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High precision current control of the LHC Power Converters

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Hugues Thiesen
CERN TE-EPC

SUMMARY

- *LHC challenges*
- *RST Digital control*
- *Application for the current control of the LHC power converters*
- *Conclusions*

LHC Challenges

LHC challenges

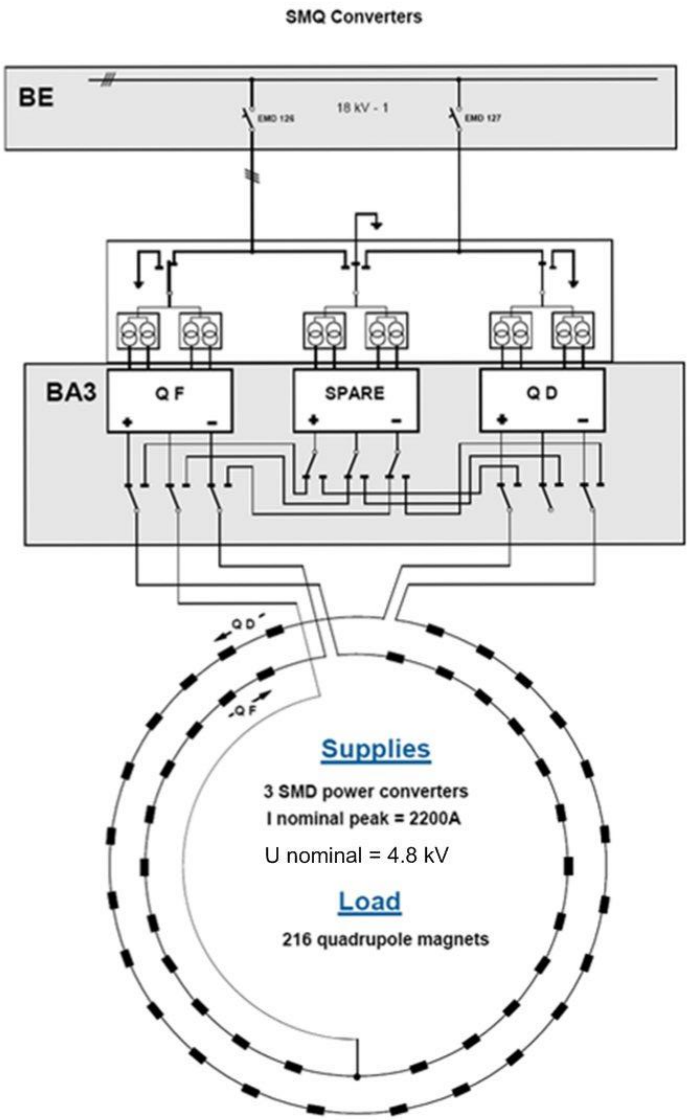
In the circular accelerator the main magnets (dipole and quadrupoles) have to generate the same magnetic field

The classical solution is to put the magnets in series (LEP, SPS)

- 3 main circuits (RB, RQD and RQF)

Example of SPS main quadrupole circuits:

- All the QD (and QF) magnets are connected in series
- The currents circulate in opposite direction to avoid making dipole loops.



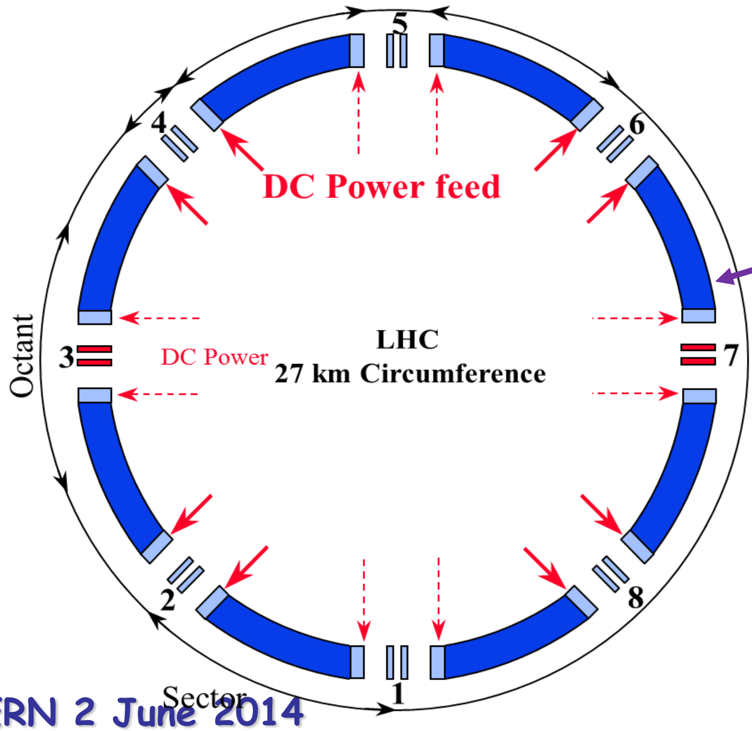
LHC challenges

For the LHC this solution was not possible due to the huge energy stored in the superconducting dipoles magnets

