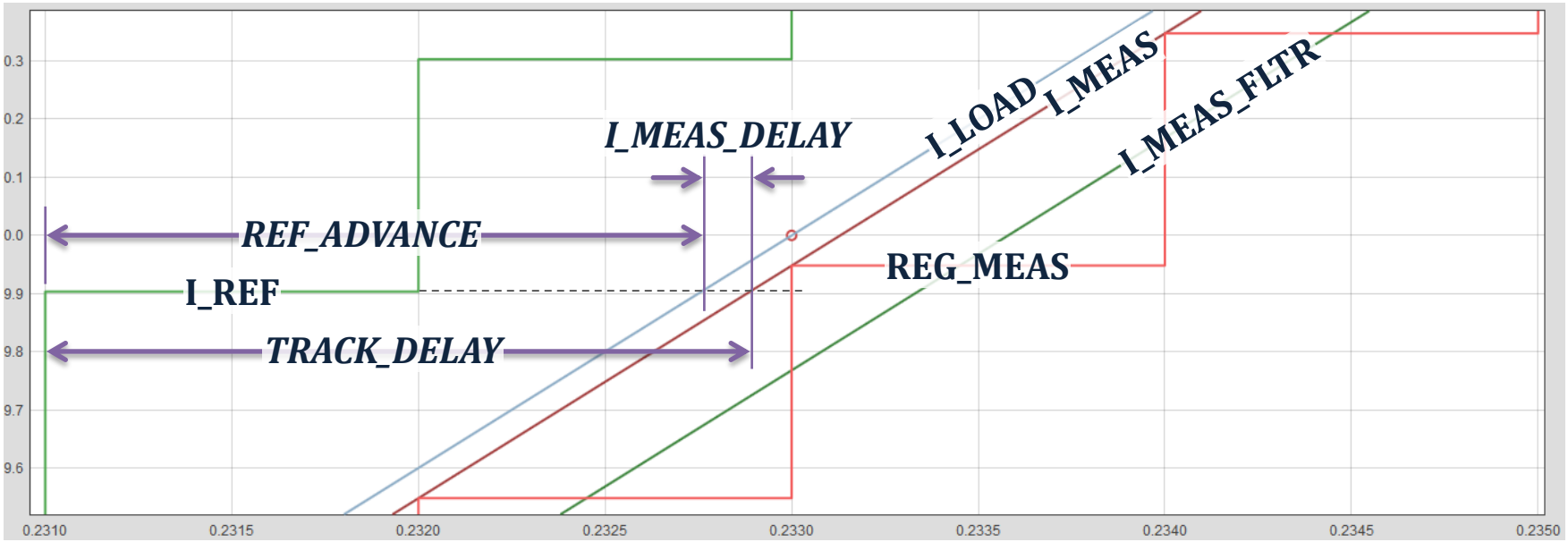
- If the power converter is the actuator for a higher level feedback loop (e.g. orbit or tune), then a real-time communication channel will be needed from the feedback controller.
- In this case, real-time reference limits must be applied.

How to calculate the Ref Advance



- When the reference function is predefined, the controller can play the function in advance so that the current in the circuit follows the reference
- The measurement of the current has a delay and this must be taken into account when setting the REF ADVANCE time

