EXCEPTION DETECTION AND HANDLING FOR DIGITAL RF CONTROL SYSTEMS

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Abstract

Exception detection and handling routines will play an important role in future large scale accelerator to ensure high availability and beam stability in presence of interlock trips, varying operational parameters, and operation close to the performance limit. For superconducting linacs typical examples for exception situations include cavity quenches, coupler and klystron gun sparks, operation close to klystron saturation, and errors in vector-sum calibration. The goal is to identify all possible exception situations which will lead to performance degradation or downtime, detect these situations and take appropriate actions as necessary.

INTRODUCTION

The performance of the LLRF control system is usually measured in terms of achieved field stability and the availability of the accelerating fields. These measures are strongly coupled to the technical performance, operability and reliability of the rf control system including its subsystems. Performance degradation and failure (recoverable and unrecoverable) of individual components can therefore reduce the performance at different impact levels, depending on the criticality of the component and the type of performance degradation or mode of failure. The subsystems relevant for the performance of the LLRF system are:

- Cavity, coupler and frequency tuner
- Klystron, modulator and rf power transmission
- Synchronization, Timing, M.O. and distribution
- LLRF System including field detection, analog I/O, digital signal procession and actuators
- Racks with air conditioning, crate power, cables, connectors, radiation shielding
- Interfaces to other subsystems such as personnel and machine interlocks and beam diagnostics

The goal of exception handler is the detection of exceptions and execution of proper procedures to minimize the resulting performance degradation. Also desirable is the detection of anticipated future exceptions so that corrective actions can be taken to avoid their occurrence.

CONCEPT FOR EXCEPTION DETECTION AND HANDLING

In digital rf control systems most physical signals are available in digital form at the front electronics, front ende servers, middle layer servers and at the client level. Exceptions which require immediate action (few microseconds) are usually detected and handled at the front end electronics level or the front end server while those requiring action on the pulse to pulse time scale can be handled at the middle layer or client level.

The exceptions can be divided in 5 categories

- subsystem failure
- technical performance degradation
- partial loss of functionality
- operational limit exceeded
- anticipated exception

The impact of the exceptions can be divided in classes with different severity of the impact:

- photon beam
- electron beam
  - energy and energy stability
  - bunch train pattern (pulse length)
  - beam current limitation
  - peak current (bunch compression)
  - arrival time jitter
- rf fields in cavities
  - stability
  - gradient limitation
  - pulse length

The exception handling goals can be of different nature:

- maintain electron beam quality
- maintain electron beam at reduced quality and/or different beam pulse pattern
- avoid damage to subsystems
- maximize life time of components

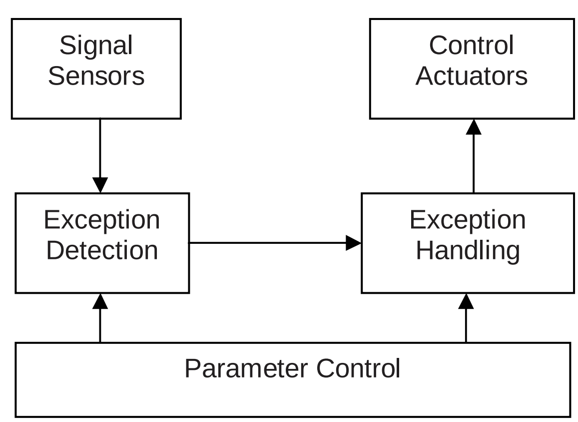

Figure 1: Exception Detection and Handling.

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Table 1: Examples for Exceptions, their impact, countermeasures and the resulting improvement

Exception	Impact	Countermeasure	Result
cavity quench hard/soft	Beam energy fluctuation	Lower grad., comp. with other cav.	Recover after few pulses
Cavity field emission	Radiation damage Electronics	Lower grad., comp. with other cav.	Reduce radiation levels
Cavity excessive detuning	Gradient / phase stability	Tune cavity to op. frequency	Recover in few pulses
Cavity incident phase error	Reduced available energy gain	Re-phase with 3-stub tuner	Recover on crest- operation
Cavity loaded Q error	Slope on individual gradient	Adjust loaded Q	Flat top in all cavities
Piezo tuner defect	No Lorentz force compensation	Not available	-
Motor tuner stuck	Cavity lost or strong field slope	Not available	-
Occasional klystron gun spark	Beam energy, Beam loss	Reset, bypass	Recovery after few pulses
Frequent klystron gun spark	Low availability, klystron damage	Lower high voltage	High avail., lower gradient
Occasional coupler spark	Shorten rf and beam pulses	Lower power	Operation at lower gradient
Preamplifier failure	Loss of rf station	Switch to redundant system	Recover after few pulses
Modulator HV unstable	Gradient / phase stability		
Preamplifier saturated	Field regulation reduced	Lower gradient	Recover after few pulses
Timing jitter LLRF/Laser	Loss in peak current, energy error	Not available	-
Timing trigger/clock missing	Loss of linac / rf station	Switch to redundant system	Recover after few pulses
Timing error subsystem	Potential loss of SASE	Adjust timing	Recover after few pulses
M.O. and distribution failure	Loss of main linac	Switch to redundant system	Recover after few pulses
Vector-modulator failure	Loss of field control	Switch to redundant vector-mod.	Recover after few pulses
Calibration reference failure	Slow phase drift, beam energy	Use beam feedback	Stable beam
RF station LO missing	Loss of Gradient	Switch to redundant feedforward	Beam at reduced stability
down converter channel defect	Red. field stability, higher grad.	Estimate cavity field	Recover field stability
Calibration error VS	Field stability	Re-calibrate vector sum	Recover after calibration
Analog input channel defect	Field stability	Estimate lost signal	Partial recovery
Cable connection missing	Field stability	Estimate lost signal	Partial recovery
Processor error fdbck loop	Field stability	Switch to redundant feedforward	Recover with red. Field stab.
Numerical error	Cavity field	Switch to redundant feedforward	Recover with red. Field stab.
Single event setup	System hang-up, calc. error	Redundant FF, Recover system	Recovery with init. Red. Stab.
Total ionizing dose damage	Noisy sign. , sensitivity, offset	Switch to red. feedforward	Recover with red. field stab.
Rack cooling failure	Potential loss of hardware	Turn power off, op. redundant FF	save hw,recover with red. stab.
Crate power failure	Loss of cavity field	Switch to redundant FF	Recover with red. field stab.
Computer network failure	Loss of control of param. settings	Establish connection via red. netw.	Regain parameter control
Communication link failure	Field stability	Switch to redundant feedforward	Recover with red. field stab.
Operator input out of range	Beam energy, beam loss	Limit input range	No impact