- Total energy stored in the main dipole:

$$E = 0.5*L*I^2 = 8.8\ GJ \quad \text{with} \begin{cases} L = 123.2\ H\ (8*15.4\ H) \\ I = 12\ kA \end{cases}$$

The LHC was divided in 8 sectors



8 powering Sectors:
- RB: 154 dipoles in series (15.4 H)
- RQD/RQF: 47 quads in series (0.25 H)

Tracking between sectors

LHC Power converter performances

Circuit Type	Nominal Current (A)	Current Polarity	One Year Accuracy (ppm of Inominal)	One day Reproducibility (ppm of Inominal)	1/2 hour Stability (ppm of Inominal)	Resolution (ppm of Inominal)
Main Bends, Main Quads	13000	Unipolar	± 50 ± 20 with calibration	± 5	± 3	1
Inner triplet	8000/ 6000	Unipolar	± 70 ± 20 with calibration	± 10	± 5	1
Dispersion suppressor	6000	Unipolar	± 70	± 10	± 5	15
Insertion quadrupoles	6000	Unipolar	± 70	± 10	± 5	15
Separators (D1,D2,D3,D4)	6000	Unipolar	± 70	± 10	± 5	15
Trim quadrupoles	600	Bipolar	± 200	± 50	± 10	30
SSS correctors	600	Bipolar	± 200	± 50	± 10	30
Spool pieces	600	Bipolar	± 200	± 50	± 10	30
Orbit correctors	120/60	Bipolar	± 1000	± 100	± 50	30

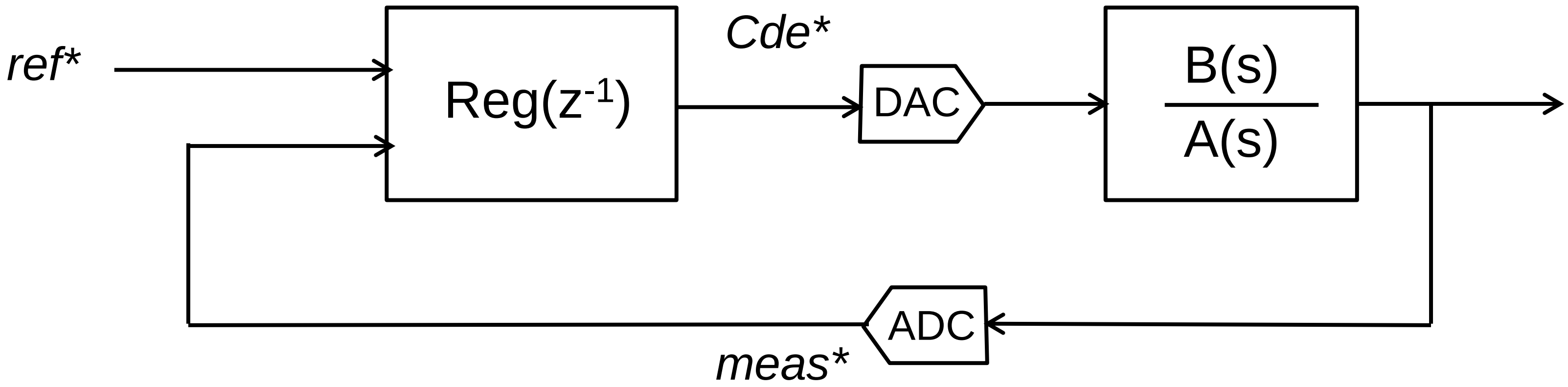
Precision (One Year Accuracy, One day Reproducibility, 1/2 hour Stability)

Control (Resolution)

RST digital control

RST digital control

<u>*Linear control*</u> with <u>*constant parameters*</u>



To define the control law we have:

- The model of the system: B(s) and A(s) (or $B^*(z^{-1})$ and $A^*(z^{-1})$)
- The reference and its history: $ref^*(k.T_e)$, $ref((k-1).T_e)$, etc…
- The measurement and its history: $meas^*(k.\ T_e)$, $meas((k-1).\ T_e)$, etc…
- The history of the command: $Cde^*(k.\ T_e)$, $Cde((k-1).\ T_e)$, etc
- Two mathematic operators: + (or -) and xCte