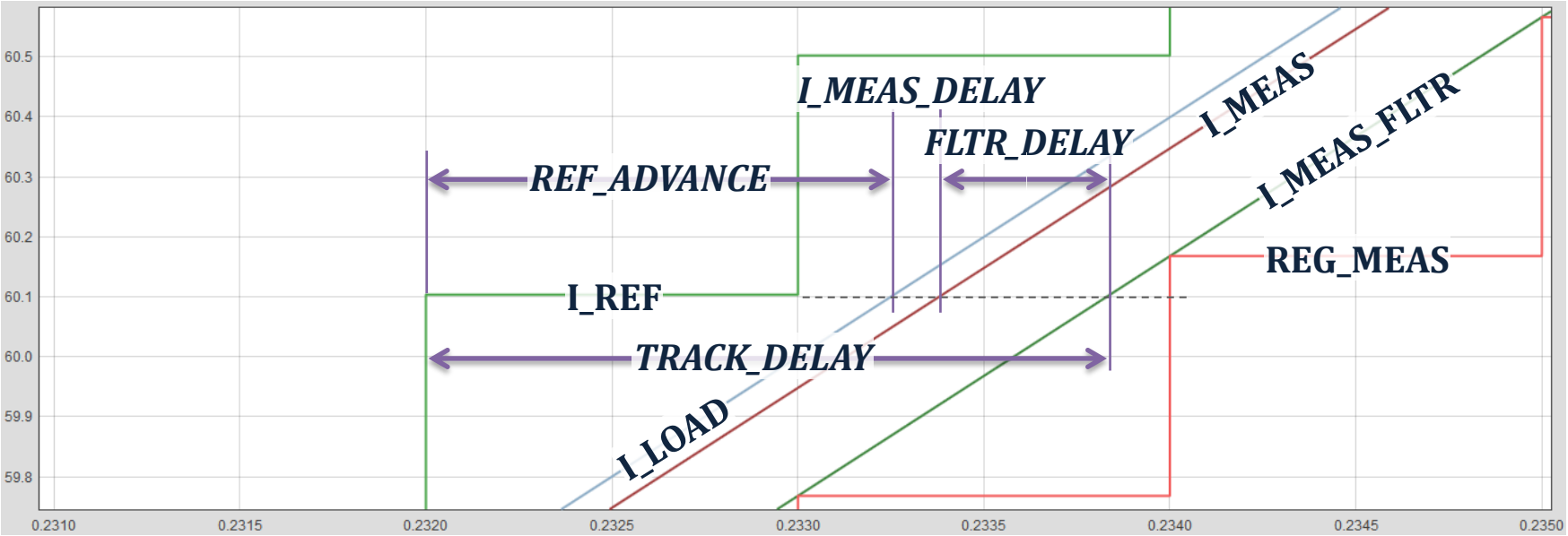
Ref Advance : Regulating I_MEAS



Example 1: Regulating I_MEAS with TRACK_DELAY = $1.9T_{reg}$

REF_ADVANCE = TRACK_DELAY - I_MEAS_DELAY

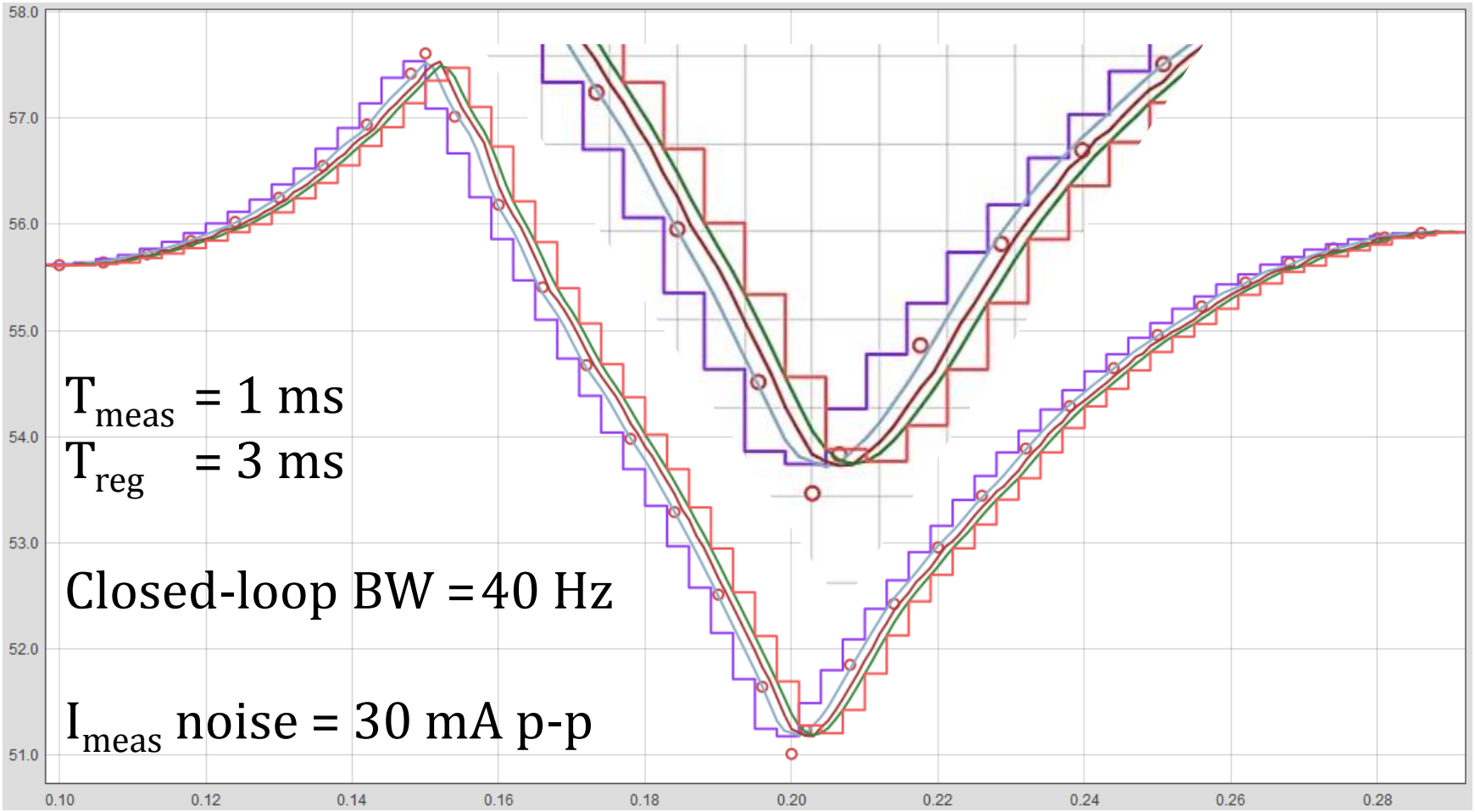
Ref Advance : Regulating I_MEAS_FLTR

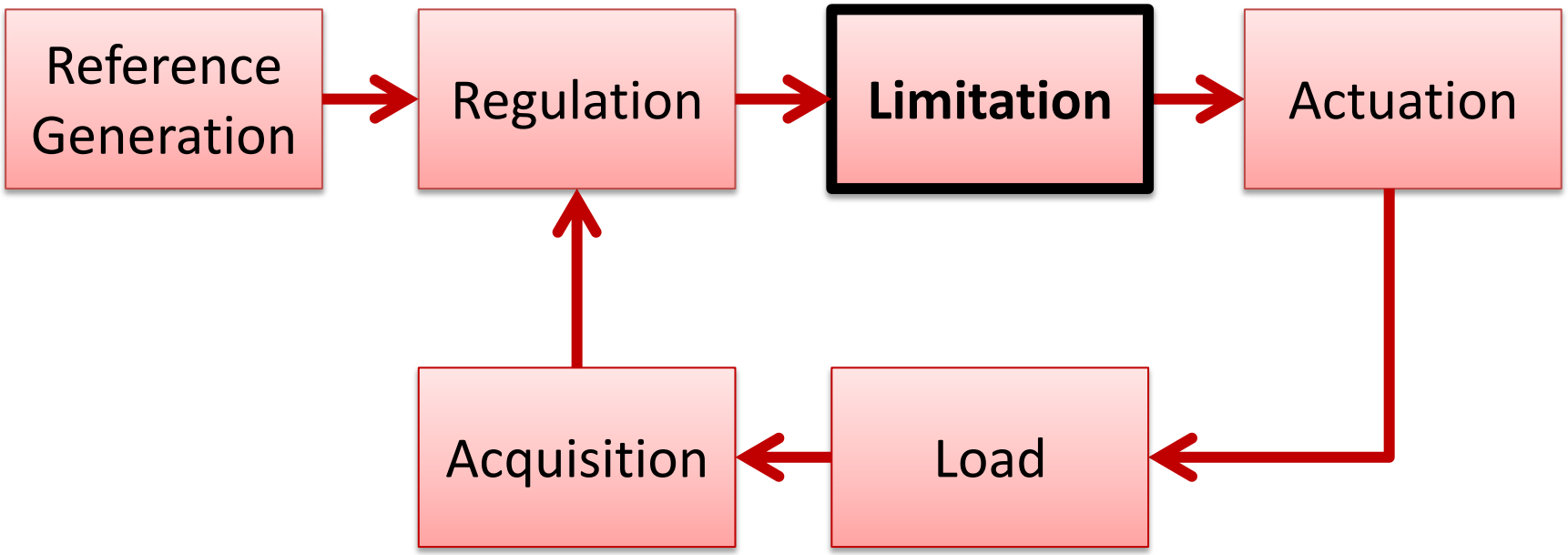


Example 2: Regulating I_MEAS_FLTR with TRACK_DELAY = $1.8T_{reg}$

REF_ADVANCE = TRACK_DELAY - I_MEAS_DELAY - FLTR_DELAY

Example of tracking performance

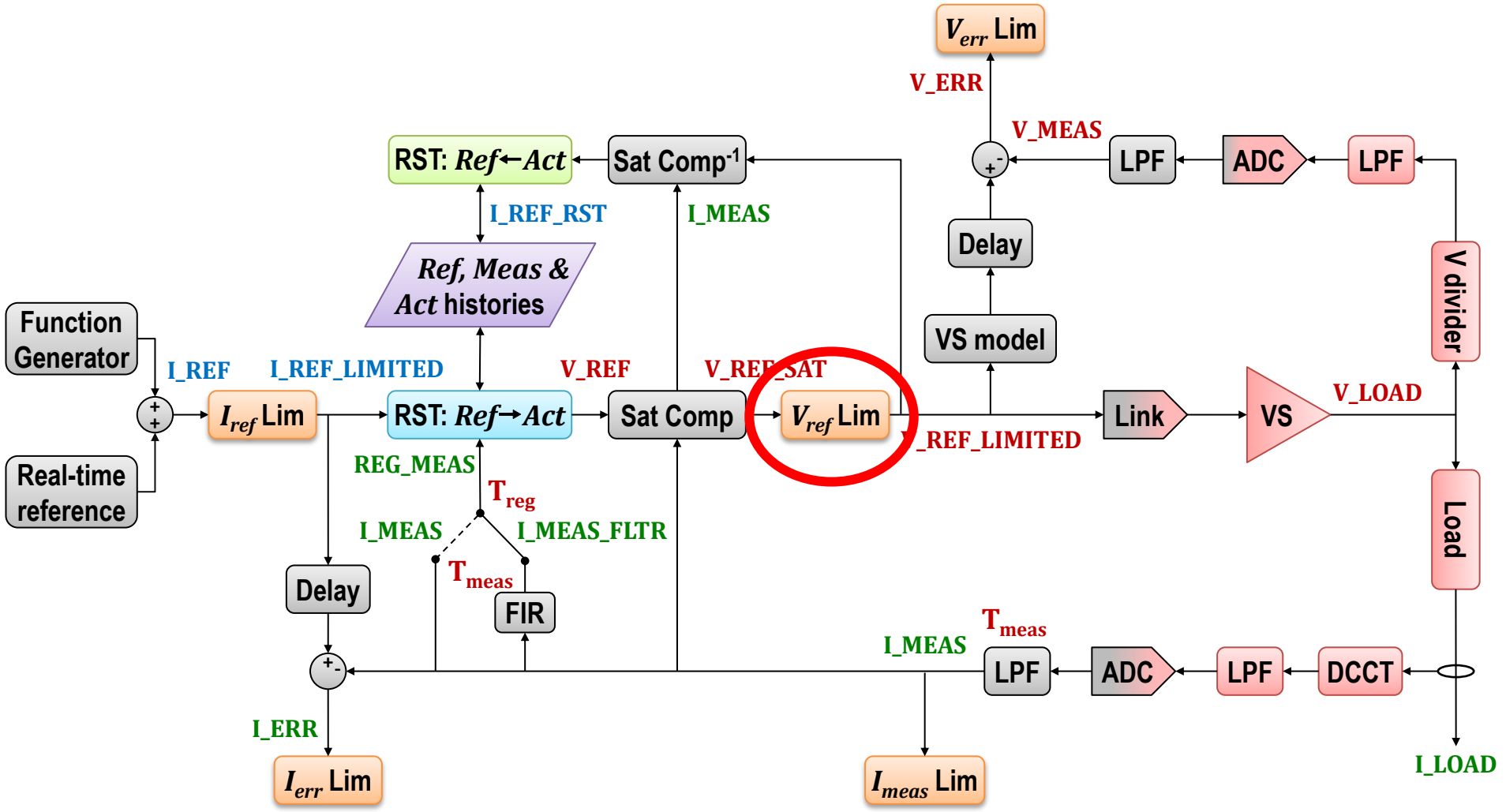



Reference Generation
Regulation
Limitation
Actuation
Acquisition
Load

Limitation

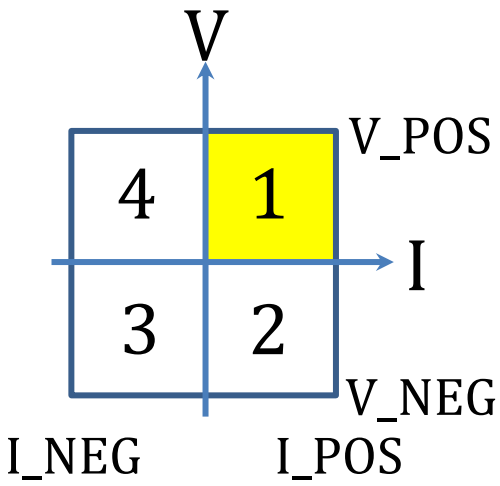
- Current and Voltage limits are vital for the safe operation of a power converter:
  - Reference Limits
  - Measurement Limits