The concept of exception detection and handling is shown in figure 1. Sensors provide the information of physical signals from which measurements are derived. The exception is detected as a function of measured signals. The exception handler consists of procedures which lead to the desired action usually by the use of actuators. Parameters are used to control the exception definition and the exception handling procedure. Interlocks are also exception handlers implemented in hardware and their action is included in the exception definition. Examples for exceptions, their impact, possible countermeasure and the resulting improvement are shown in table 1. The short description gives only an idea of the possibilities and much more detailed description are necessary to describe the severity of the impact of the exceptions and the many possibilities for recovery.

Exception Detection

Exception detection relevant for rf control takes place in the llrf control system, the affected subsystems or in dedicated electronics added for diagnostic purposes. The exception can be detected by dedicated interlock circuitry or is derived from measured signals. The time scale required for exception detection can range from microseconds to minutes depending on the type of exception.

Exception Handling

Exception handling involves the execution of a procedure which prevents hardware damage and/or maximizes machine availability and technical performance. In case of interlock trips the exception (or fault) signal activates an actuator (often a switch) which turns off the power of a subsystem. In case of exceptions detected by software, the exception handling procedure may involve a graceful shutdown, reduction of operating parameters, or operation at reduced performance.

EXAMPLES FOR EXCEPTION DETECTION AND HANDLING

Typical examples for exception detection and handling are related to subsystem trips (faults) and automated recovery from faults, reduced amplitude and phase stability of the accelerating fields and the subsequent optimization of technical performance, and component degradation.

Cavity and Coupler

Exception that are anticipated to occur in cavities and couplers are:

- cavity operation gradient limit exceeded
  - cavity quench
  - cavity field emission
- cavity tuning error
- coupler interlocks
  - spark, temperature, vacuum

While the cavity quench, field emission, and cavity tuning will be detected in the llrf control system, the coupler spark exception will be reported by dedicated coupler interlocks which are implemented in hardware and which are connect to the rf interlock switch to inhibit rf power.

The cavity quench is detected in the llrf system by diagnosing inconsistencies between cavity gradient and incident power or by detection of a small droop in loaded Q which indicates a significant reduction in unloaded Q. Excessive field emission will be detected by build- in dosimetry. The dosimetry can distinguish between gamma and neutron radiation to allow for proper action.

Cavity quenches or excessive field emission can be avoided by lowering of the gradient in the associated vector sum of 32 cavities and making up for the reduction in energy gain in nearby rf stations. This can be accomplished even within a 1 ms pulse provided that fast communication links are available between the llrf systems.

Klystron/Modulator and Power Transmission

Klystron and modulator failures can lead to complete loss of rf power or limitations in the maximum power available for control. In the first case the complete station must be by-passed (including detuning of cavities) while in the second case the power demand should be reduced. This can be accomplished with reduced modulator setting by lowering of gradients at the affected rf station and increasing gradients at other stations.

Synchronisation and Timing

The timing and synchronisation system consist of single point of failure masters and distributions and local receivers and sub distributions at the individual rf stations. Therefore the master oscillator with its synchronized clock and trigger generators must be implemented as redundant system. Local receivers and distribution would lead to the loss of one rf station and redundancy is desirable.

LLRF Feedback System

The complexity of the digital feedback system makes it quite susceptible to hardware deficiencies or programming errors in software. In addition single event up-set can cause bit-flips in the memory or hang-up of the computers. The most efficient way to increase availability is redundancy. A simple feedforward which operates at reduced field stability will be sufficient in the main linac if only a few systems fail. This approach is also very cost efficient.

Possible exceptions include power failures in crates, defect measurement channels, failure of networks or communication links, and wrong operating parameters. In many cases a signal integrity check using redundant signals can indicate the problem while the redundant feedforward provides a simple solution to reduce the impact to a moderate level.

SUMMARY

Exception detection and handling will be essential for the LLRF system availability and performance at the European XFEL. With digital rf system, the exception management can be mainly implemented in software which facilitates future upgrades and performance improvements.