DATA-DRIVEN CONTROLLER DESIGN FOR HIGH PRECISION PULSED POWER CONVERTERS FOR BUMPER MAGNETS OF THE PS BOOSTER

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Abstract

A data-driven approach using the frequency response function of a system is proposed for designing robust digital controllers for the injection bumper magnet (BSW) power supplies of the PS Booster. The powering of the BSW requires high precision 3.4 kA to 6.7 kA trapezoidal current pulses with 2 ms flat-top and 5 ms ramp-up and ramp-down time. The tracking error must remain within +/- 50 parts-per-million (ppm) during the flat-top of the trapezoidal reference, and +/- 500 ppm during the ramp-down. The BSW is powered with a SIRIUS P2P power converter and the current through the magnet is controlled in closed-loop form with a 2-degree-of-freedom controller at a sampling rate of 10 kHz. A convex optimization algorithm is performed for obtaining the controller parameters. The effectiveness of the method is illustrated by designing the controller for a full-scale prototype of the BSW system at CERN, which is in the framework of the LHC Injector Upgrade (LIU) project.

INTRODUCTION

The data-driven control strategy mitigates the problems with model-based controller designs by avoiding the problem of unmodeled dynamics associated with low-order parametric models. A survey on the differences between the model-based control and data-driven control schemes has been addressed in [1] among many others. With the data-driven control scheme, the parametric uncertainties and the unmodeled dynamics are irrelevant and the only source of uncertainty comes from the measurement process. In this paper, the frequency-domain approach will be utilized for the controller design.

Robust controller design methods belonging to the $\mathcal{H}_\infty$ control framework minimizes the $\mathcal{H}_\infty$ norm of a weighted closed-loop sensitivity function. In [2–5], frequency-domain approaches are proposed in order to design controllers that satisfy the $\mathcal{H}_\infty$ condition. The work in this paper presents a method based on [5] and uses a convex optimization algorithm to compute robust *RST* controllers for high precision pulsed power converters. CERN adopted the RST control strategy for the control of the current in the magnets within the FGC platform [6]. The RST controller structure is indeed an effective discrete-time two-degree of freedom (2DOF) polynomial controller where the tracking and regulation characteristics of a closed-loop system can be formulated independently, which is definitely an important feature in many applications.

This frequency-domain approach for the design of *RST* controllers is applied here to the 3.4 kA SIRIUS P2P power converter control system for the powering of BSW magnets. Experimental results obtained with a dummy load that mimics the dynamics of the BSW magnets are reported. Validation of the proposed method is proven by examining the closed-loop time-domain response.

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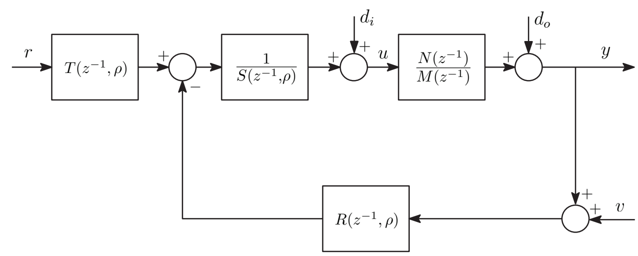

Figure 1: *RST* controller structure.

CONTROLLER DESIGN METHOD

The structure of the *RST* controller is shown in Fig. 1. 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 frequency response function (FRF) of such a factorized discrete-time SISO plant 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 $\Omega \in [0, \pi/T_s]$ (with T_s [s] being the sampling time). $N(e^{-j\omega})$ and $M(e^{-j\omega})$ must be FRF's of bounded analytic functions outside the unit circle; for stable plants (as in this application) $N(e^{-j\omega}) = G(e^{-j\omega})$ and $M(e^{-j\omega}) = 1$ is assumed.

Each controller in the *RST* framework is realized as a polynomial function as follows:

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

where $\{n_s, n_r, n_t\}$ are the orders of the polynomials R, S and T, respectively. These controllers can also be represented in a linear regression form as

$$R(z^{-1},\rho) = \rho_R^\top \phi_{n_r}(z^{-1}) = [r_0, r_1, \ldots, r_{n_r}]\phi_{n_r}(z^{-1});$$
$$S(z^{-1},\rho) = \rho_S^\top \phi_{n_s}(z^{-1}) = [1, s_1, \ldots, s_{n_s}]\phi_{n_s}(z^{-1});$$
$$T(z^{-1},\rho) = \rho_T^\top \phi_{n_t}(z^{-1}) = [t_0, t_1, \ldots, t_{n_t}]\phi_{n_t}(z^{-1});$$

where $\rho^\top = [\rho_R^\top, \rho_S^\top, \rho_T^\top]$ and $\phi_x^\top(z^{-1}) = [1, z^{-1}, \ldots, z^{-x}]$ (with $x \in \{n_r, n_s, n_t\}$).

