CHALLENGES FOR THE LOW LEVEL RF DESIGN FOR ESS

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Abstract

The European Spallation Source (ESS) is a planned neutron source to be built in Lund, Sweden, which is planned to produce the first neutrons in 2019. It will have an average beam power at the target of 5 MW, an average current along the linac of 50 mA, and a pulse repetition rate and length of 20 Hz and 2.86 ms, respectively. The linac will have around 200 LLRF stations employed to control a variety of RF cavities such as RFQ, DTL, spoke and elliptical superconducting cavities. The challenges on LLRF systems are mainly the high demands on energy efficiency on all parts of the facility, an operational goal of 95% availability of the facility and a comparably short time from start of final design to commissioning. Running with long pulses, high current and spoke cavities also brings new challenges on LLRF design. In this paper we will describe the consequences these challenges have on the LLRF system, and the proposed solutions and development projects that have started in order to reach these demands.

INTRODUCTION

The LLRF design is undergoing at ESS where about 200 LLRF stations are expected to be built by the year 2019 for a variety of RF cavities such as RFQ, DTL, spoke and elliptical superconducting cavities, which are planned to be individually powered, i.e. one klystron per cavity in current design [1]. Careful consideration and extensive investigation are required at the beginning of design for such a large-scale system. First of all, it is essential to identify and recognize the issues and challenges to be addressed in LLRF system, which will provide clear information and guidance to later specification and implementation. The general challenge and task of the LLRF system at ESS are to find appropriate solutions to enormous issues in each of the sub-modules as shown in Figure 1 [2]. Many of them are widely investigated in present and near future accelerator facilities. It is valuable for us to learn from their experience and lessons and find suitable solutions for ESS.

In addition to these issues, new and tough challenges are arising as a result of specific stringent demands from ESS itself, which is to be built as a green plant placing very high demands on powers conservation and recycling of energy. The green plant scheme is expected to be achieved by careful design and modern power recapture methods, such as using the cooling water to heat the surrounding municipalities. It leads to stringent demands on LLRF systems, especially as the plant at the same time has an operational goal of 95% availability and a comparably short time from start of final design to commissioning. In addition, running with long pulses, high current and spoke cavities might also bring challenges.

In the following sections we will describe in detail some specific challenges met at ESS for the LLRF design, and the proposed solutions and development projects that have started in order to reach this goal.

EFFICIENCY

Typically linear accelerators use klystrons as RF power amplifiers, as these can deliver the high power to get the necessary accelerating gradients in the cavities of the linac. In order to facilitate the control of the phase and the amplitude of the fields in the cavities, the klystrons are typically run far below saturation in a linear region of operation, which leads to a reduced efficiency. Within the ESS project we will look into and test the use of linearization techniques to reduce this overhead and decrease the power consumption.

There are many different linearization methods such as feedback, feedforward, and predistortion, which are widely applied in communication system. Feedback linearization is relatively simple but puts the operation at risk of instability due to loop delay, while feedforward has the disadvantages of low power efficiency and increased complexity. For the accelerator cavity application with narrow bandwidth, the digital predistortion method appears to be the most promising linearization technique with high flexibility and precise linearization [3].

Figure 2 shows a typical digital predistortion linearization scheme. It is realized by introducing a predistorter block having the inverse nonlinear characteristics of the klystron to compensate the non-linearization. The adaption algorithm is crucial here in order to compensate the possible changes of the environmental and operating conditions such as high voltage variations, temperature drift, and components aging [4]. Furthermore, as the complete linac at ESS will incorporate around 200 different RF sources, working at powers from 20 kW to 900 kW, a self-learning and adaptive system would minimize the commissioning time for the complete system. Careful and adequate measurements of the characteristics of the klystron should be taken in order to calculate the accurate coefficients of the linearization table.

Deeper investigation of the linearization techniques is to be carried out at ESS. With the FPGA-based LLRF architecture that is planned to be used, the final solution does not need to be decided at the time of locking the LLRF hardware design, which will give the necessary time for development and testing of these algorithms.