  - Regulation Error Limits

Example of Current Regulation using the RST algorithm

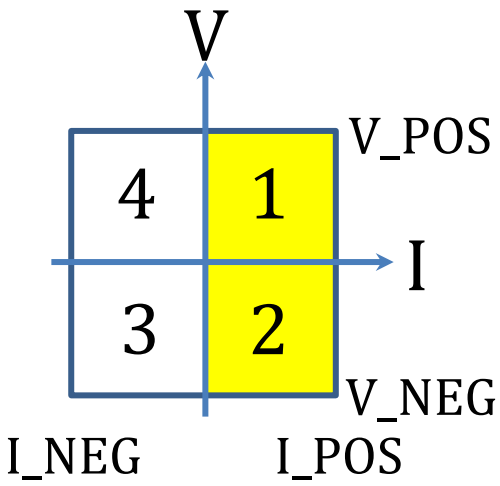


Voltage Reference Limits

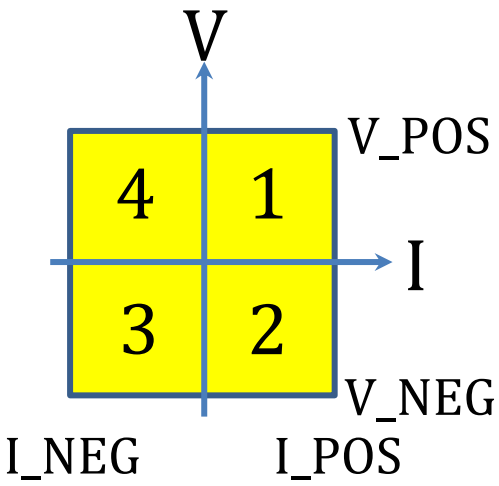
The voltage source will have an operating range that can be represented as quadrants:



1-Quadrant



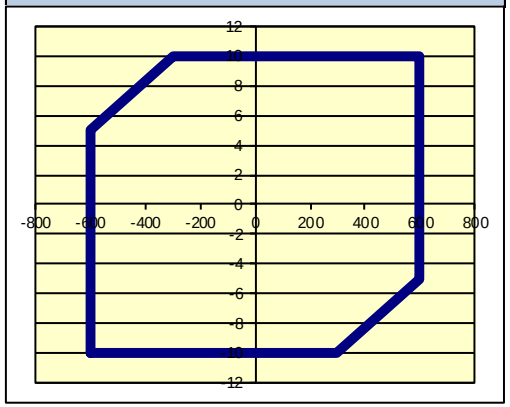
2-Quadrant



4-Quadrant

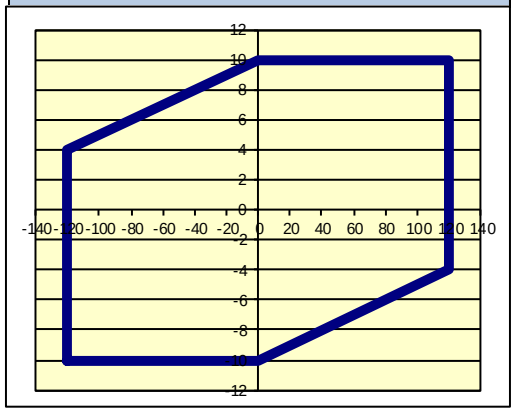
- With some 2 and 4 quadrant converters, the circuit energy recovery rate may need to be limited to protect the output stage of the converter.
- This is can be defined as an excluded segment of quadrant 4-1, which is applied automatically to segments 2-3 by rotating 180°.

600A 10V



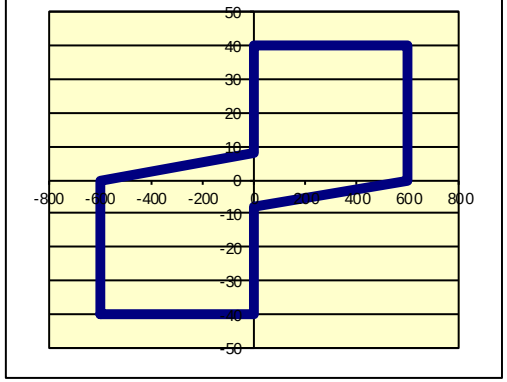
I_QUADRANT41 -600, -300
V_QUADRANT41 5, 10

