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Temperature Control of the ESS Phase Reference Line
Björn Olofsson*, Bo Bernhardsson*, Rihua Zeng**, and Pontus Andersson*
*Department of Automatic Control, Lund University, Lund, Sweden (bjorn.olofsson@control.lth.se)
**RF Group, Accelerator Division, European Spallation Source, Lund, Sweden

Introduction and Background

Fig. 1: Phase reference line of copper (left), heating cables and temperature sensors attached (middle), and insulation applied (right).

- Phase reference signals for all accelerating components along the 600 [m] linear accelerator.
- Radio-frequency (RF) wave in a rigid coaxial line made of copper. Temperature changes induce phase instability because of length variations of the line (17 [ppm/deg C]).
- Phase change $\Delta \phi$ between $x_1$ and $x_f$ at time $t$ proportional according to
  \[ \Delta \phi \approx \int_{x_1}^{x_f} T(x,t) - T_{cal}(x) \, dx, \]
  with $T$ and $T_{cal}$ the current temperature and the temperature at calibration, respectively.
- Requirement: $\max_{x} |T(x,t) - T_{cal}(x)| \leq 0.1$ [deg C] for 600 [m] phase reference line.

- Inputs and disturbances: Ambient air temperature was increased $\Delta T$ because of length variations of the line (17 [ppm/deg C]).
- Models of the heat dynamics developed and simulated using both analytic and numerical solutions of the partial differential equation for heat diffusion $\nabla \cdot k \nabla T + Q = \rho c \frac{dT}{dt}$.
- Inputs and disturbances: Ambient air $T_{air}$, heat by controller $u$, and RF heat losses $\text{RF}$.  

Control Design

Fig. 5: Control architecture for temperature stabilization with controllers in EPICS (also monitoring and supervision functions).

- Dynamic models used for designing PID controllers for temperature zones along the phase reference line. Pole placement gives the parameters $(K, T, \tau)$ in the control law:
  \[ u(t) = K \left( e(t) - \frac{1}{T} \int e(\tau) d\tau + T \frac{de(t)}{dt} \right), \quad e(t) \text{ control error}. \]
- Control architecture based on RTD Pt100 temperature sensors, heating cables, A/D and D/A converters, solid-state relays for power control. Beckhoff EtherCAT modules for I/O or Eurotherm Mini8 controller for both I/O and controller execution.
- Control hardware placed in the gallery because of radiation. Special attention for materials used for temperature sensors and heating cables in the accelerator tunnel.

Simulation Results

Fig. 3: Stationary temperature in cross section with heat losses in conductors (left) and time & radial temperature dependence (right).

- Feedback control used for temperature stabilization of the line within the requirements.
- Models of the heat dynamics developed and simulated using both analytic and numerical solutions of the partial differential equation for heat diffusion $\nabla \cdot k \nabla T + Q = \rho c \frac{dT}{dt}$.
- Observations: $e_{max}$/(180°) [deg C] in the experiment.

Prototype Setup at Lund University

Fig. 4: A 4.5 [m] prototype with two directional couplers was setup and used for controller development and experimental evaluation.

- A prototype control system for temperature stabilization of the ESS phase reference line.
- Observed control error variations with respect to the calibrated temperature (also for out-of-loop temperature sensors) clearly within $\max_{x} |T(x,t) - T_{cal}(x)| \leq 0.1$ [deg C].

Conclusions

Further experimental results available in the report:

8th International Particle Accelerator Conference, Copenhagen, Denmark, May 14–19, 2017