Beam loading Compensation of LANSE Digital Low Frequency Radio Frequency System
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Abstract
The Los Alamos Neutron Science Center (LANSE) proton accelerator supports multiple experimental areas and accelerates several beam species, each having to own peak current value, repetition rate, and chopping characteristics. A new digital low-level RF system (LLRF) was designed and deployed on 201 MHz drift-tube linac 850MHz side-coupled-cavity linac section of LANSE. This new system is part of a modernization of the existing analog cavity-field controllers that were originally developed and put into service forty-five years ago. For stabilization of the cavity field amplitude and phase during beam loading, a proportional-integral feedback controller has been implemented. For the multi-beam loading compensation, a static beam feedforward controller, a disturbance observer based controller, a disturbance derivative controller, and an iterative learning controller have been implemented in parallel. In this paper, the controller's architectures are described, and the performances of the controllers are presented.

1. Overall Control System Block Diagram

II. PI Feedback Control
Discrete Time PI Controller (16 bit signed integer format implementation on FPGA):

\[ C(s) = K_p \frac{1}{1 + sT_i} \]

Continuous Time PI Controller:

\[ C(s) = K_p (1 + \frac{1}{sT_i}) \]

Output Response:

\[ Y(s) = T(s)R(s) + S(s)D(s)T(s) \]

Error Response:

\[ E(s) = S(s)(R(s) + T(s)) \]

Complementary Sensitivity Function:

\[ T(s) = \frac{GC}{1 + GC} \]

Sensitivity Function:

\[ S(s) = \frac{1}{1 + GC} \]

III. Beam Feedforward Control (BFFC)

Beam loading of the cavity field disturbs the beam tracking, and the beam loading is a perturbation. A beam feedforward controller is designed to pre-compensate the beam loading. The beam feedforward controller is applied because of the amplitude error without the beam feedforward controller causes the fast protecting returning to turn-off the beam. The static beam feedforward controller is \( K_f = 1000 \). For the K_c, the \( \zeta \)-filter is set that the \( Q \)-filter pole is 0.85. The error data is obtained from the field control module (FCM).

The performance of the iterative learning controller for ECH-1 (LLRF) beam after ILC converges. ECH-1 long beam with 320usec ramp is loaded at 350usec. The PI feedback controller is the default controller and the zero-beam based beam feedforward controller is applied because the amplitude error without the beam feedforward controller causes the fast protecting returning to turn-off the beam. The static beam feedforward controller is \( K_f = 1000 \). For the K_c, the \( \zeta \)-filter is set that the \( Q \)-filter pole is 0.85. The error data is obtained from the field control module (FCM).

IV. Iterative Learning Control (ILC)

Controller Output Convergence Condition:

\[ \left| \frac{D(1 - L)}{1 + GC} \right| < 1 \]

Asymptotic Behavior of the Error:

\[ \lim_{k \to \infty} \epsilon_k = 0 \]

Sensitivity Function, \( S(s) \):

\[ S(s) = \frac{1}{1 + GC} \]

V. Disturbance Observer (DOB) Based Control

DOB Performance:

\[ \epsilon_k = \frac{1}{1 + \alpha_o \omega_o} \int_0^t \epsilon \, dt \]

DOB Performance with Beam Loading:

\[ \epsilon_k = \frac{1}{1 + \alpha_o \omega_o} \int_0^t \epsilon \, dt \]

VI. Longterm Phase Stability

Longterm measurement of cavity field phase stability shows the phase deviation (\( \epsilon(t) \)) of the beam loading over time change. The laser temperature drift, etc. in order to compensate for the phase drift, a drift-compensate m-script based PI controller is implemented. The controller input is the \( \alpha(0,\Omega) \) RF phase detector output and the controller output is added to the ILC drive phase output of ECH.

\[ \alpha(0,\Omega) = \alpha(0,\Omega) + \alpha(0,\Omega) - \epsilon(0,\Omega + \zeta(0,\Omega)) \]

References