120A 10V



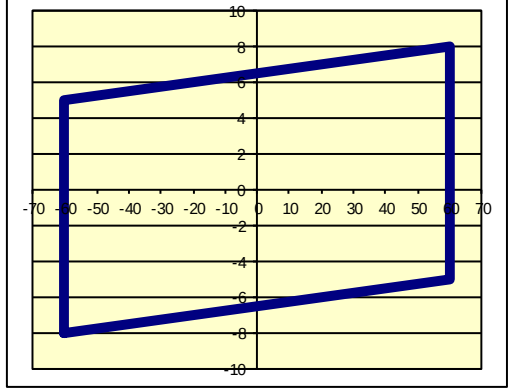
I_QUADRANT41 -120 0
V_QUADRANT41 4, 10

600A 40V

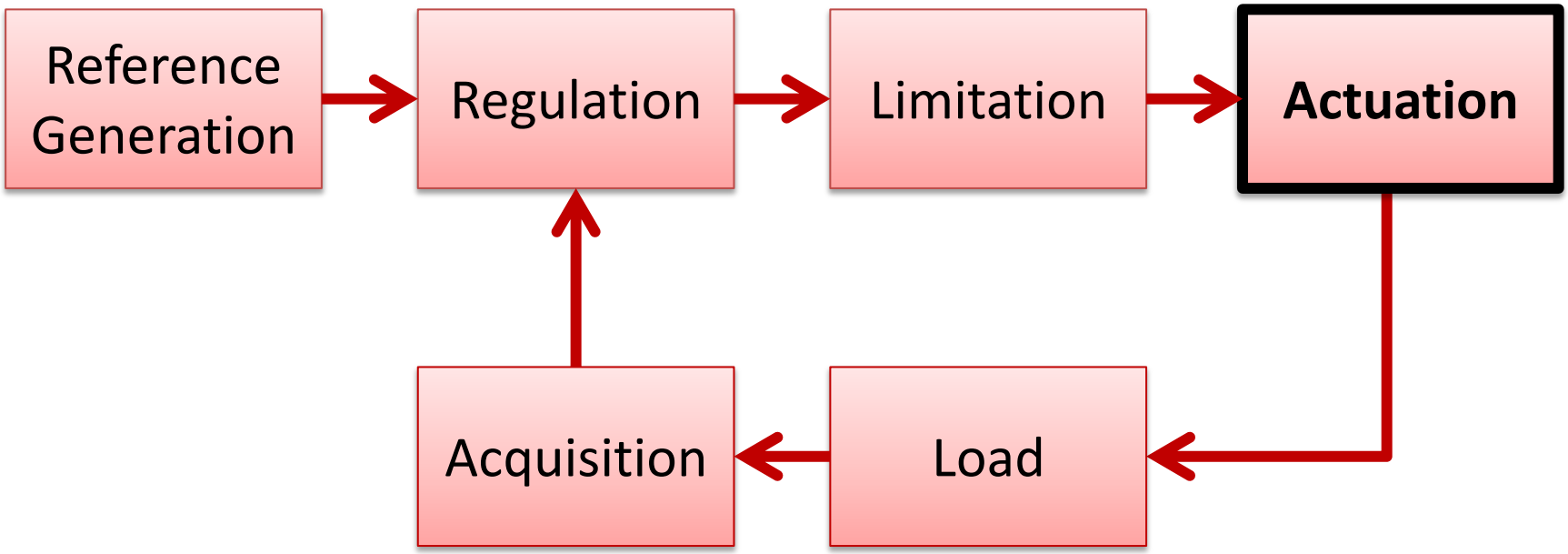


I_QUADRANT41 -600, 0
V_QUADRANT41 0, 8

60A 8V

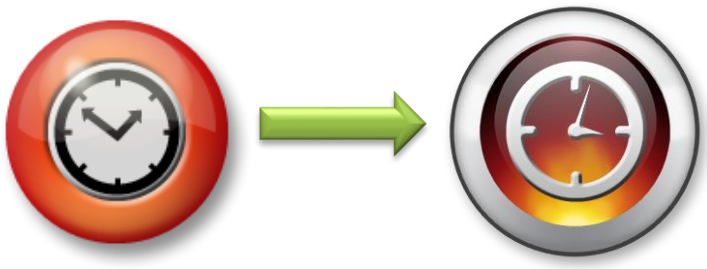


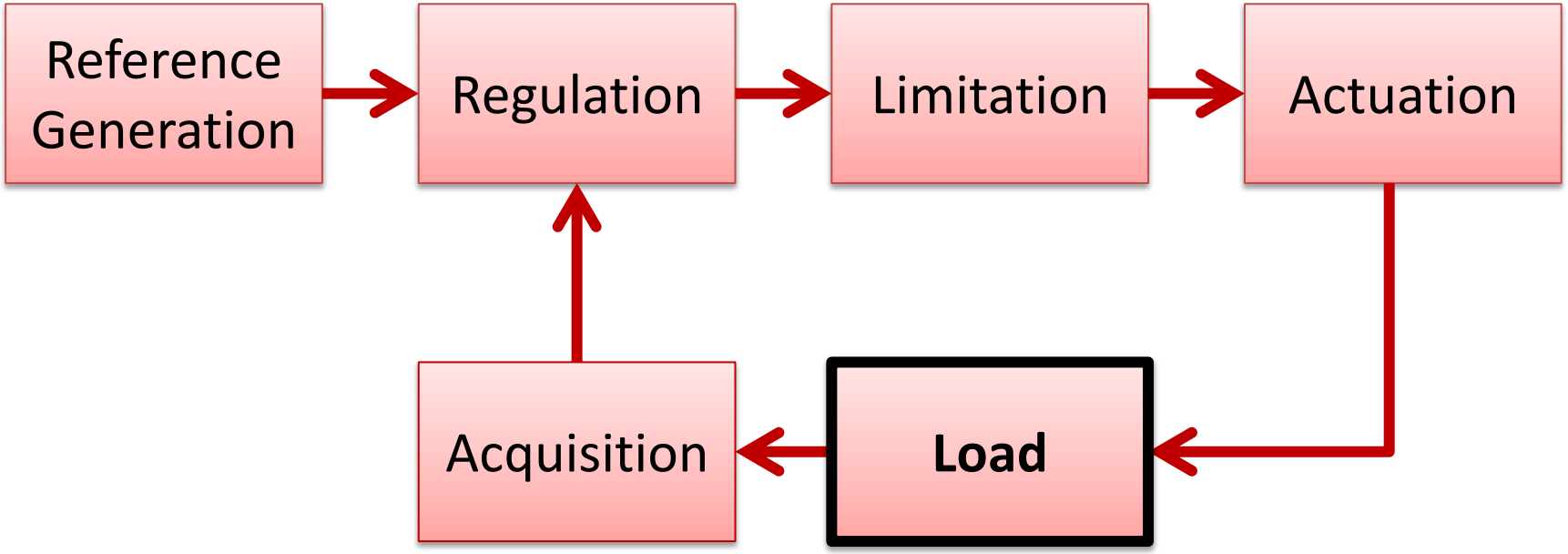
I_QUADRANT41 -60, 60
V_QUADRANT41 5, 8


Reference Generation
Regulation
Limitation
Actuation
Load
Acquisition

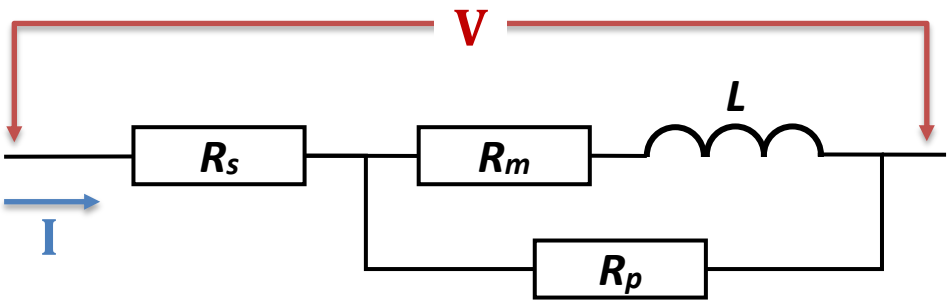
Actuation

- Take care with the synchronisation of the current regulation and the voltage regulation loops.
- If they are not synchronised, then you may need to filter the V_{ref} signal to reduce aliasing.
- This will cost additional delay which will need to be taken into account and **may limit the bandwidth** of the current loop.