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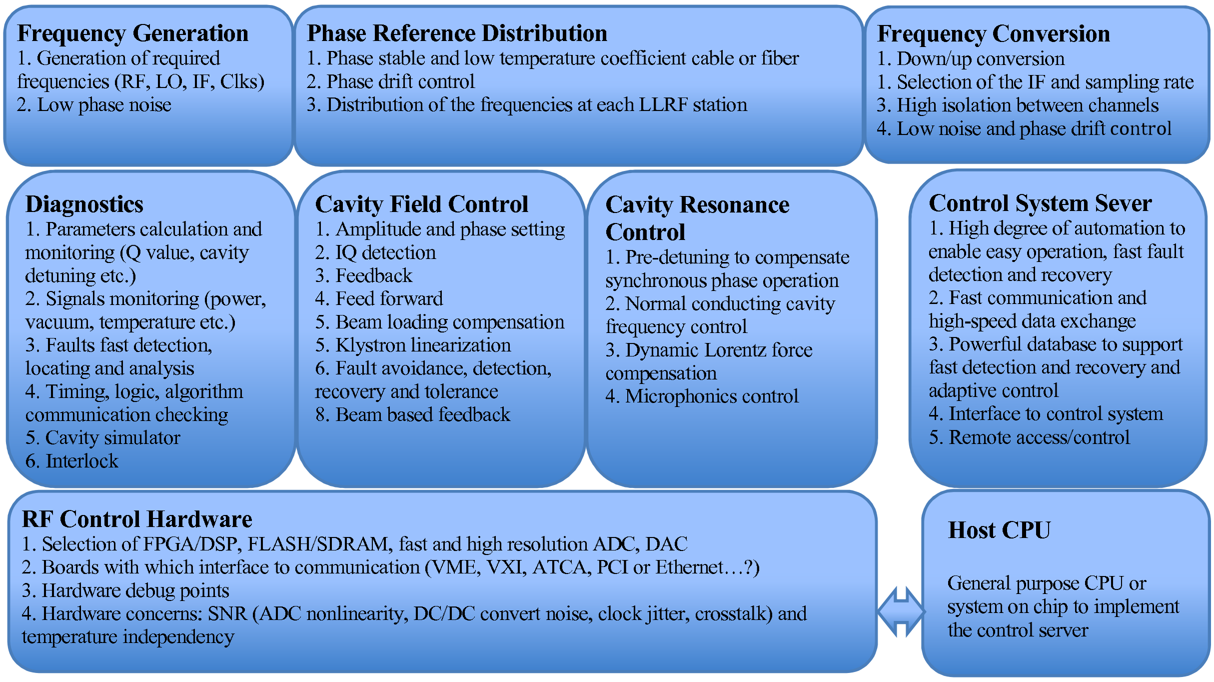

Figure 1: Issues to be addressed in each of the sub-modules of the LLRF system

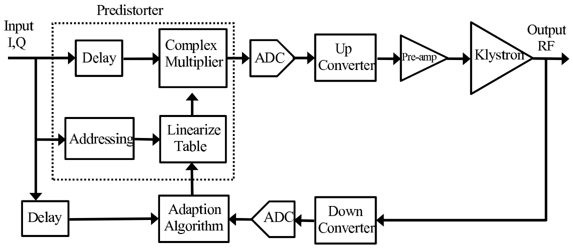

Figure 2: Digital predistortion linearization scheme

Another important aspect to improve the efficiency is to minimize the RF power needed for the LLRF control. Extra RF power is required by feedback and feedforward to compensate the effects of Lorentz force detuning, microphonics, synchronous phase operation, load Q variations and other perturbations (like klystron output droop and ripple, beam loading, etc.). It is therefore important to reduce these perturbations as much as possible, for example, by applying the piezo tuning and limiting the klystron output droop and ripple. On the other hand, it should be kept in mind that we also need proper RF power overhead to be able to quickly react and recovery from the failure or trip to maximize the ESS availability. The design tradeoff needs to be optimized between efficiency and availability.

AVAILABILITY

The system availability can be simply calculated by: Availability= Uptime/(Uptime + Downtime). The goal of the availability of the ESS is 95%, which places far more stringent requirements on the LLRF systems. It requires careful design of the hardware and software, and requires failure handling scheme at the systems level, e.g. the possibility to run with one or more cavities in a detuned position due to LLRF, klystron or modulator failure. Important points in the design process are:

- Avoid single points of failure that causes the whole system to fail.
- Automatically detect the failure as fast as possible.
- Bypass the failure point and recovery the system performance as soon as possible.
- And all the time try to reduce the complexity of the system.

