FUNCTION GENERATION AND REGULATION LIBRARIES AND THEIR APPLICATION TO THE CONTROL OF THE NEW MAIN POWER CONVERTER (POPS) AT THE CERN CPS

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Introduction

Power converter control for the LHC is based on an embedded control computer called a Function Generator/Controller (FGC). Every converter includes an FGC with responsibility for the generation of the reference current as a function of time and the regulation of the circuit current, as well as control of the converter state. With many new converter controls software classes in development it was decided to generalise several key components of the FGC software in the form of C libraries: function generation in libfg, regulation, limits and simulation in libreg and DCCT, ADC and DAC calibration in libcal. These libraries were first used in the software class dedicated to controlling the new 60 MW power converter (POPS) at the CERN Proton Synchrotron (CPS) where regulation of both magnetic field and circuit current is supported.

Software for download under the LGPL

All the libraries and associated test programs are available for download under the GNU Lesser General Public License from the website: http://cern.ch/cclibs

A test program for **libfg** and **libreg** called **cctest** is available. As well as testing the libraries, **cctest** is also a useful template for a real-time power converter regulation program. Makefiles are included for Linux and results are written to stdout as comma-separated values that can be analysed with any suitable tool such as GNUplot, Matlab or Excel.

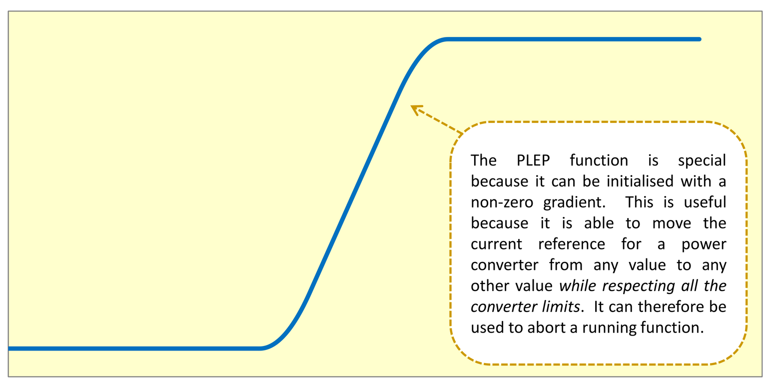
The libraries are written in standard C and have been compiled and tested under Linux and on two Texas Instruments DSPs, the TMS320C32 and the TMS320C6727. They should be easy to use on any floating-point processor.

libfg

Calculating a reference value as a function of time is a key requirement for most regulated systems. **Libfg** is a C library that can generate ten different types of reference function, as listed in the table to the right. Example functions generated by the **cctest** program using **libfg** are shown in the figures.

Name	Function description
PLEP	Single parabola-linear-exponential-parabola segment
PPPL	Multiple parabola-parabola-parabola-linear segments
TABLE	Table interpolated with linear segments
SPLINE	Table interpolated with parabolic splines
LINEAR	Single linear segment in a given time
CUBIC	Single cubic segment in a given time
SINE	Sine with optional window for a smooth start and end
COSINE	Cosine with optional window for a smooth start and end
SQUARE	Offset square wave
STEPS	Staircase of one or more steps

PLEP



PPPL

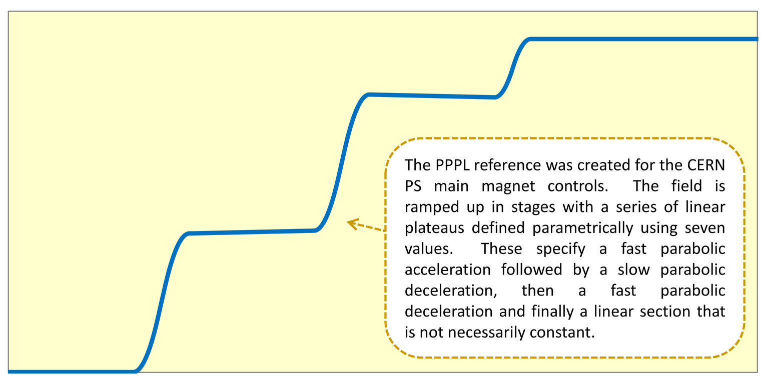
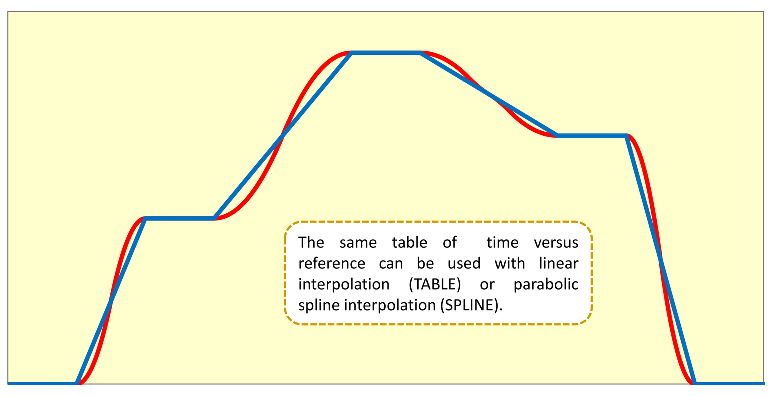
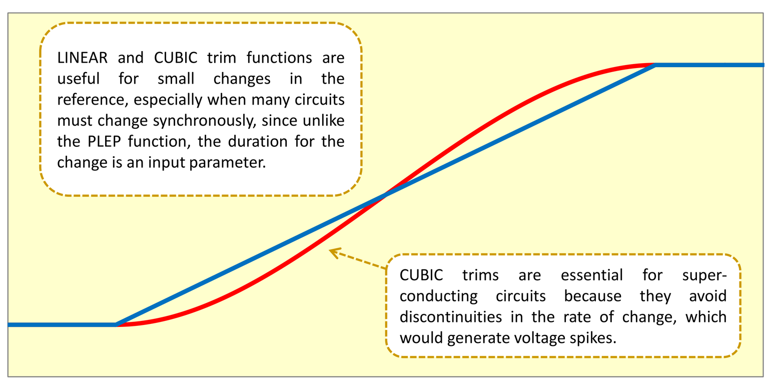