Reference Generation
Regulation
Limitation
Actuation
Acquisition
Load

Load Model

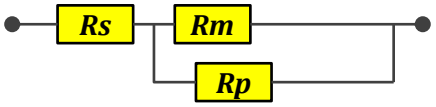


$$G(s) = \frac{1}{R_s + \frac{1}{\frac{1}{R_p} + \frac{1}{R_m + sL}}}$$

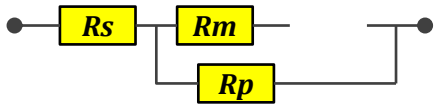
- Our most common load is a first-order magnet circuit
- Magnet inductance: **L**
- Cables provide a series resistance: **R_s**
- Warm magnets have a non-zero resistance: **R_m**
- For superconducting magnets: **$R_m = 0$**
- Some circuits include a parallel damping resistor: **R_p**

Load Model: Gain (I/V) Bode Plot

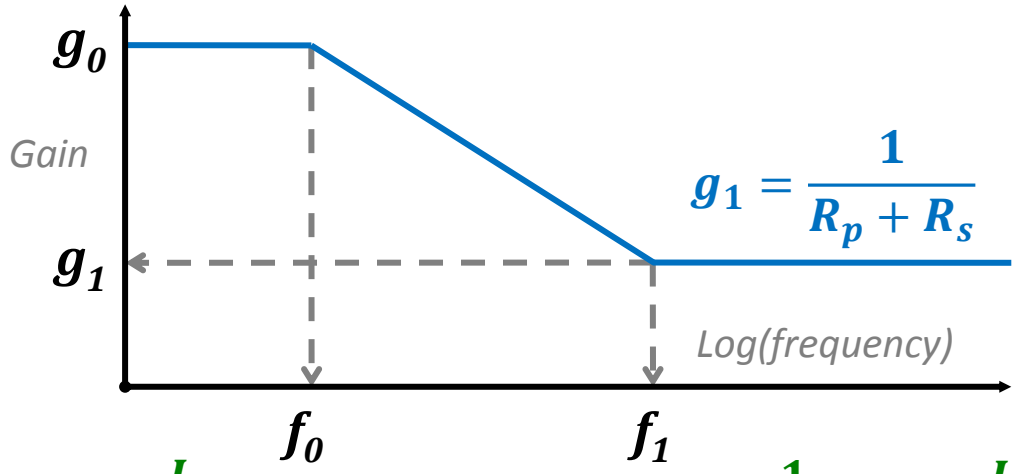
$F \to 0$



$F \to \infty$



$$g_0 = \frac{1}{R_s + \frac{R_p R_m}{R_p + R_m}}$$

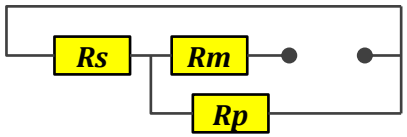


$$g_1 = \frac{1}{R_p + R_s}$$

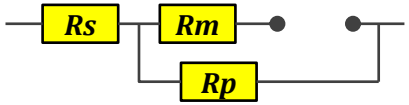
$$\tau_0 = \frac{1}{2\pi f_0} = \frac{L}{R_m + \frac{R_p R_s}{R_p + R_s}}$$

$$\tau_1 = \frac{1}{2\pi f_1} = \frac{L}{R_p + R_m}$$

$F \to f_0$

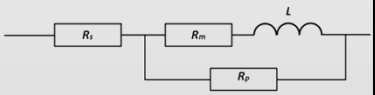


$F \to f_1$



Load Model : Effects of the parallel resistor

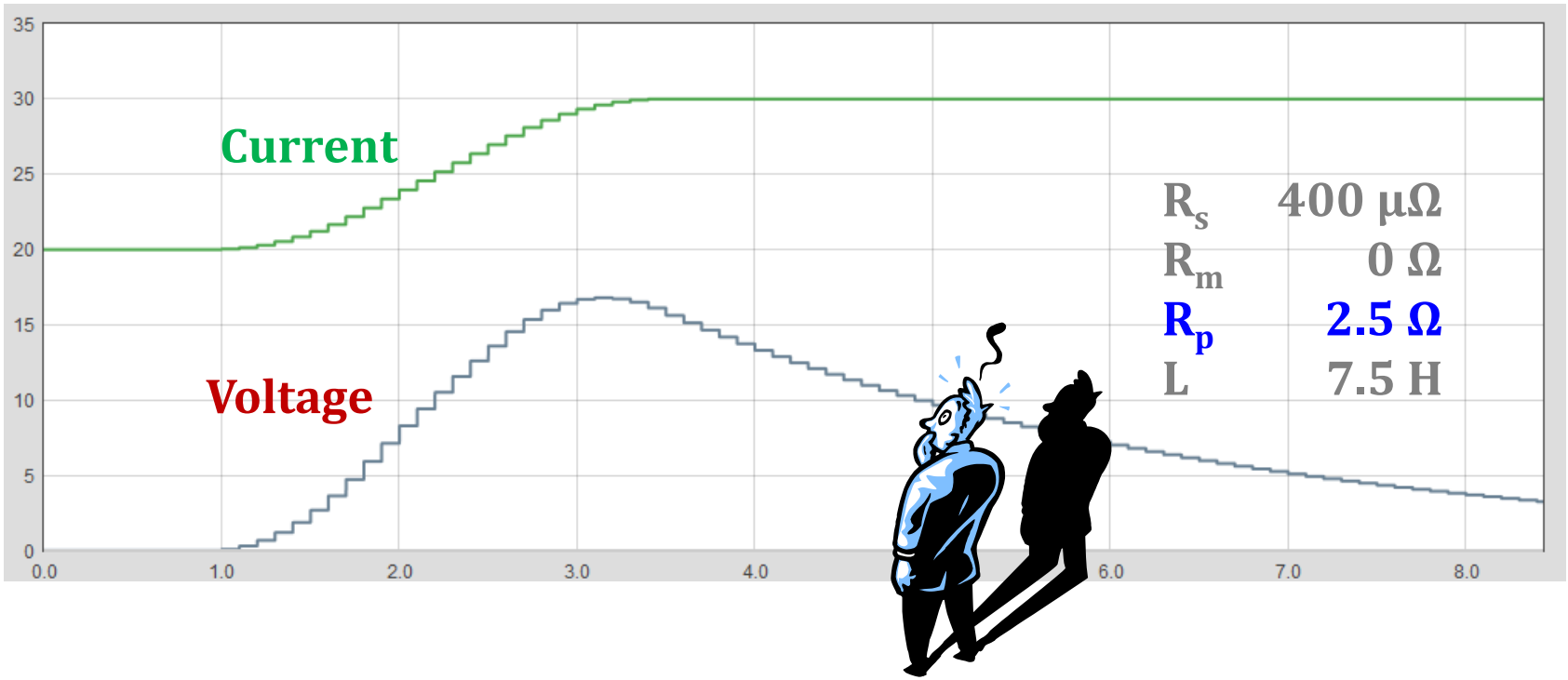
Response to a step in voltage



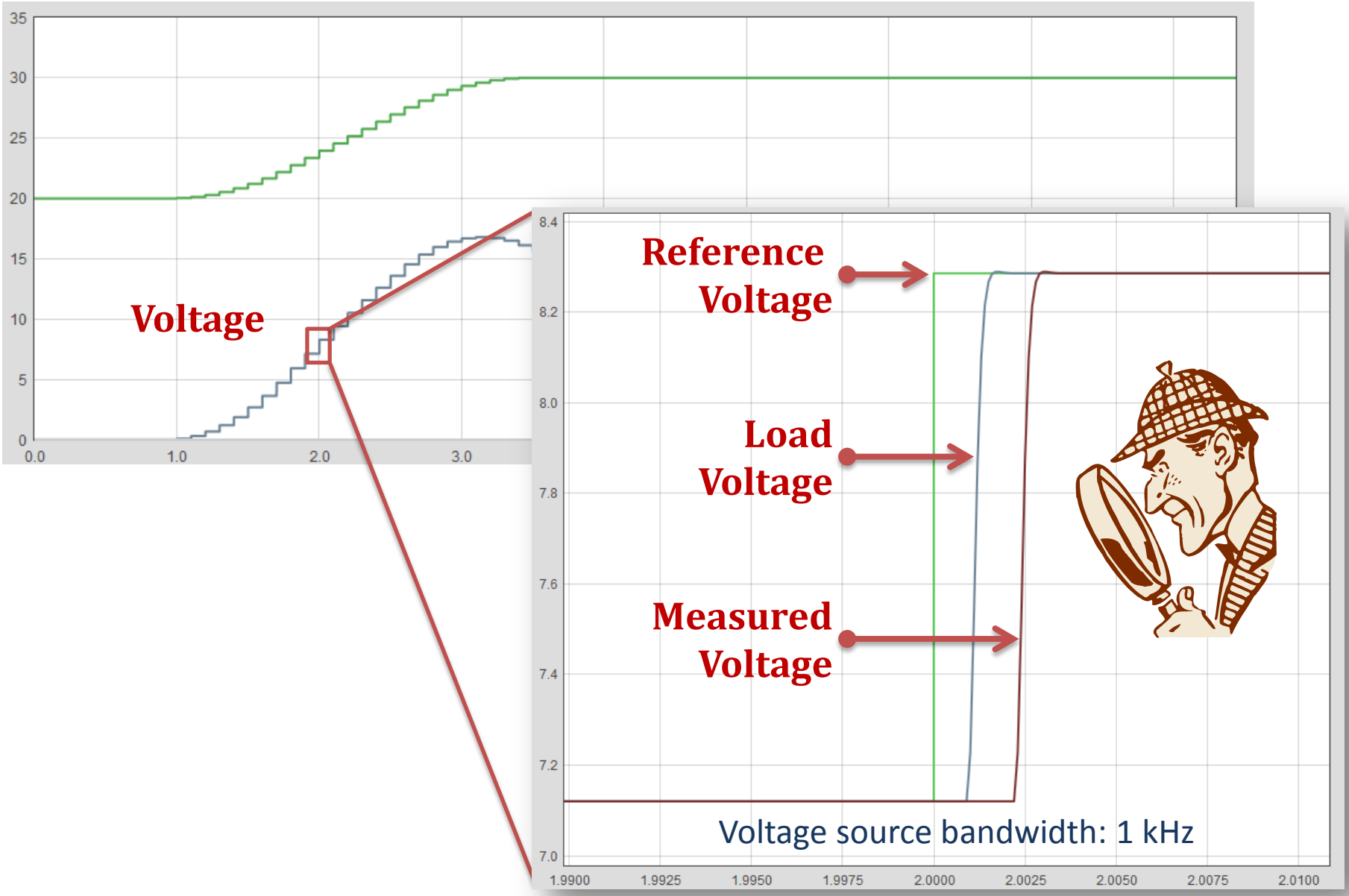
$$g_0 = \frac{1}{R_s + \frac{R_p R_m}{R_p + R_m}}$$