$\mathcal{H}_\infty$ Performance via Convex Optimization

In the general $\mathcal{H}_\infty$ control problem, the objective is to find the controller parameter vector ρ such that

$$\sup_{\omega\in\Omega} |H_q(e^{-j\omega}, \rho)| < \gamma \tag{5}$$

where $\gamma \in \mathbb{R}^+$, $H_q(e^{-j\omega}, \rho) = W_q(e^{-j\omega})\mathcal{S}_q(e^{-j\omega}, \rho)$. $\mathcal{S}_q$ is the sensitivity function of interest (for example, the ratio of the FRF of y to the FRF of r in Fig. 1) and W_q is the FRF of a stable weighting filter such that $H_q(e^{-j\omega}, \rho)$ has a bounded infinity norm. For notation purposes, the dependency in $e^{-j\omega}$ will be omitted, and will only be reiterated when deemed necessary. For the RST control structure shown in Fig. 1, an optimization problem can be formulated to obtain the admissible $R(\rho)$, $S(\rho)$, and/or $T(\rho)$ controllers as follows:

$$\begin{aligned} \underset{\{\gamma,\rho\}}{\text{minimize}} \quad & \gamma \\ \text{subject to:} \quad & \gamma^{-1}|W_q\Delta_q(\rho)| < \Re\{\psi(\rho)\} \\ & \forall\omega \in \Omega \end{aligned} \tag{6}$$

where $\psi(\rho) = NR(\rho) + MS(\rho)$; $\Delta_q(\rho)$ is the numerator of the q-th sensitivity function of interest (for example, the one from $r-y$ to y is $\Delta_2(\rho)\psi^{-1}(\rho)$, where $\Delta_2(\rho) = \psi(\rho)-NT(\rho)$ which is generally used to achieve tracking performance); $\Re\{\cdot\}$ is the real part of the argument. For a fixed γ, the above optimization problem is quasi-convex and has an infinite amount of constraints. To solve this problem, a semi-definite programming (SDP) approach can be used to grid the frequency vector into a finite amount of points and solve the optimization problem with a bisection algorithm (i.e., fixing γ and perform an iterative algorithm until the optimal solution is obtained) [5].

EXPERIMENTAL VALIDATION

For the powering of BSW magnets, the RST controller was designed with a twofold goal: to achieve the desired tracking requirements and simultaneously ensure sufficient stability margins. The *primary* tracking requirements concern the repeatability of the produced current in two different phases: flat-top and ramp-down. For the flat-top, the requirements must be met over the time frame when the beam is passing through (which starts about 600 µs before the ramp-down). The amount of absolute error between the reference and output current is also to be minimized, but this is considered a *secondary* requirement as this can also be optimized within the process of generation of the reference pulses for the current.

Experimental Test Setup

The setup used for the experimental assessment of the performance of the designed controller is composed of:

- A SIRIUS P2P power converter. (SIRIUS employs a grid supply unit that consists of a passive rectifier unit with boost converter that acts as grid current regulator.

Figure 2: SIRIUS P2P power converter.

  The grid supply unit limits the power taken from the power grid to just 20 kVA with a modest 32A/400V 3-phase line voltage. This family of power converter serves to improve power quality towards the power network by limiting the input power fluctuations.)

- A dummy load whose RL characteristics match those of the BSW magnets.

- The software diagnostics tool interfaces with the main digital controller module, the FGC3 [6] which is able to acquire the relevant signals at a sampling rate up to 10K samples per second.

A preliminary identification experiment was performed for two different systems: BSW3 and BSW4. The measured FRF of the systems were then used to synthesize the RST controllers by means of the optimization algorithm in (6).

Design

The regulation period was selected as $T_s = 100$ µs, which is the fastest option for FGC3. The estimated delay due to the online control-measurement-actuation *chain* was estimated to be about 230 µs which represents 2.3 regulation periods; this presents a major challenge for the achievement of the required performance (both for tracking and stability).

