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DATA-DRIVEN CONTROLLER DESIGN USING THE CERN POWER CONVERTER CONTROL LIBRARIES (CCLIBS)

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Abstract

The data-driven control approach is a control methodology in which a controller is designed without the need of a model. Parametric uncertainties and the associated unmodeled dynamics are therefore irrelevant; the only source of uncertainty comes from the measurement process. The CERN Power Converter Control Libraries (CCLIBS) have been updated to include data-driven H-infinity control methods recently proposed in literature. In particular, a two-step convex optimization algorithm is performed for obtaining the 2-degree-of-freedom controller parameters. The newly implemented tools in CCLIBS can be used both for frequency response measurement of the load and for controller synthesis. A case study is presented where these tools are used for an application in the CERN East Area Renovation Project for which a high-precision 900 A trapezoidal current pulse is required with 450 ms flat-top and 350 ms ramp-up and ramp-down times. The tracking error must remain within +/- 100 parts-per-million (ppm) during the flat-top (before the ramp-down phase starts). The magnet considered in the case study is of non-laminated iron type, hence the necessity of data-driven techniques since the dynamics of such a magnet is difficult to be modeled accurately (due to eddy currents losses). The power converter used is a SIRIUS 2P (with a current and voltage rating of 400 Arms and 450 V, respectively) whose digital control loop is regulated at a sampling rate of 5 kS/s.

INTRODUCTION

The CERN power converter control libraries [1] have recently been updated to include tools both for frequency response function (FRF) measurement and for data-driven design of power converters digital control. The data-driven approach mitigates the problems associated with model-based controller designs (such as unmodeled dynamics); this ensures that the measurement process is the only source of uncertainty. A survey on the differences between the model-based control and data-driven control schemes has been addressed in [2], among many others. Data-driven control schemes can be realized in the time-domain and frequency-domain; in CCLIBS, or more accurately, in an extension of the Function Generator/Controller (FGC) [3] system that combines embedded control computers along with expert software tools, the frequency-domain approach is used (CCLIBS will be used as a shorthand both for CCLIBS themselves and this FGC extension). The implemented algorithms are based on minimizing the $\mathcal{H}_p$ norm

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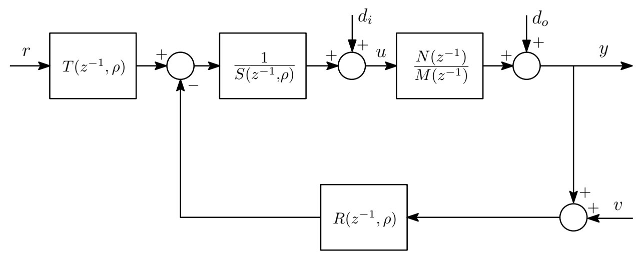

Figure 1: *RST* controller structure.

(for $p \in \{2, \infty\}$) of a model reference cost function. A two-step process is proposed for obtaining a local minimum of the $\mathcal{H}_p$ problem for fixed-structure controllers; these two steps follow the ideas presented in [4] and [5] for achieving the desired tracking and robustness specifications. CERN adopted the RST control structure for the control of the current in the particle accelerator magnets since LHC; the control is implemented by the FGC platform [3]. The RST controller structure, shown in Fig. 1, is a discrete-time two-degree of freedom polynomial controller where the tracking and regulation characteristics can be formulated independently, which is definitely important for the applications. Particle accelerator magnets sometimes suffer from eddy currents losses which complicates their modeling process as electrical load of the power converter. Data-driven design is therefore an asset as it is completely independent of the load model. The new CCLIBS data-driven tools are illustrated here for application in the East Area Renovation Project at CERN with SIRIUS 2P power converters. The family of SIRIUS power converters employs a grid supply unit that consists of a passive rectifier unit with boost converter that acts as a grid current regulator. The grid supply unit limits the power taken from the power grid to just 20 kV A with a modest 32 A / 400 V 3-phase line voltage. This family of newly designed power converters serves to improve power quality towards the power network by limiting the input power fluctuations.