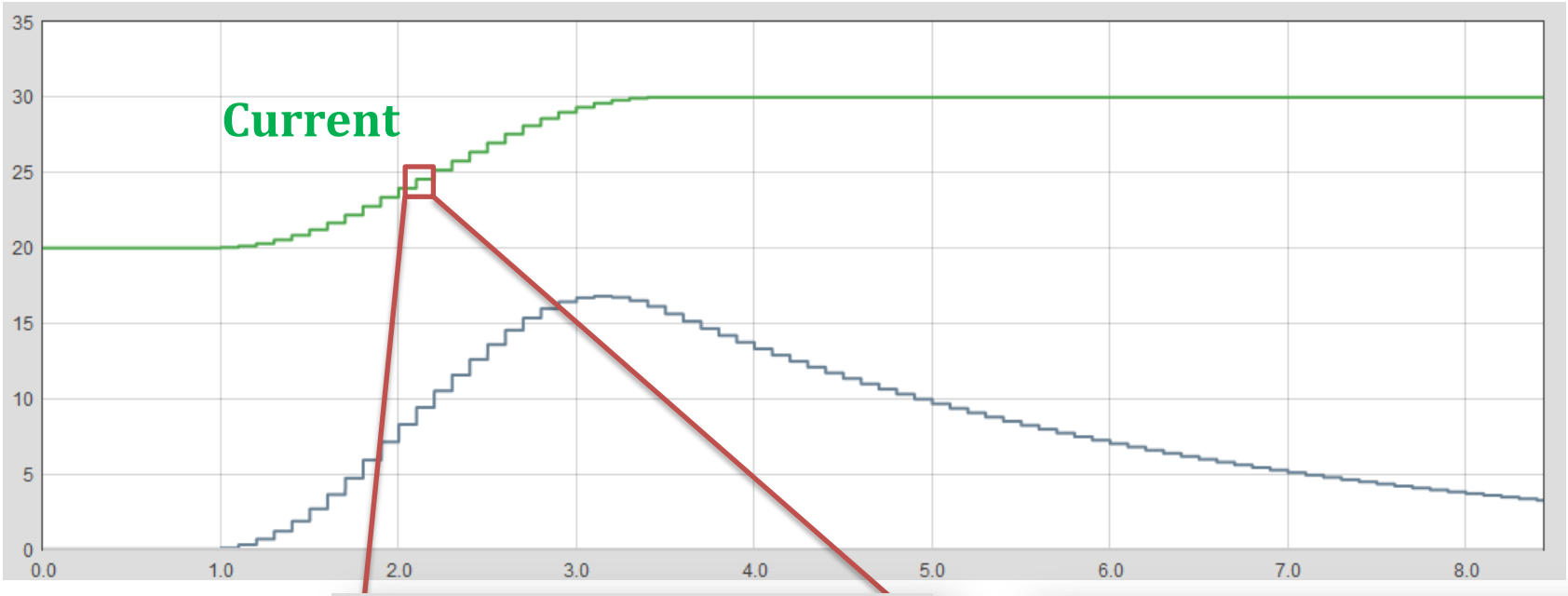
$$g_1 = \frac{1}{R_p + R_s}$$

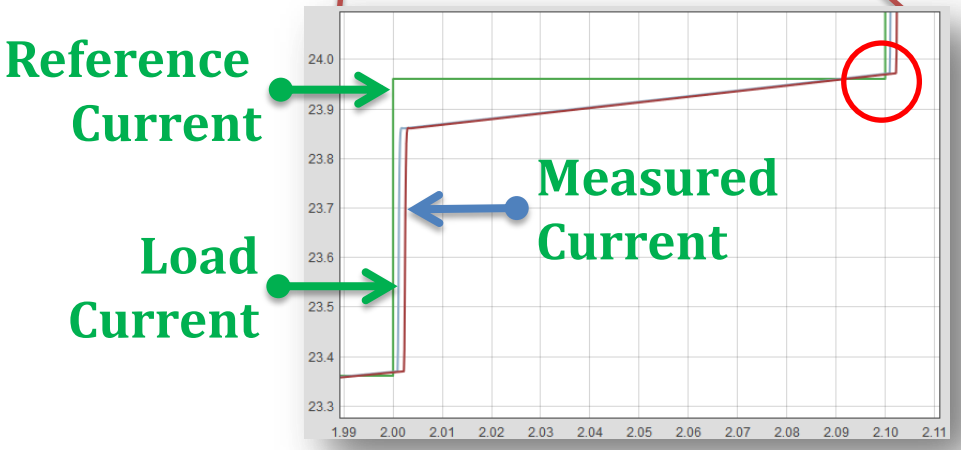
Parallel resistor example

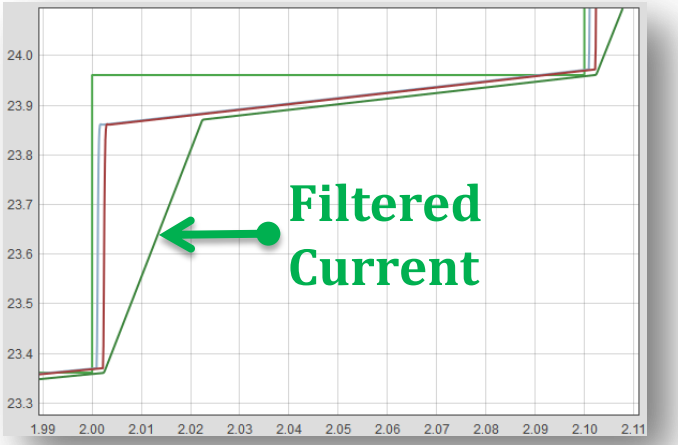


Why is the voltage reducing while the current is constant?