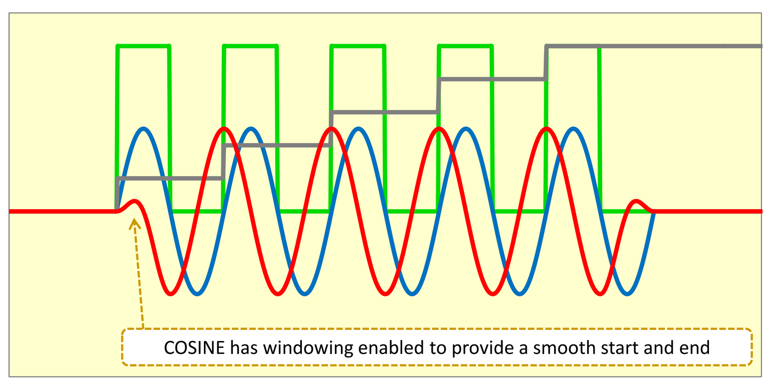
TABLE and SPLINE



LINEAR and CUBIC



SINE, COSINE, SQUARE and STEPS



libreg

Libreg is based on the **RST equation** which is a flexible and elegant way to implement any linear regulation algorithm up to order N. The equation uses three polynomials, R_i, S_i and T_i to balance the new and previous N samples of the Reference, Measurement and Actuation. For the new sample, if two of the three are known, *then the third can be calculated*.

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**

Reference ← $$Ref_0 = \frac{\sum_0^N\{Act_i \cdot S_i\} + \sum_0^N\{Meas_i \cdot R_i\} - \sum_1^N\{Ref_i \cdot T_i\}}{T_0}$$ ← *Actuation*, ↑ *Measurement*

Back-calculation of the Reference from the Actuation and Measurement

Reference → $$Act_0 = \frac{\sum_0^N\{Ref_i \cdot T_i\} - \sum_0^N\{Meas_i \cdot R_i\} - \sum_1^N\{Act_i \cdot S_i\}}{S_0}$$ → *Actuation*, ↑ *Measurement*

