CCLIBS: THE CERN POWER CONVERTER CONTROL LIBRARIES

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Abstract

Accurate control of power converters is a vital activity in large physics projects. Several different control scenarios may coexist, including regulation of a circuit's voltage, current, or field strength within a magnet. Depending on the type of facility, a circuit's reference value may be changed asynchronously or synchronously with other circuits. Synchronous changes may be on demand or under the control of a cyclic timing system. In other cases, the reference may be calculated in real-time by an outer regulation loop of some other quantity, such as the tune of the beam in a synchrotron. The power stage may be unipolar or bipolar in voltage and current. If it is unipolar in current, it may be used with a polarity switch. Depending on the design, the power stage may be controlled by a firing angle or PWM duty-cycle reference, or a voltage or current reference. All these cases are supported by the CERN Converter Control Libraries (CCLIBS). These open-source C libraries include advanced reference generation and regulation algorithms. This paper introduces the libraries and reviews their origins, current status and future.

INTRODUCTION

The CERN converter control libraries are a collection of libraries written in C, available under the GNU Lesser General Public License from https://github.com/cclibs.

The libraries were started in 2010 by extracting the measurement calibration, function generation and current regulation code from the operational software used to control the power converters in the CERN LHC. This software was originally deployed in the LHC magnet test facility in 2000 [1,2], so the libraries built on ten years of experience with the high-precision control of current in magnet circuits [3].

Figure 1 shows an overview of the architecture of a power converter controller based on CCLIBS. The long-term objective is to move all the re-usable generic software components into CCLIBS and to leave the application with just the hardware specific components.

In 2012, the new libraries [4] were deployed into operation on two different hardware platforms [5] and a third platform was added the following year.

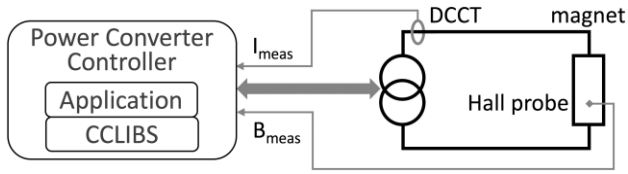

Figure 1: The role of CCLIBS in converter control

In 2013, a second version of the libraries was started with the objective to support regulation of magnetic field measured by a hall probe. Hall probes have more noise than current transducers (DCCTs), so more advanced anti-aliasing filtering is needed. This in turn requires more advanced algorithms for the computation of the coefficients for the RST regulator, to accommodate the additional delay from the filters.

Then in 2015, a new reference manager library, libref, was created to support the three different operating modes used with magnet circuits at CERN. This is well advanced and will be deployed into operation in 2016, along with two more libraries, libsig and liblog. Several other features will also be added, including voltage regulation for thyristor converters.

THE LIBRARIES

Taken together, the Converter Control Libraries have too many features to cover them all in this short paper. Furthermore, the first versions of libfg and libreg were described in [4] so this paper will report some of the improvements made to libfg and libreg as well as the main features of the new libraries and test programs.

Libcal: Calibration

The calibration library was part of CCLIBS from the start. It provides a three-point calibration scheme for ADCs and DCCTs, with second order temperature compensation. This accommodates an offset and separate positive and negative gain errors. The library also supports three-point DAC calibration and a simple scaling for hall probes and voltage probes (i.e. no offset and just one gain that applies to both positive and negative measurement values). The library will be optimised for better performance in 2016.

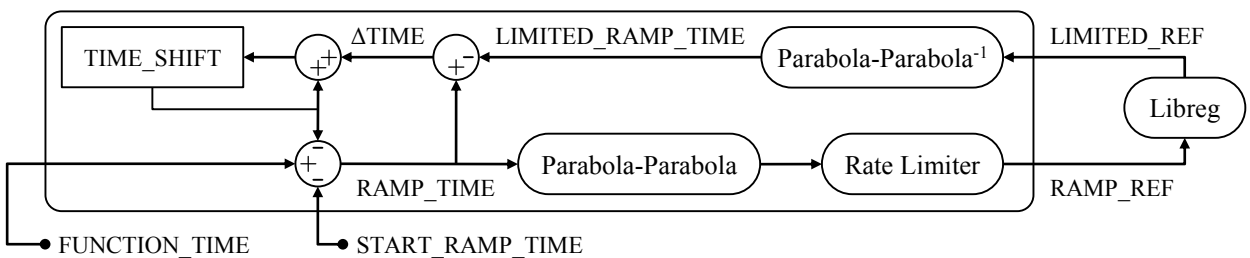

Figure 2: The RAMP function algorithm

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Libfg: Function Generation

The new version of libfg has a simplified API and now supports twelve reference functions, including a new RAMP function with special powers. It can start with a non-zero rate of change, which allows it to take over smoothly from a running function. The start and end of a RAMP are always smooth because it is based on two parabolic segments. What makes RAMP uniquely powerful is the way it can respond to the clipping of the reference, either by RAMP's rate limiter or by libreg.