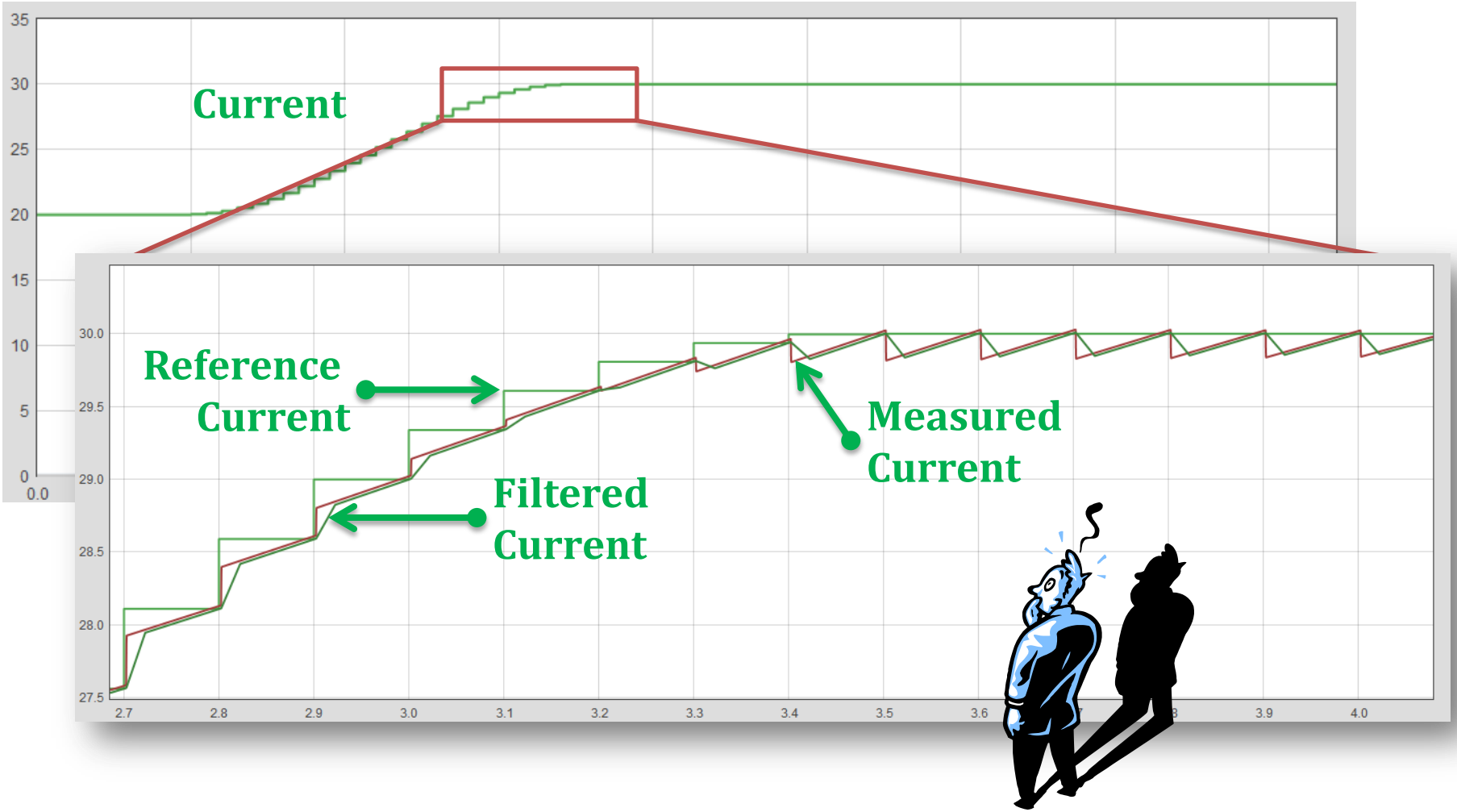

Voltage
Reference Voltage
Load Voltage
Measured Voltage
Voltage source bandwidth: 1 kHz







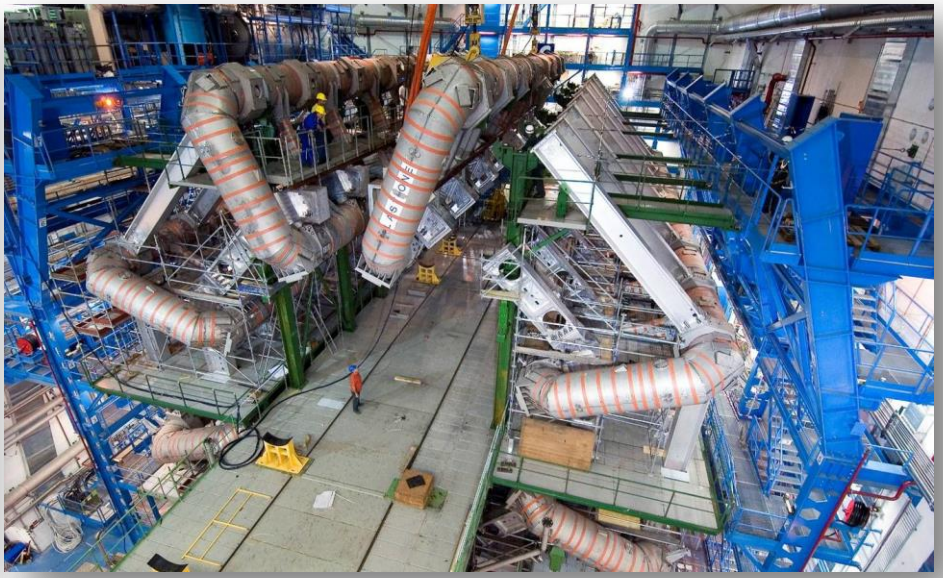
- The PII algorithm is incredibly good at tracking the reference
- But it needs a stable voltage source gain



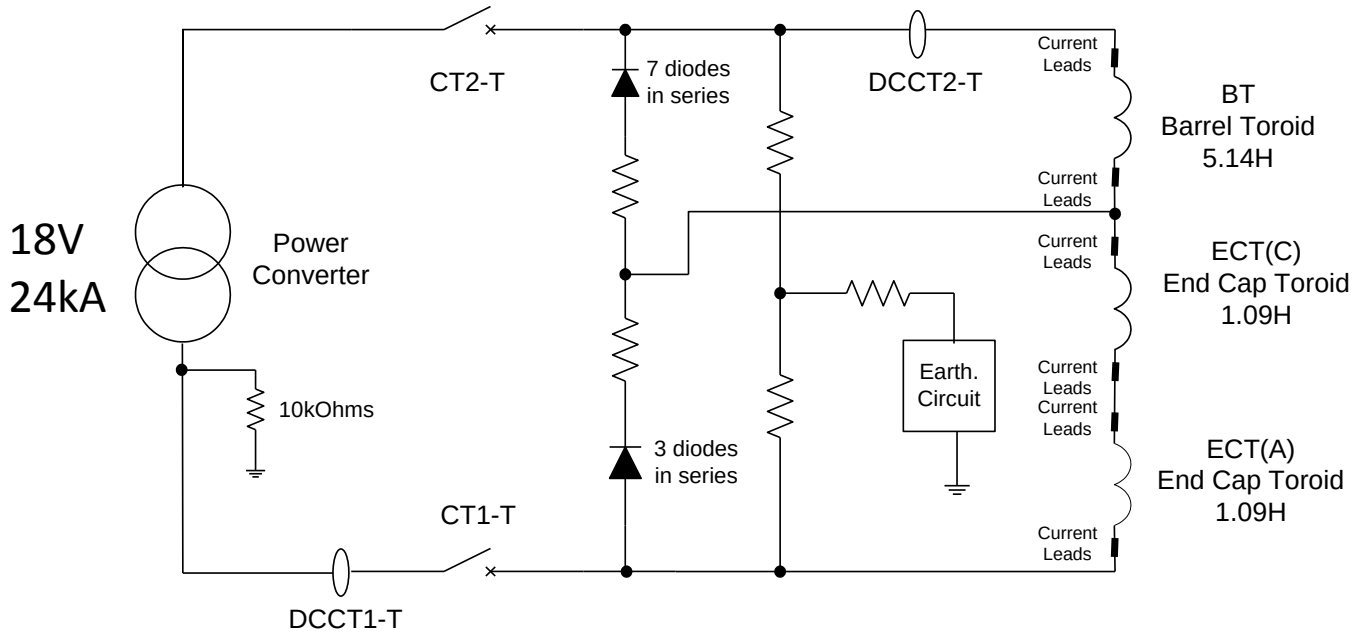
What is going on?