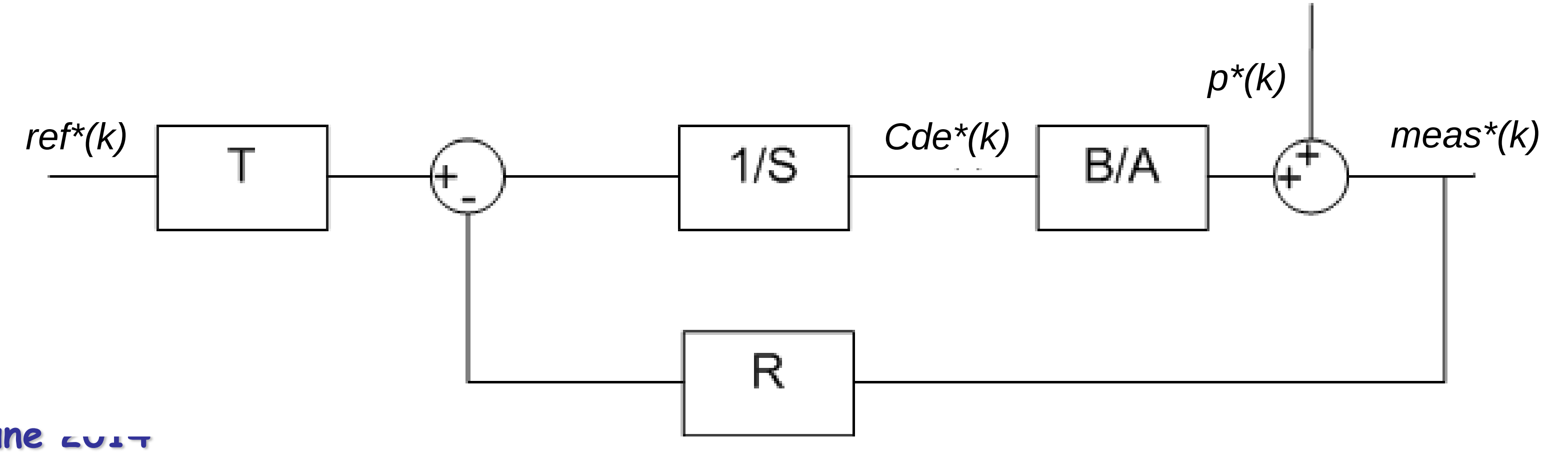
RST digital control

RST representation

$$Cde^*(k) = t_0.ref^*(k) + t_1.ref^*(k-1) + t_2.ref^*(k-2) + \ldots$$
$$- r_0.meas^*(k) - r_1.meas^*(k-1) - r_2.meas(k-2) + \ldots$$
$$- s_1.Cde^*(k-1) – s_2.Cde^*(k-2) - \ldots$$

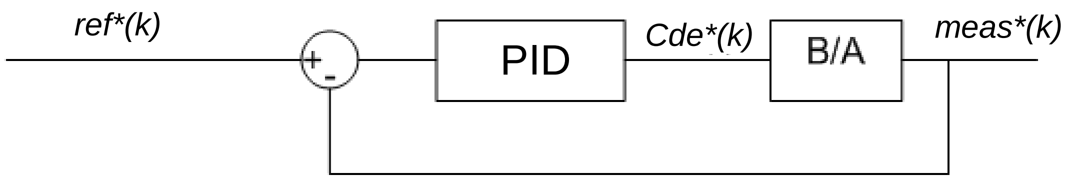
$$S(z^{-1}).Cde^*(k) = T(z^{-1}).ref^*(k) - R(z^{-1}).meas^*(k)$$

$$\begin{cases} R(z^{-1}) = r_0 + r_1.z^{-1} + r_2.z^{-2} + \ldots \\ S(z^{-1}) = s_0 + s_1.z^{-1} + s_2.z^{-2} + \ldots \\ T(z^{-1}) = t_0 + t_1.z^{-1} + t_2.z^{-2} + \ldots \end{cases}$$



PID regulator

Classical representation



$$\operatorname{Re} g(s) = K \cdot \left[1 + \frac{1}{T_i \cdot s} + \frac{T_d \cdot s}{1 + \frac{T_i}{N} \cdot s} \right]$$

$$\operatorname{Re} g(z^{-1}) = K \cdot \left[1 + \frac{T_e}{T_i} \cdot \frac{1}{\left(1 - z^{-1}\right)} + \frac{\frac{N \cdot T_d}{T_d + N \cdot T_e} T_d \cdot \left(1 - z^{-1}\right)}{1 - \frac{T_d}{T_d + N \cdot T_e} \cdot z^{-1}} \right]$$