Figure 2 shows how the LIMITED_REF value returned from libreg is used to calculate the TIME_SHIFT variable, which is then subtracted from the FUNCTION_TIME to generate the RAMP_TIME. It uses the classic formula to invert the quadratic equations of the parabolas:

$$\frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \rightarrow LIMITED\_RAMP\_TIME$$

The difference between LIMITED_RAMP_TIME and the actual RAMP_TIME is accumulated as TIME_SHIFT. In this way the parabolic functions are distorted by effectively slowing down time while the reference is being limited.

Libreg: Regulation

The new version of the regulation library builds on the original and has many new features and improvements; the API has been simplified to ease integration, new algorithms have been added to calculate and validate the RST coefficients, a two-stage sliding average anti-aliasing filter is available for measurement signals and field regulation is now supported as well as dynamic switching between current, field and voltage regulation modes.

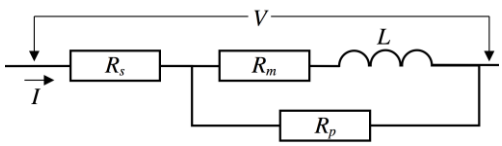

Figure 3: First order magnet circuit supported by libreg

The new algorithms for calculating the RST coefficients implement an internally stable pseudo-deadbeat regulator for the first-order magnet circuit shown in Fig. 3. They can accommodate up to 2.4 periods of loop delay (compared to only 0.4 periods in the first version of libreg). As before, the RST coefficients can also be calculated externally and in both cases libreg checks the stability of the regulator using Jury's test. For an internally generated regulator, the modulus margin is calculated to check the vulnerability of the regulator to errors in the model.

The new library also implements an open-loop controller for the first-order magnet circuit shown in Fig. 3. The circuit current $I(t)$ respects the differential equation:

$$(R_p + R_m)V(t) + L\frac{dV}{dt}(t) =$$
$$(R_p + R_s)L\frac{dI}{dt}(t) + (R_s(R_p + R_m) + R_pR_m)I(t)$$

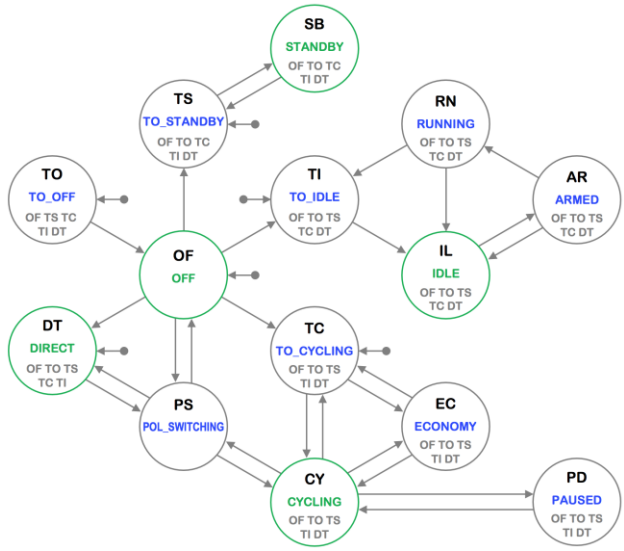

Figure 4: The Reference State Machine

This is implemented in libreg with a forward Euler approximation. It can run forwards (ref→actuation) or backwards (actuation→ref) in a similar way to the closed-loop RST algorithm. Libreg will automatically use the open-loop controller for one and two-quadrant power converters when the current (or field) is below the closed-loop threshold. This is the level below which the voltage source gain is non-linear and closed-loop regulation becomes unreliable. This feature makes starting and stopping of one and two-quadrant converters very easy to implement in the new reference manager library.

Another new feature of libreg helps with the reality that there is rarely enough time to commission accelerator circuits in depth because of the pressure to get an accelerator into production as quickly as possible. With a rapid cycling machine, sometimes the operators can allocate one cycle per super-cycle without beam, to allow the continued refinement of the regulation parameters in parallel with operation. On these cycles, libreg can switch automatically to use a set of test RST coefficients.

Libref: Reference Management

The reference manager library uses libfg and libreg to provide a full range of advanced features to the converter control application. Its behaviour is controlled by the Reference State machine, which is illustrated in Fig. 4. This supports three operating modes, associated with the states DIRECT, CYCLING and IDLE (see below).