As already mentioned, the RST should guarantee proper tracking requirements while ensuring satisfactory stability margins; a modulus margin of at least 0.5 was imposed.

For tracking, the sensitivity function $\mathcal{S}_2(\rho) = 1 - y/r = \Delta_2(\rho)\psi^{-1}(\rho)$ must be suitably shaped. Therefore, the follow-

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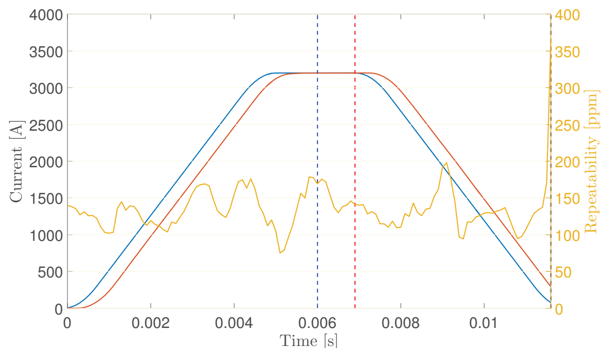

Figure 3: Repeatability (in ppm) of current response of the BSW3.

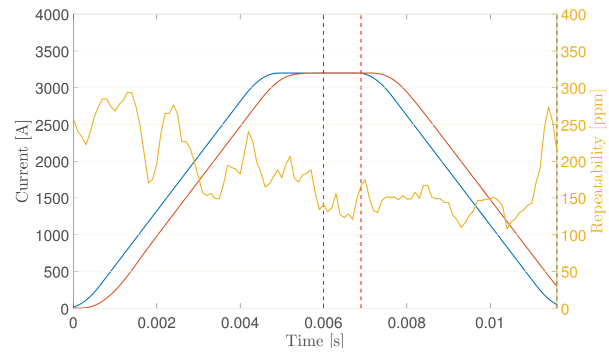

Figure 4: Repeatability (in ppm) of current response of the BSW4.

ing optimization problem was considered:

$$\begin{aligned} \underset{\{\gamma,\rho\}}{\text{minimize}} \quad & \gamma \\ \text{subject to:} \quad & \Re\{\psi(\rho)\} > \gamma^{-1}|W_2\Delta_2(\rho)| \\ & \Re\{\psi(\rho)\} > 0.5|S(\rho)| \\ & \Re\{S\} > 0 \end{aligned} \tag{7}$$

The weighting function W_2 was chosen for the closed-loop system to behave as a *canonical* 2-order system:

$$T_d(s) = \frac{\omega_d^2}{s^2 + 2\zeta\omega_d s + \omega_d^2} \tag{8}$$

where $\zeta = 0.9$ is the desired damping factor and ω_d is selected such that the desired closed-loop bandwidth is 700 Hz. The last constraint in (7) ensures that the zeroes of S are all within the unit circle (as is required by the FGC3 control algorithm).

Experimental Results

Figures 3 and 4 show the reference current (solid blue line), the measured current (solid red line) and repeatability (solid yellow line) over 10 different pulses expressed in ppm of 3.4 kA (the nominal current) for both converters. The repeatability represents the difference between the maximum and minimum value of the error measured at each time instant over all 10 acquired pulses . The repeatability during the 600 µs time frame between the dashed-blue line and the dashed-red line is required to be below 100*ppm* (±50 ppm of the reference) while the repeatability during the time frame between the dashed-red line and the dashed-black line (rightmost side of the plot) is required to be below 1000*ppm* (±500 ppm of the reference). It can be observed that for both systems, the repeatability during the ramp-down of the pulse largely satisfies the specifications, whereas the repeatability during the flat-top of the reference slightly exceeds the 100 ppm limit.

CONCLUSION & FUTURE WORK

A frequency-domain approach for synthesizing *RST* controllers for controlling the pulsed current produced by the SIRIUS P2P converter for the powering of BSW magnets has been presented. A convex optimization problem was formulated and solved for shaping the desired sensitivity functions and satisfying the $\mathcal{H}_\infty$ criterion. The proposed design ensures that the repeatability requirement is met at least during the ramp-down while attaining the desired stability margins. Due to hardware unavailability for further *tuning*, the tracking requirements for the flat-top could not be fully attained. Future work will aim at optimizing the design to fully attain the desired repeatability during the flat-top and further reduce the amount of the absolute error with respect to the reference.

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