CONTROLLER DESIGN METHOD

The plant model is represented as a coprime factorization $G(z^{-1}) = N(z^{-1})M^{-1}(z^{-1})$, where $N(z^{-1})$ and $M(z^{-1})$ are stable, proper transfer functions and z is the complex frequency variable used to represent discrete-time systems. Let the FRF of such a factorized discrete-time SISO system be defined as follows:

$$G(e^{-j\omega}) = N(e^{-j\omega})M^{-1}(e^{-j\omega}), \qquad \forall\omega \in \Omega \tag{1}$$

where $\Omega = [0, \pi]$. $N(e^{-j\omega})$ and $M(e^{-j\omega})$ must be FRFs of bounded analytic functions outside the unit circle; for

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power converters connected to particle accelerator magnets $N(e^{-j\omega}) = G(e^{-j\omega})$ and $M(e^{-j\omega}) = 1$ is assumed (as they always represent stable systems).

The RST structure is realized by polynomial functions as follows:

$$R(z^{-1}, \rho) = r_0 + r_1 z^{-1} + \cdots + r_{n_r} z^{-n_r} \tag{2}$$
$$S(z^{-1}, \rho) = 1 + s_1 z^{-1} + \cdots + s_{n_s} z^{-n_s} \tag{3}$$
$$T(z^{-1}, \rho) = t_0 + t_1 z^{-1} + \cdots + t_{n_t} z^{-n_t} \tag{4}$$

where $\{n_r, n_s, n_t\}$ are the orders of the polynomials R, S and T, respectively. The controller parameter vector $\rho \in \mathbb{R}^n$ (vector of decision variables) is defined as:

$$\rho^\top = [r_0, r_1, \ldots, r_{n_r}, s_1, s_2, \ldots, s_{n_s}, t_0, t_1, \ldots, t_{n_t}]$$

where $n = n_r + n_s + n_t + 2$; in CCLIBS, $S^{-1}(\rho)$ includes two integrators, thus $n_s > 2$.

$\mathcal{H}_p$ *Performance via Convex Optimization*

For notation purposes, the dependency in $e^{-j\omega}$ will be omitted. For the CERN power converter control system, there are three main requirements to be met: find an RST controller that (i) attain the desired closed-loop bandwidth by minimizing the model-reference cost function, (ii) ensure robustness by specifying a desired modulus margin, and (iii) ensure controller stability (i.e. $S^{-1}(\rho)$ is stable) as this is a specific CCLIBS requirement [1]). Let us define $\mathcal{S}_1$ as the FRF from d_o to y (i.e., $\mathcal{S}_1(\rho) = S(\rho)\psi^{-1}(\rho)$) and $\mathcal{S}_2$ as the closed-loop FRF (i.e., $\mathcal{S}_2(\rho) = GT(\rho)\psi^{-1}(\rho)$) where $\psi(\rho) = GR(\rho) + S(\rho)$. An optimization problem can be formulated to obtain the admissible $R(\rho)$, $S(\rho)$, and/or $T(\rho)$ controllers as follows:

$$\begin{aligned} \underset{\rho}{\text{minimize}} \quad & \|W[\mathcal{S}_2(\rho) - \mathcal{S}_2^d]\|_p \\ \text{subject to:} \quad & \|m_d \mathcal{S}_1(\rho)\|_\infty < 1 \\ & \Re\{S(\rho)\} > 0 \\ & \forall \omega \in \Omega \end{aligned} \tag{5}$$

where W is a weighting function, $\mathcal{S}_2^d$ is the desired closed-loop FRF and m_d is the desired modulus margin. In CCLIBS, $\mathcal{S}_2^d$ is set as a second order system : $\mathcal{S}_2^d(s) = \omega_d^2(s^2 + 2\zeta\omega_d s + \omega_d^2)^{-1}$, where ζ is the desired damping factor and ω_d is selected such that the desired closed-loop bandwidth is attained. The condition $\Re\{S(\rho)\} > 0$ is sufficient for the stability of the RST controller itself (where $\Re\{\cdot\}$ signifies the real part of the argument). This problem, as stated, is not convex and does not guarantee the closed-loop stability of the system. For $p \in \{2, \infty\}$, the Schur complement lemma [6] can be used to linearize the non-convex problem around an initial controller parameter vector ρ_0. For $p = \infty$, this linearization leads to the following convex problem:

$$\begin{aligned} \underset{\rho,\gamma}{\text{minimize}} \quad & \gamma \\ \text{subject to:} \quad & \\ & \begin{bmatrix} \Psi(\rho) & [W(GT(\rho) - \psi(\rho)\mathcal{S}_2^d)]^\star \\ W(GT(\rho) - \psi(\rho)\mathcal{S}_2^d) & \gamma \end{bmatrix} > 0 \\ & \begin{bmatrix} \Psi(\rho) & [m_d M S(\rho)]^\star \\ m_d M S(\rho) & 1 \end{bmatrix} > 0 \\ & \Re\{S(\rho)\} > 0 \\ & \omega \in \Omega \end{aligned} \tag{6}$$

where $\Psi(\rho) = \psi^\star(\rho)\psi_0 + \psi_0^\star\psi(\rho) - \psi_0^\star\psi_0$ and $\psi_0 = \psi(\rho_0)$. A similar optimization problem can be formulated for $p = 2$. According to [5], ψ_0 must be selected such that the Nyquist stability criterion is satisfied (to ensure the closed-loop stability). Additionally, $S(\rho)$ and $S(\rho_0)$ must share the same zeros on the stability boundary; thus $S^{-1}(\rho_0)$ must also contain as many integrators as desired in $S^{-1}(\rho)$. In order to obtain the initial controller parameter ρ_0, another optimization problem is solved based on the work in [4]; in this method, a convex approximation of the $\mathcal{H}_\infty$ problem is solved where the solution to this convex problem converges to the global solution of the $\mathcal{H}_\infty$ problem as the controller order goes to infinity (while guaranteeing the closed-loop stability). Implementing large order controllers, however, is not desirable due to rounding errors and computational burden. Thus the following two steps are implemented for obtaining the optimal controller for the problem in (5):

(i) use the convex approximation method in [4] to obtain ψ_0 for an arbitrarily large order controller;

(ii) use this ψ_0 to solve the problem in (6) for a fixed-structure low order controller.

Note that the solution to (6) ensures the local solution to the $\mathcal{H}_\infty$ problem for fixed-structure controllers. The optimization problem in (6) is convex and has an infinite amount of constraints. To solve this problem, a semi-definite programming (SDP) approach is used to grid the frequency vector into a finite amount of points; the frequency points may be equally spaced, logarithmically spaced, or chosen using a randomized approach (see [7, 8]). The MATLAB® environment is called (by the graphical user interface called FGCRun+) to run these SDP-based libraries.

EXPERIMENTAL VALIDATION

The new libraries were validated on a SIRIUS 2P converter (shown in Fig. 2) powering the non-laminated iron MDX test magnet (R = 300 mΩ, L = 200 mH) with a trapezoidal reference current having ramp-up/ramp-down times of 350 ms and a 900 A flat-top of 450 ms duration. The MDX magnet was chosen as representative of solid yoke magnets to be powered in the East Area; the challenge of the application is to guarantee that the tracking error remains within ±100 ppm (of 900 A) 50 ms after the ramp-up phase has terminated (see Fig. 4).

Measurement of the Open-Loop FRF

Part of the CCLIBS upgrade is a new set of libraries implementing a *software TFA* (Transfer Function Analyzer). They allow measuring the FRF of the *trans-admittance* (voltage source, cables, magnet, ADC/DAC interfaces), both in

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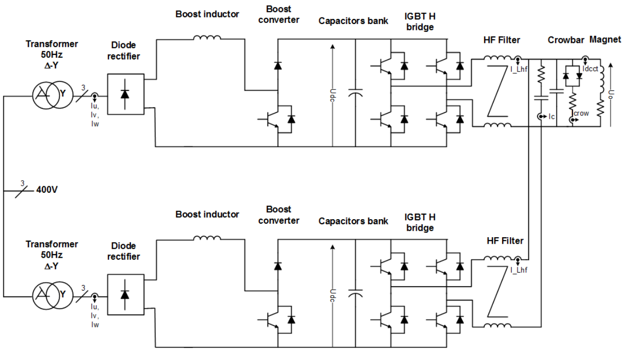

Figure 2: SIRIUS 2P power converter.