Libref uses the new RAMP function together with the new open-loop regulator in libreg to implement the smooth starting and stopping of one and two-quadrant converters. This is an elegant solution that makes the handling of one and two-quadrant converters equivalent to that of four-quadrant converters.

Libref manages the switching between the three regulation modes supported by libreg (field, current and voltage). It allows the application to prepare to run a reference function for a given regulation mode. This is known as "arming" the function.

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Libref also implements polarity switch management. This allows a low-cost unipolar converter to be used with a bipolar circuit. Switching can be on-demand, or automatic in DIRECT and CYCLING states, based on the polarity of the reference function.

THE TEST PROGRAMS

One of the motivations for the creation of the converter controls libraries was to make it possible to test these critical software components outside of the embedded systems in which they run operationally. This is because debugging is much easier on a desktop computer, where resources are abundant. A growing portfolio of test scripts is run automatically as part of the group's continuous integration system, both nightly and following commits to CERN's git repository (this is not github).

CCLIBS currently has two different test programs, cctest and ccrt, but by 2017, ccrt will be able to cover all the testing requirements for CCLIBS and support for cctest will be dropped.

Single-Threaded Test Program: cctest

Cctest, was created in 2010 at the same time as the first libraries. It reads commands interactively from standard input or from files when running in batch mode. It only tests libfg and libreg and it runs simulations of a power converter with an inductive load for a specified series of reference functions. A large number of digital and analog signals are logged and then written to files in HTML, JSON or CSV formats. Examples can be seen on the project web site: https://cern.ch/cclibs.

Cctest, like the libraries, is written in standard C and has very few dependencies. It compiles and runs under Linux, MacOS and MinGW on Windows.

Multi-Threaded Test Program: ccrt

In 2015, libref was created to manage reference generation. The library is designed to work with a real-time thread (or interrupt) and a background thread. This requires a multi-threaded test program, so ccrt was created by forking cctest.

Ccrt tests libref, libfg and libreg, and it will be extended in 2016 to test libsig, libcal and liblog. It implements some important features that are missing from cctest, including parameter assertions (equals, not equals, less than, greater than and approximately equals), as well as synchronisation commands to sleep, wait for a reference state or wait for a function to complete. This allows detailed use cases to be tested rigorously without the need for a human to review simulation results graphically (as is the case with cctest).

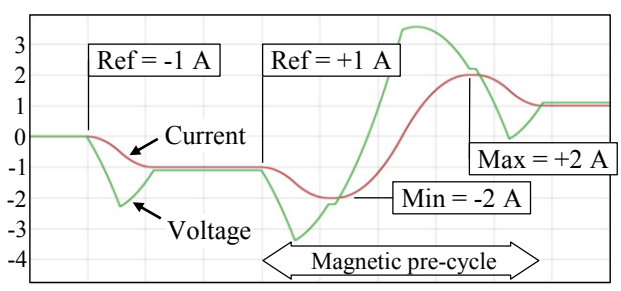

Figure 5: Example of an UPMINMAX pre-cycle

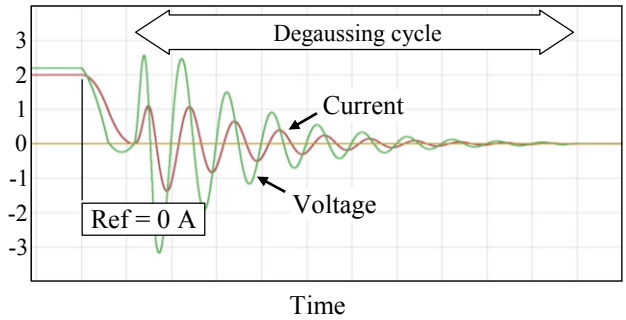

Figure 6: Example of a degaussing cycle

There are still a few features of libfg and libreg that can only be tested in cctest, but in 2016, these missing features will be added to ccrt so that in 2017, support for cctest will be dropped. Ccrt uses Posix threads and currently runs only under Linux, but it will be adapted to run under MacOS. In principle, it should then also work under MSYS2/MinGW-w64 on Windows.

DIRECT, CYCLING AND IDLE

Libref will cover all the operational use cases of power converter control present in CERN's accelerators. These divide into three operating modes that are managed by the DIRECT, CYCLING and IDLE states.

DIRECT for DC Circuits

The DIRECT state was added to support circuits which operate with a stable DC reference (which defines the field, current or voltage according to the regulation mode). The reference value may need to be modified from time to time, but the form and synchronisation of the ramp to the new reference value is not important to the accelerator operators. So libref is responsible for this change and it uses the RAMP function. The acceleration, deceleration and linear rate limit are taken from default parameters. If the ramp speed is important, the rate limiter can be disabled and the ramp will be limited only by the available voltage.