Load model: ATLAS magnet

- The ATLAS toroidal field is created by 8 barrel toroid magnets and two end-cap toroid magnets
- 2-4T 7.6H 1.5GJ Tc = 5 hours



Load model: ATLAS magnet



- There is no significant parallel resistance across the magnets
- Tuning the RST regulation was difficult
- The circuit was measured with a TFA

Load model: ATLAS magnet

Key

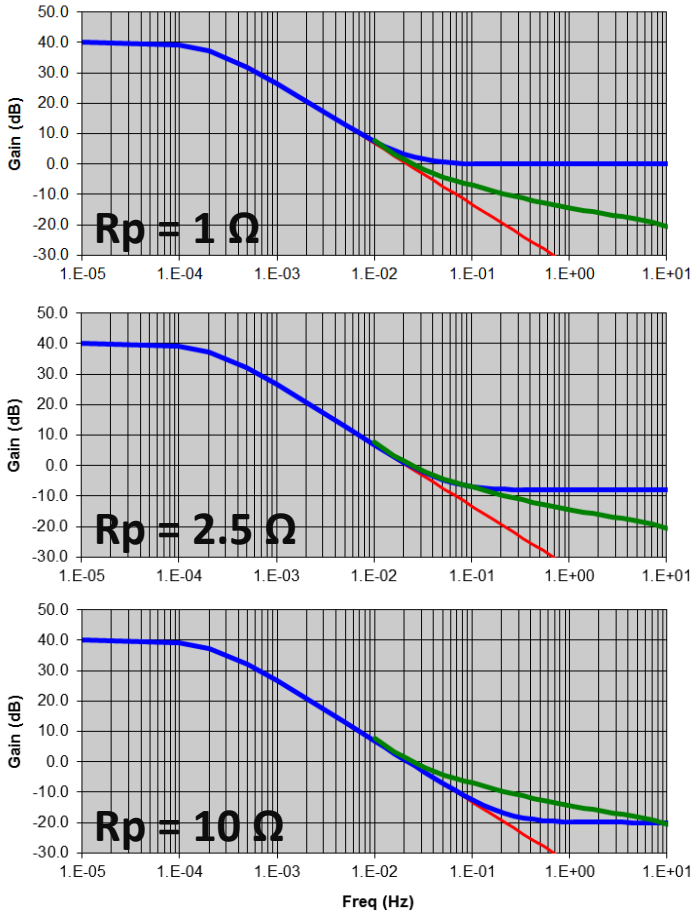
Rs/Rm/Rp Model

Measured 10mHz – 10Hz

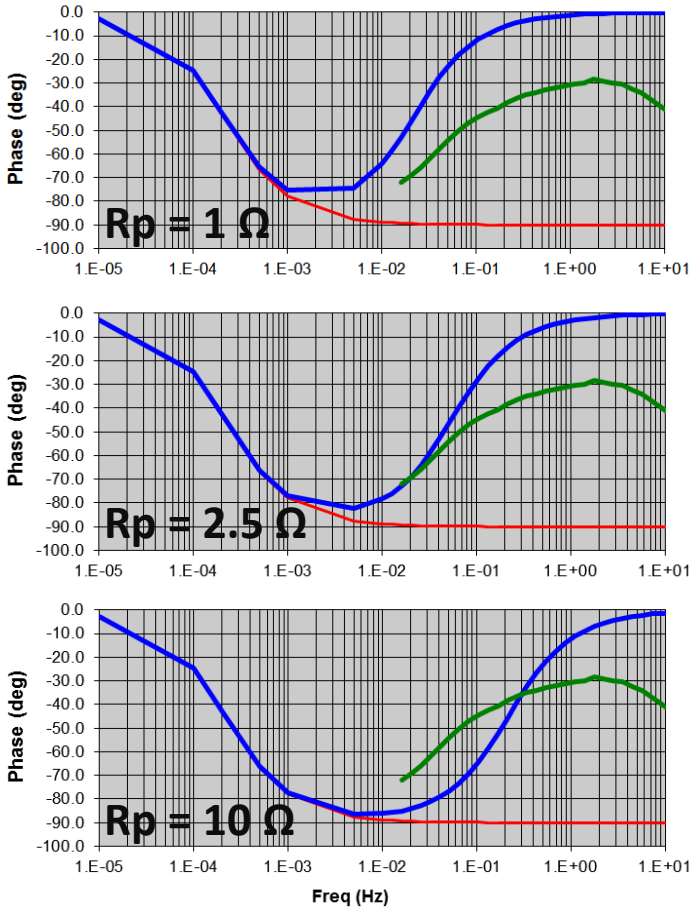
Rs/Rm Model

2.5Ω provides the best fit with measurement up to around 0.1Hz

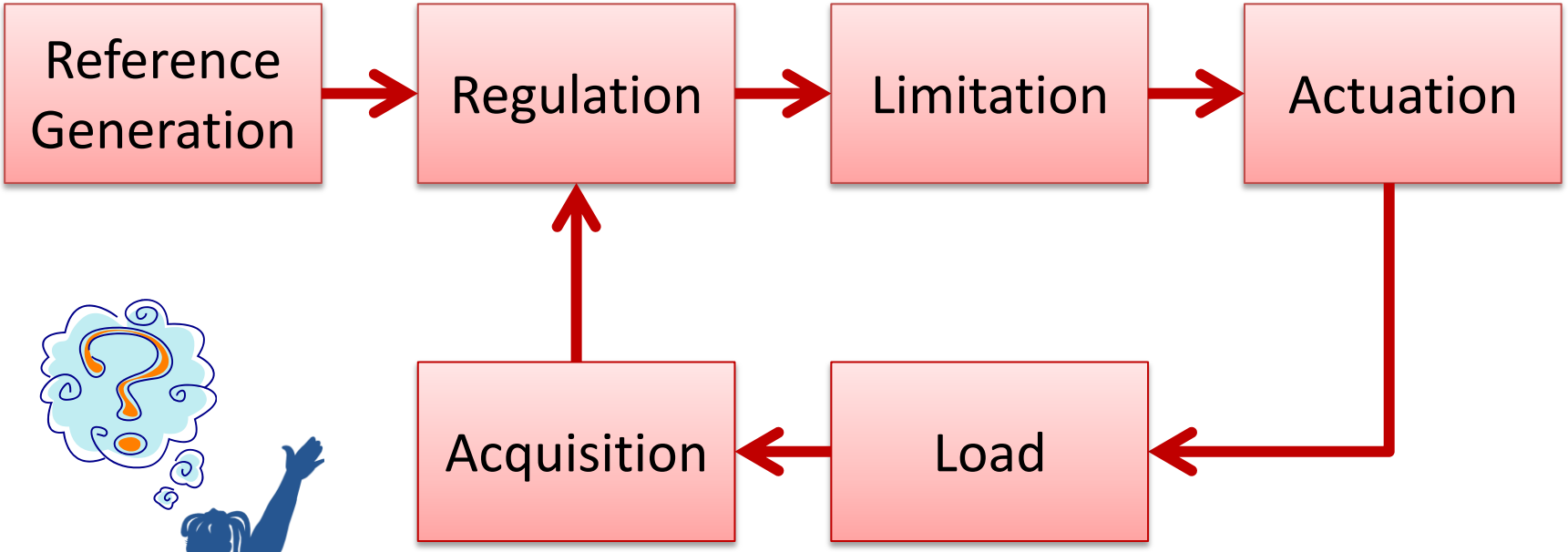
Admittance Gain



Admittance Phase



Thank you for your attention



Any questions?

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With thanks to all members of the CERN Electrical Power converter Group