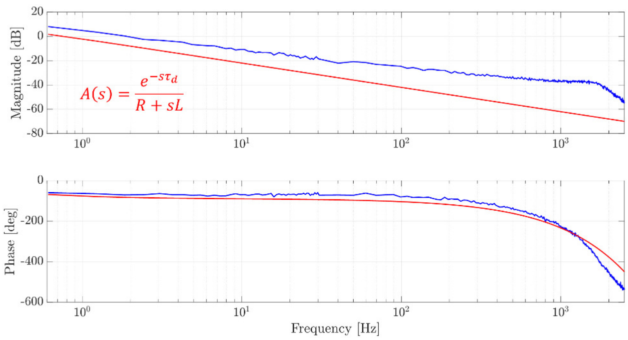

Figure 3: Frequency response of the *trans-admittance* from the power converter reference voltage to the measured current in the magnet. Measured (blue); *nominal* R-L series model including an estimated *digital* delay $\tau_d \approx 400\,\mu s$ (red).

open-loop and in closed-loop, either by sine wave excitation (by means of a *3-parameter sinefit* [9]) or by pseudo-random-binary-sequence (PRBS) excitation. The latter (with a 14-bit sequence excitation signal of 20 V ± 10 V sampled at 10 kS /s) was used to measure the open-loop FRF shown in Figure 3. It can be observed that the measured FRF is quite different from the *nominal* one: the amplitude slope is approximately −14 dB/dec over about two decades where the phase stays rather constant at about −63°. This behaviour is typical of solid yoke magnets that, due to eddy currents losses, can only be modeled by fractional-order (i.e.: non-integer order) differential equations.

Design and Experimental Results

With a closed-loop bandwidth of 300 Hz, a desired damping factor of $\zeta = 0.8$, a modulus margin of 0.5 and a sampling rate of 5 kS/s, the measured FRF was then used to design a 10$^{\text{th}}$ order RST controller (CCLIBS can handle up to the 15$^{\text{th}}$ order) to achieve $\mathcal{H}_2$ performance. Figure 4 shows the experimental results; it can be observed that the challenging requirements have been successfully satisfied.

CONCLUSION & FUTURE WORK

A frequency-domain approach for synthesizing RST controllers for power converter control systems has been implemented in CCLIBS. The control methodology is based on achieving $\mathcal{H}_p$ performance for $p \in \{2, \infty\}$ by solving a set of convex optimization problems in a data-driven setting; the

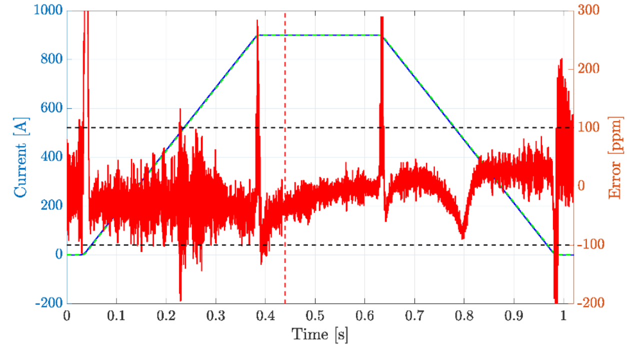

Figure 4: Reference (blue) and output (green-dashed) current. The tracking error (red) must remain within ± 100 ppm during the flat-top (on the right side of the vertical red-dashed line).

solutions to these problems ensures the $\mathcal{H}_p$ performance and closed-loop stability for fixed-structure controllers. These design and FRF measurement tools were tested on a solid yoke magnet powered by the SIRIUS 2P power converter; the experimental results have confirmed their effectiveness.

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