Among common failures seen in other facilities are cavity quenches, field emissions, software and hardware errors, klystron and modulator failures. To deal with these events in the ways mentioned above, on-line diagnostics is required for detection, and RF power overhead together with adequate redundancy as well as a high degree of automated operation for recovery. For example, a cavity quench can be handled quickly by lowering the gradient of the troubled cavity and adjusting the phase and gradient of the adjacent cavities, but only if it is correctly captured very early and only if there is enough power overhead available for the surrounding cavities. Errors of the timing system, hardware, or even control configurations can be detected easily and solved effectively if there is adequate redundancy in signals, hardware and software [5]. For failures in klystrons and modulators, we could recover the system in a relatively short time by adjusting the adjacent cavities gradients and phases and thus consuming more power, or in a relatively long time by adjusting all the downstream cavity phases with a reduced system operating performance [6, 7]. The tradeoffs are typically between complexity and fault recovery, and redundancy and power consumption.

Furthermore, with more and more extra modules being introduced into system to deal with the failures, it is unavoidable to increase the system burden and complexity, which in turn has the bad effects on availability. It is therefore also essential to reduce the complexity as much as possible during the design and implementation.

One design approach aimed for at moment is to make use of a common hardware platform for all the LLRF systems and, as far as possible, also for the beam instrumentation systems. This will simplify service and reduce the cost of the necessary inventory of spare parts. In addition, the redundant structures in the LLRF chain will be also decided on the experience of other facilities, such as the SNS and LHC, and on analysis of the prototype hardware.

COMMISSIONING

In order to facilitate the commissioning, it would be advantageous to be able to run the LLRF system together with the control and timing systems without having to be fully powered up and having a beam in the accelerator. In order to make this possible, the LLRF systems will be designed so that they can be run on their own, with a simulated cavity and beam. This will make it possible to test the whole control system of the linac before all the parts of the accelerator itself are in place. The model of the cavity and beam will either be implemented in the FPGA, or as a separate circuit connected to it. Both variants have different strengths and risks connected to them.

The possibility to also include simulated faults in these modules, such as klystron degradation or modulator failure, will make it possible to test the contingency parts of the control system, and prepare the system for the high availability goal.

A Labview-based simulation of the cavity and the LLRF system is done at ESS.

OTHERS

In terms of the current design at ESS, the pulsed beam with peak current of 50 mA, repetition rate of 20 Hz and pulse length 2.86 ms will be accelerated through the linac, and the accelerating gradient could be up to 20 MV/m in high beta superconducting cavities. All these factors result in tough issues for LLRF system to address. For example, a high beam current leads to heavy beam loading effect in the cavity and excites high amplitude pass band modes which increase the risk of instability in feedback loop; Long pulse will probably result in large droop and ripple in klystron output due to limitations in the modulator design; High accelerating gradient field will inevitably bring high Lorentz force detuning. In addition, there might be also the uncertainties and unpredictable problems in spoke cavities which have never been operated in accelerators before.

For the random and unpredictable perturbations, a high gain feedback is desirable, which requires not only careful design to obtain low loop delay but also specific considerations to reduce the risk of feedback instabilities caused by other factors like pass band modes [8]. On the other hand, the feedforward is highly required as well for the repetitive perturbations like beam loading and Lorentz force detuning. Furthermore, it is also essential to take into account the other advanced control methods such as adaptive control, model predictive control, Kalman filtering and identification tools to obtain a better performance when coping with these issues.

SUMMARY

The investigation and design of the LLRF system at ESS has been carried out and there are many issues and challenges to be addressed, especially the high demands on energy efficiency on all parts of the facility, an operational goal of 95% availability, and a comparably short time from start of final design to commissioning. The klystron linearization techniques, the fault avoidance, detection and recovery, and other related schemes are investigated for the purpose of increasing the efficiency and availability. The cavity and system modelling is undergoing in Labview and expecting to be further improved to better simulate the system behaviour with beam and failure cases. The feedback, feedforward and other advanced control methods are discussed to deal with various kinds of perturbations. Further study and investigation are required to better understand and address the challenges in LLRF system.

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