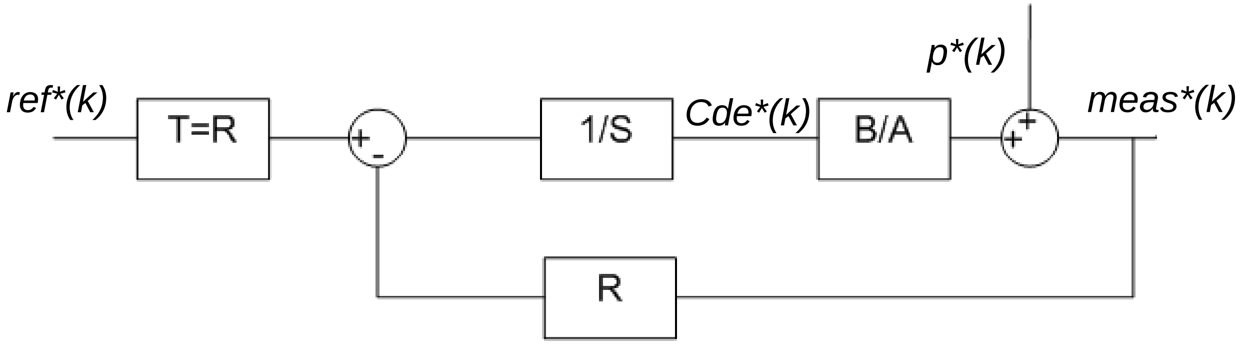
PID in "s" domain

PID in "z" domain

RST digital control

PID regulator

RST representation



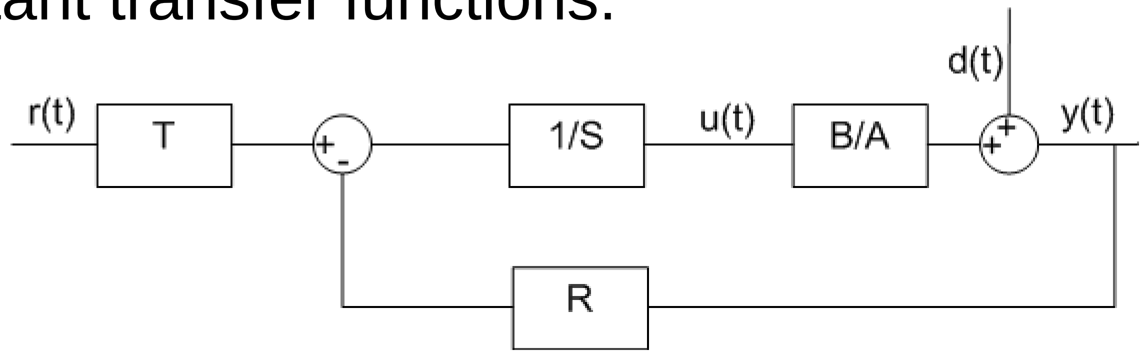
$$\begin{cases} T(z^{-1}) = R(z^{-1}) = r_0 + r_1 \cdot z^{-1} + r_2 \cdot z^{-2} \\ S(z^{-1}) = (1 - z^{-1}) \cdot (1 + s_1 \cdot z^{-1}) \end{cases}$$

with

$$\begin{cases} s_1 = \dfrac{-T_d}{T_d + N \cdot T_e} \\ r_0 = K \cdot \left(1 + \dfrac{T_e}{T_i} - N \cdot s_1\right) \\ r_1 = K \cdot \left[s_1 \cdot \left(1 + \dfrac{T_e}{T_i} + 2 \cdot N\right) - 1 \right] \\ r_2 = -K \cdot s_1 \cdot (1 + N) \end{cases}$$

RST digital control

2 important transfer functions:



REGULATION $\frac{y}{d} = \frac{A \cdot S}{A \cdot S + B \cdot R}$

TRACKING $\frac{y}{r} = \frac{B \cdot T}{A \cdot S + B \cdot R}$

The poles (stability) are defined by the denominator:

$$A(z^{-1}) \cdot S(z^{-1}) + B(z^{-1}) \cdot R(z^{-1}) = P_{des}(z^{-1})$$

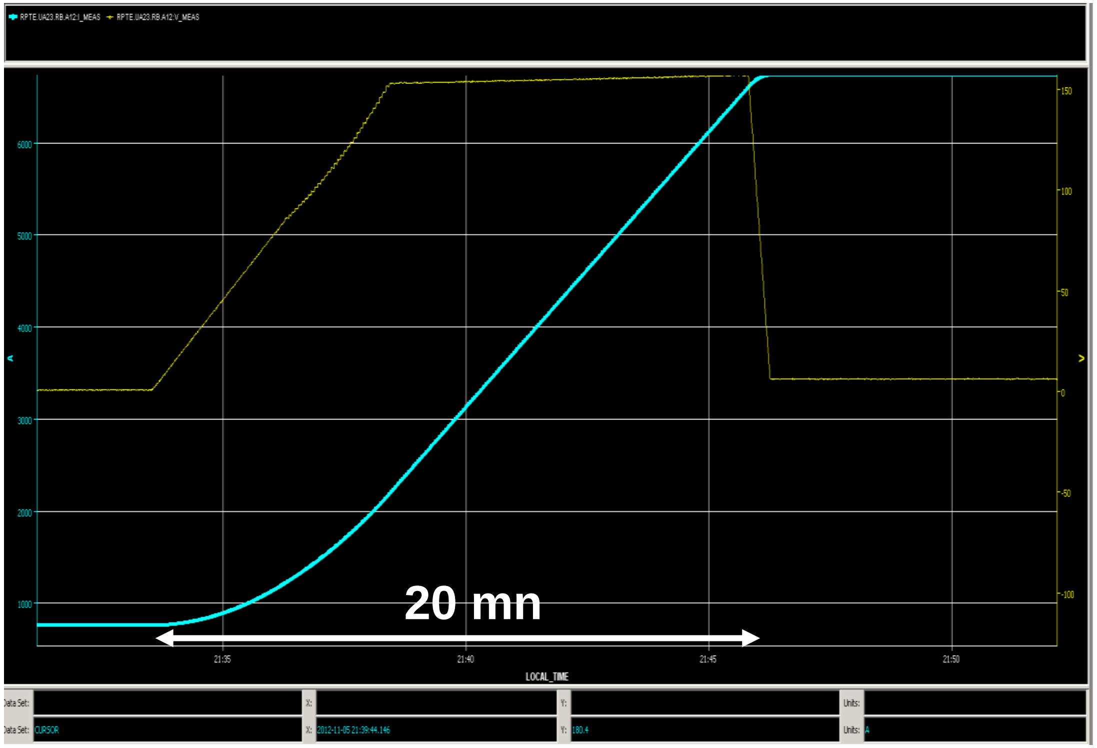
independent of T

Application for the control of the LHC power converters

Application for the LHC power converters

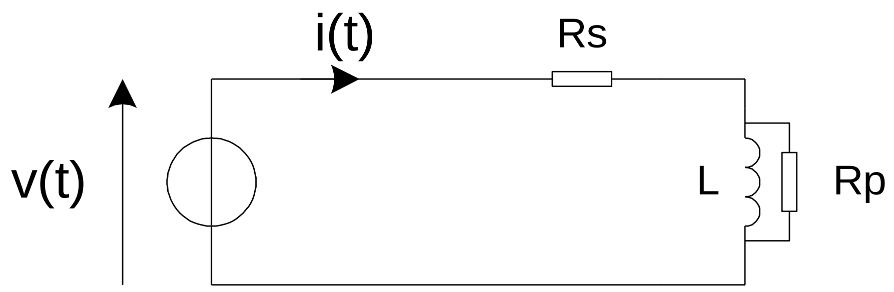
LHC requirements:

- Perfect tracking between the 8 sectors
- The load is a “ideal” R-L load (without saturation and thermal effect)
- The power converter (bandwidth = 1 kHz) is considered as a gain: $G_{pc} = 1$
- PLEP reference with 20 mn for ramping



Application for the LHC power converters

Model of the system:



$$\frac{I(s)}{V(s)} = \frac{1}{Rs} \cdot \frac{1+\frac{L}{Rp}\cdot s}{1+\frac{Rp+Rs}{Rp\cdot Rs}\cdot L \cdot s} = G1 + \frac{G2}{1+\tau 2 \cdot s}$$

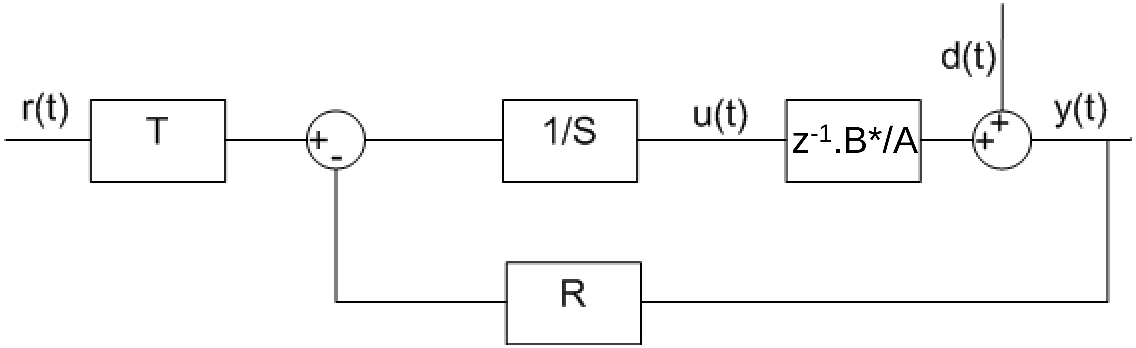
$$\begin{cases} G1 = \dfrac{1}{Rp+Rs} \\ G2 = \left(\dfrac{1}{Rs} - \dfrac{1}{Rp+Rs}\right) \\ \tau 2 = L \Big/ \left(\dfrac{Rp\cdot Rs}{Rp+Rs}\right) \end{cases}$$

$$\frac{i(z^{-1})}{v(z^{-1})} = Gz \cdot z^{-1} \cdot \frac{1+b_1\cdot z^{-1}}{1+a_1\cdot z^{-1}} = \frac{z^{-1}\cdot B^*(z^{-1})}{A(z^{-1})}$$

$$\begin{cases} Gz = G1 + G2\cdot\left(1-e^{-te/\tau 2}\right) \\ b1 = \dfrac{-G1\cdot e^{-te/\tau 2}}{G1+G2\cdot\left(1-e^{-te/\tau 2}\right)} \\ a1 = -e^{-te/\tau 2} \end{cases}$$