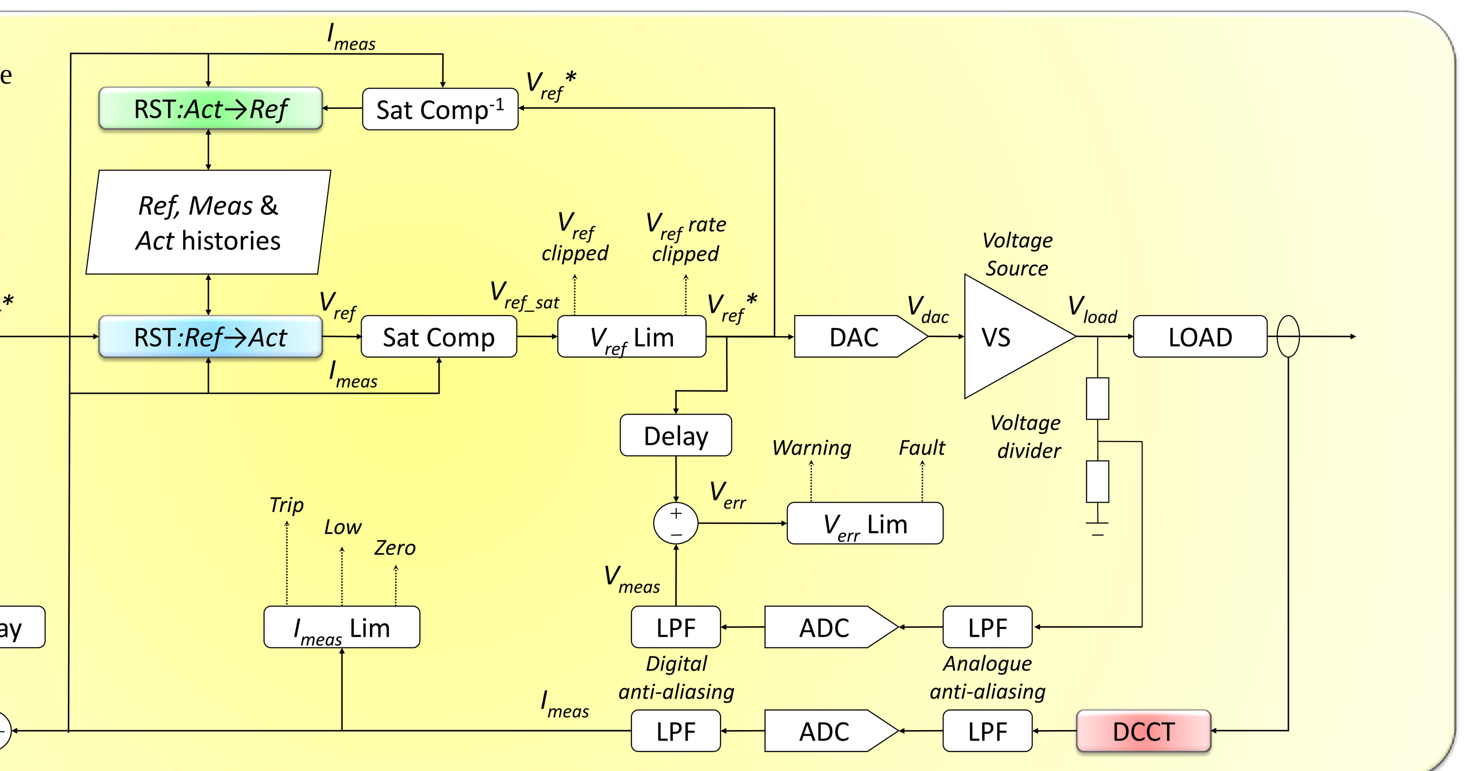
Forward-calculation of the Actuation from the Reference and Measurement

Libreg uses the Landau RST notation. In the other popular notation, the *R* and *S* polynomials are *exchanged*.

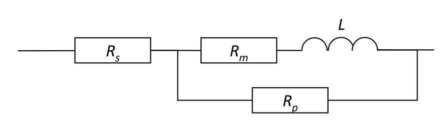
Libreg is toolbox with all the functions needed to assemble a complete converter regulation program, including :

- Reference limits
- Measurement limits
- RST algorithm
- Deadbeat RST calculation
- Signal delay
- Regulation error
- Load model
- Magnet saturation
- Magnet field to current
- Voltage source simulation
- Load simulation

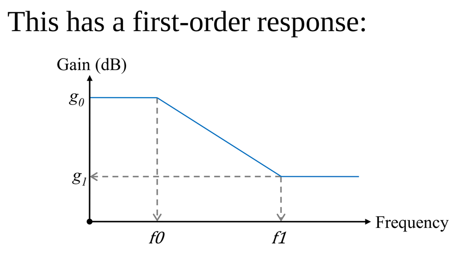
Figure 1: Current regulation of an analogue voltage source with magnet saturation compensation.



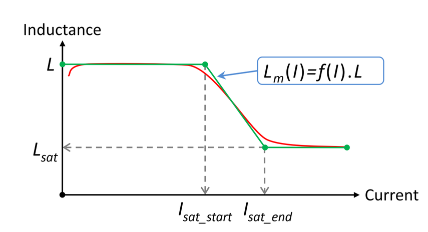
Libreg supports the following magnetic load model, which includes a damping resistor R_p:



This has a first-order response:



Magnet saturation is modelled with a simple linear model:



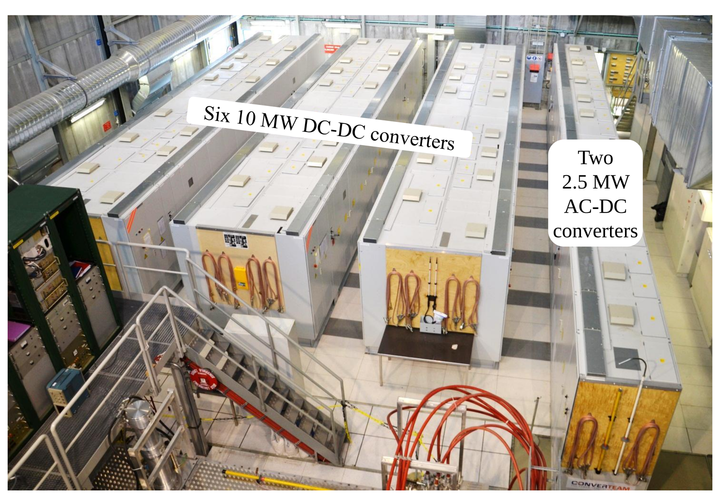
POPS

The POwer for PS converter is the most powerful individual converter at CERN with a peak power of 60 MW (±10kV, ±6kA). It uses six 3 MJ external capacitor banks to store the energy needed to ramp up the current in the PS main magnets and to recuperate the energy when the current is ramped down. Resistive losses are compensated by two 2.5 MW AC-DC front-end converters.

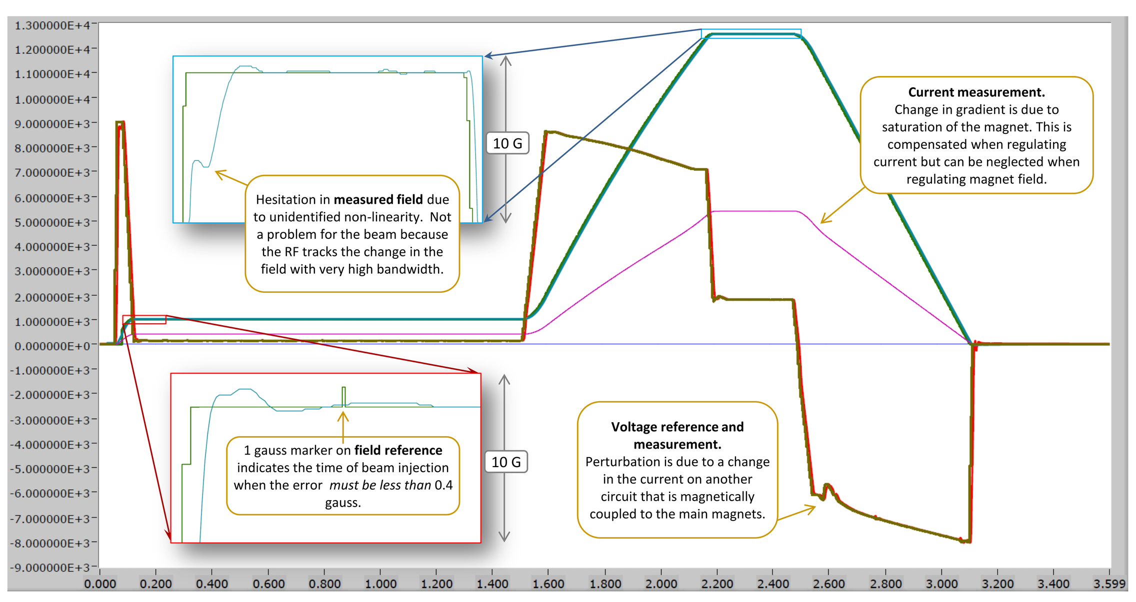
POPS is controlled digitally with a VME crate driving the IGBT firing and regulating the voltage. The outer current or magnetic field regulation is provided by libreg running in a Function Generator/Controller (FGC) linked to the VME crate by optical fiber links (see photo).

The reference function is generated in real-time by the FGC using libfg. Functions for up to 24 different types of cycle can be armed at the same time. The sequence of cycles to be played is defined in real-time by the central timing system which controls all the accelerators that inject the LHC. Cycles in the PS are between 1 and 6 basic-periods of 1.2 seconds. For each type of cycle the reference can be chosen to be either voltage, current or magnet field.

Function Generator/Controller regulating magnetic field with the POPS converter



Three basic-period cycle used for beams destined for the LHC



The open-loop response of the converter was identified using a step:

$$H(z) = \frac{0.1233\,z^3 + 0.2233\,z^2 - 0.2748\,z - 0.02186}{z^6 - 1.678\,z^5 + 0.8952\,z^4 - 0.1673\,z^3}$$

From this we calculated the RST coefficients for the voltage loop running at 1 kHz in the VME CPU.

The same approach was then used to identify the closed-loop response of the converter together with the load:

$$H(z) = \frac{0.002163\,z^3 + 0.005448\,z^2 + 0.0006797\,z + 1.636 \cdot 10^{-6}}{z^5 - 0.9578\,z^4 - 0.03295\,z^3 - 0.008221\,z^2}$$

From this, we calculated the RST coefficients for the field and current regulation loops running at 333.3 Hz in the FGC.