Libref implements three advanced features in DIRECT state to cover particular use cases at CERN: magnetic pre-cycling, automatic degaussing and automatic polarity switch control.

Magnetic pre-cycling improves the reproducibility of the field in a magnet by always approaching the new reference following the same magnetisation curve. Two options are supported: DOWNMAXMIN and UPMINMAX.

With UPMINMAX, the reference will always approach the new value from above. Thus, when going down, no pre-cycle is needed, but when going up, the reference must first visit the minimum and maximum values. In each case, the reference will pause for a time chosen to allow the eddy currents to decay. This is illustrated in Fig. 5, where the initial ramp is from 0 A to -1 A. This is followed by a request to go up to +1 A, which triggers the MINMAX pre-

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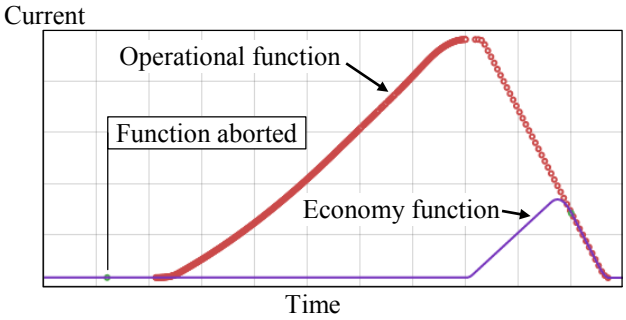

Figure 7: A dynamic economy cycle from the CERN SPS

cycle. The behaviour of DOWNMAXMIN is simply the mirror image of UPMINMAX.

If the remanent magnet field must be minimised, a degaussing cycle can be enabled. In this case, a ramp to zero amps (or zero gauss if regulating the field) will trigger a degaussing waveform. This is an exponentially decreasing sine wave, windowed to have a smooth start and end. The amplitude and period can be selected according to the needs of the magnet. Figure 6 shows an example of a degaussing waveform, triggered by setting the current reference to zero while at 2A.

CYCLING for Rapid Cycling Machines

The accelerators that collectively inject particles into the LHC all operate periodically under the control of a sophisticated timing system. Super-cycles typically lasting thirty seconds are assembled from cycles with particular uses. The identity of the next cycle (the "cycle selector") is broadcast in real-time over a dedicated timing network to all the equipment in the accelerator, which must be ready to execute whichever cycle is specified. Libref supports this by allowing the application to arm a different function and regulation mode for every cycle selector. The timing events must be passed to the library, giving it the cycle selector and absolute start time of the next cycle. The library then takes care of executing the selected function at the correct time.

Function generation can be suspended and resumed by timing events. When suspended the state machine will be in the PAUSED state. The active function can be replaced by another function while paused and if the reference changes, the PAUSED state will use a RAMP function to change smoothly to the new value.

If a polarity switch is in use with a unipolar converter, then the CYCLING state is able to switch polarity between cycles based on the polarity of the next reference function (which must be all positive or all negative).

In large non-super-conducting circuits, the resistive losses can be significant. If beam for a given cycle selector is not available, then it is desirable to suppress the execution of the function in real-time. However, this disturbs the magnetic field of the following cycle because the eddy currents that would normally be induced by the ramp down are not present. This is addressed by the dynamic economy feature. It allows a running function to be aborted if there is no beam. The reference ramps down to the minimum RMS level and then ramps up to join the end of the original function smoothly at a user-specified time. This can be at as little as 25% of the maximum reference value, but the remaining ramp down excites the eddy currents that are expected at the start of the next cycle. The result is a major reduction in resistive losses. This behaviour is provided in the ECONOMY state. Figure 7 shows an example of a dynamic economy cycle from the CERN SPS accelerator.

IDLE for Single-Use Reference Functions

The LHC cycles aperiodically with every ramp triggered by the operators. Although a ramp in energy might be repeated from cycle to cycle, when this is converted into a ramp in current for a given super-conducting circuit, it is always different because it depends upon the powering history of that circuit. So functions are only ever used once and are then disarmed automatically.

This functionality is provided by the states IDLE, ARMED and RUNNING. A new function can only be armed in the IDLE state, and must begin from the actual reference. Once a function has been armed, the state changes to ARMED and the function can be started synchronously with a timing event. The function will be generated in the RUNNING state, and upon completion, it is disarmed and the state machine returns to IDLE.

The running function can be aborted before the end with another timing event, changing the state to TO_IDLE. This will smoothly decelerate and return parabolically to the reference value that was latched at the moment of the abort event. The state then returns to IDLE.

CONCLUSION

The CERN converter controls libraries build on more than fifteen years of experience with accurately regulating the current in magnet circuits. They will form the heart of CERN's converter controls software for years to come and are freely available under the GNU Lesser General Public License.

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