Application for the LHC power converters

Identification of R, S and T:



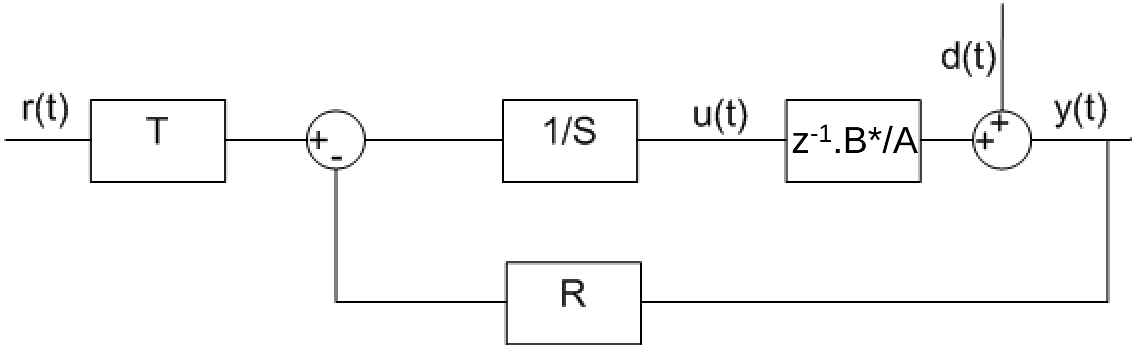
$$S = B^{*} \cdot \left(1 - z^{-1}\right)^{2}$$ **!! Only if B* is "stable" !!**

$$\frac{y}{d} = \frac{A \cdot S}{A \cdot S + B \cdot R} = \frac{A \cdot B^{*} \cdot \left(1 - z^{-1}\right)^{2}}{A \cdot B^{*} \cdot \left(1 - z^{-1}\right)^{2} + z^{-1} \cdot B^{*} \cdot R} = \frac{A \cdot \left(1 - z^{-1}\right)^{2}}{A \cdot \left(1 - z^{-1}\right)^{2} + z^{-1} \cdot R} = \frac{A \cdot \left(1 - z^{-1}\right)^{2}}{P_{des}}$$

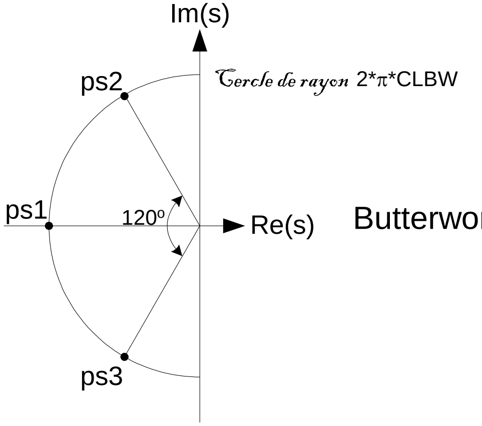
$$\frac{y}{r} = \frac{T \cdot B}{A \cdot S + B \cdot R} = \frac{T \cdot z^{-1} \cdot B^{*}}{A \cdot B^{*} \cdot \left(1 - z^{-1}\right)^{2} + z^{-1} \cdot B^{*} \cdot R} = \frac{T \cdot z^{-1}}{A \cdot \left(1 - z^{-1}\right)^{2} + z^{-1} \cdot R} = z^{-1}$$

Application for the LHC power converters

Identification of R, S and T:



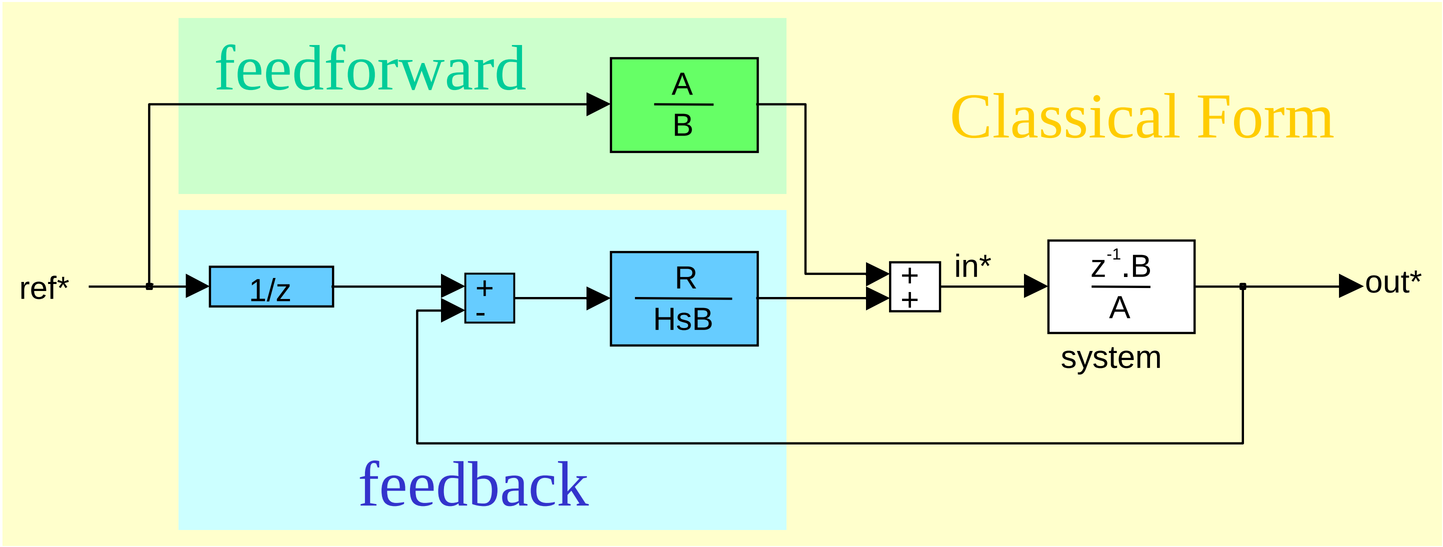
$$\begin{cases} S = B^* \cdot \left(1 - z^{-1}\right)^2 \\ R = z \cdot \left(P_{des} - A \cdot \left(1 - z^{-1}\right)^2\right) \\ T = A \cdot \left(1 - z^{-1}\right)^2 + z^{-1} \cdot R \end{cases}$$



Butterworth method

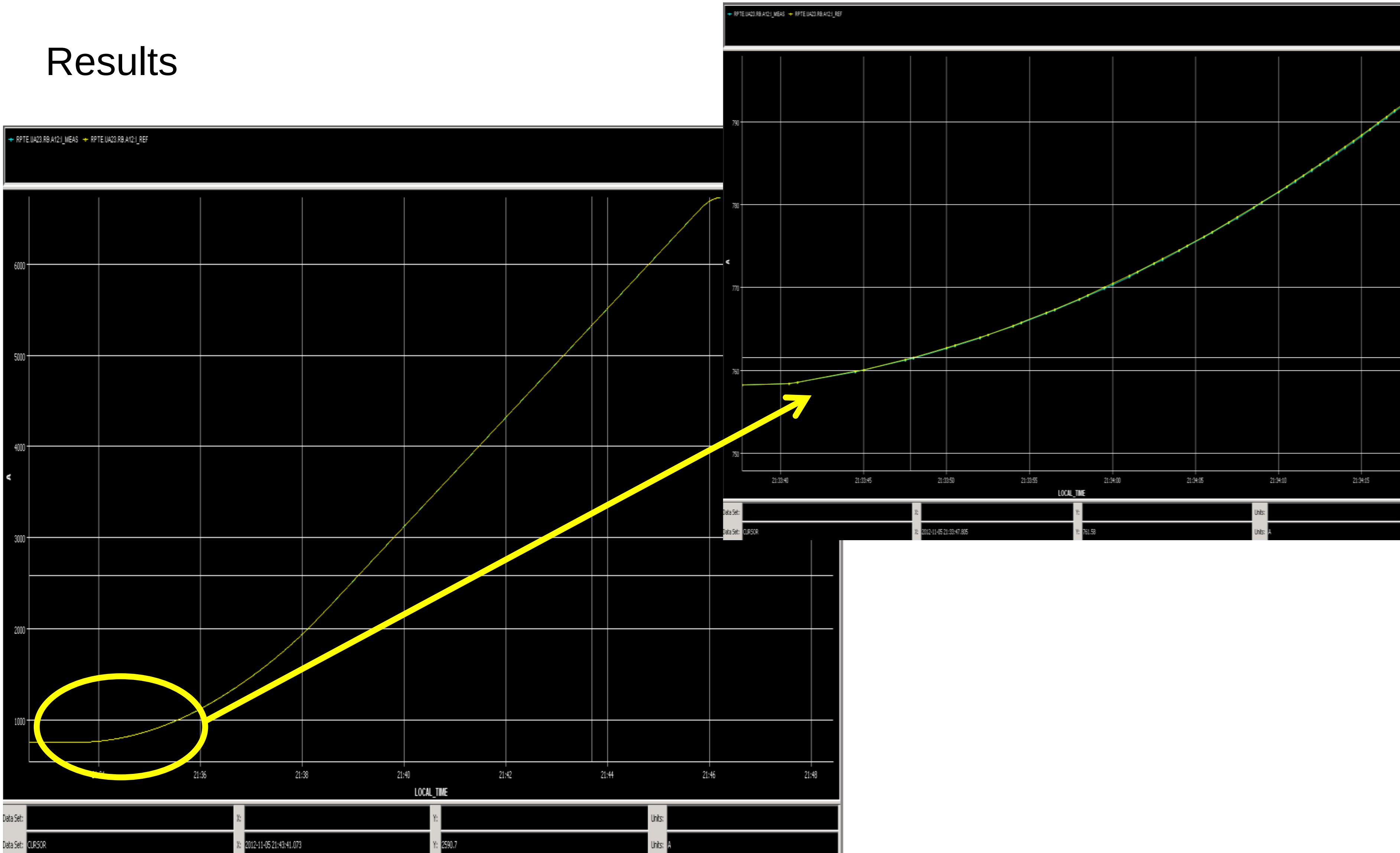
Application for the LHC power converters

Equivalent structure



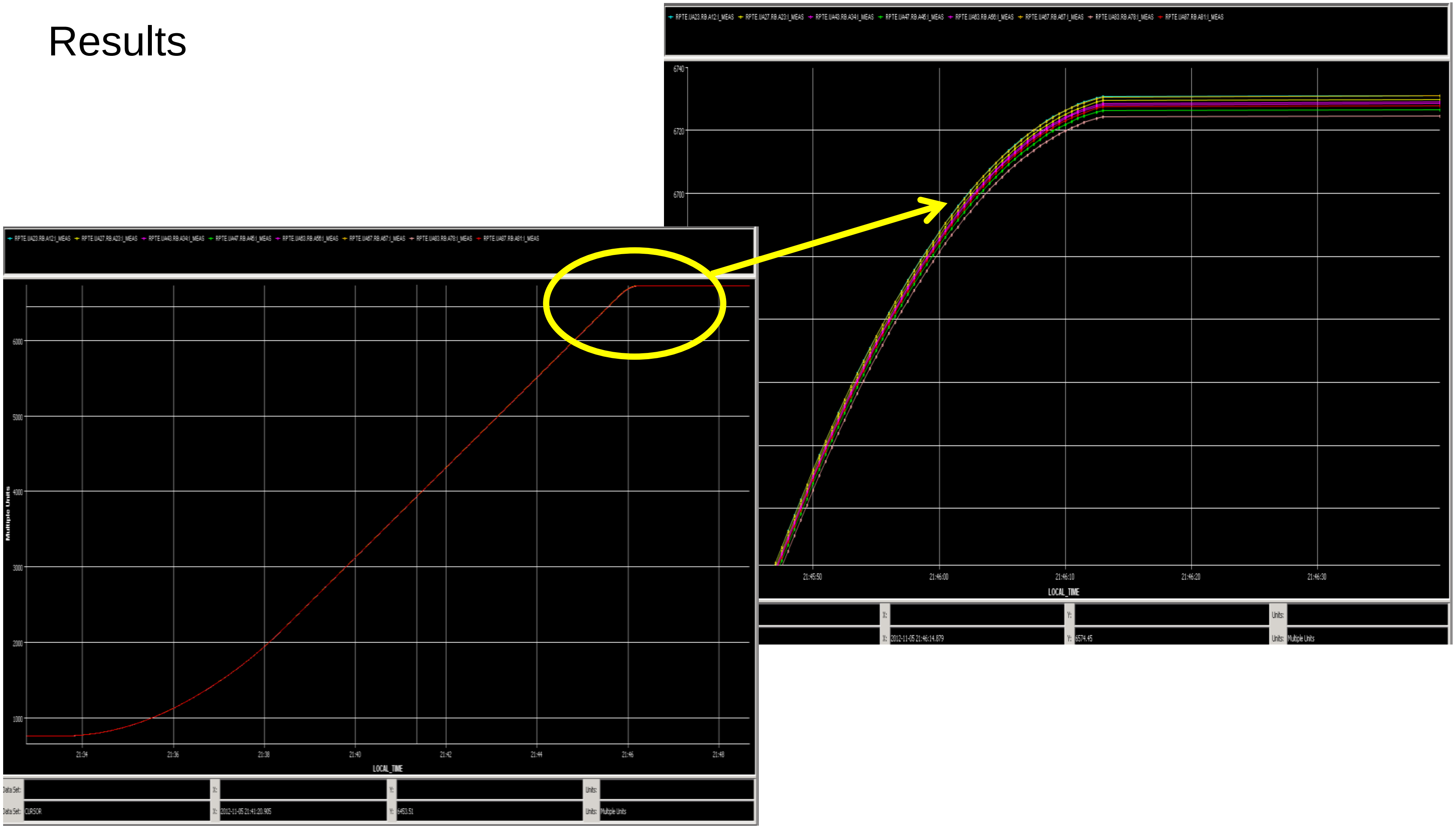
Application for the LHC power converters

Results



Application for the LHC power converters

Results



Conclusion

- ***The LHC requests a very high precision concerning the control of the power converter current***
- ***Digital regulation has been developed based on RST theory***
- ***All the linear regulator can be converted in RST***
    - ***Same implementation on the DSP***
- ***Today the RST control is used for all the new power converters and also for the voltage loop***

Bibliography

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