CONTROL OF AN RF AMPLIFIER FOR JAPANESE HADRON FACILITY

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Abstract: A 1296-MHz high power rf amplifier, which consists of a low power rf unit, a pulse modulator, a klystron assembly and a control unit, is designed for the high-β section of the 1-GeV proton linac for the Japanese Hadron Facility. The low power rf unit controls amplitude, phase and timing of a pulsed rf wave, and amplifies it up to 600 W for exciting the klystron. An accelerating cavity field will be also regulated by feedback and feedforward controllers in the unit to compensate beam loading. The control unit works basically as a remote controller of the high power rf amplifier and has optical interfaces with the low power unit and the pulse modulator to avoid noise problems. Trouble shooting and maintenance are the most important to realize stable operation of the amplifier, therefore we are planning to give the control unit following functions: operation history recording, trouble diagnosis and operation support.

Introduction

An rf source of the 1-GeV proton linac is planed to be composed of 14 UHF klystron amplifiers for a RFQ and 13 DTL's, and 36 L-band klystron amplifiers for 36 CCL's. The UHF amplifier generates an output power of 1.5 MW, and uses a modulating anode type klystron capable of producing an output power of 2 MW. Power capability of L-band klystrons is desired to be 5.5 MW or more, depending on acceleration cavity structures.

The L-band amplifier is composed of a low power rf unit, a high power pulse modulator, a klystron assembly and a control unit. The low power rf unit and the control unit have a function of rf amplifier control.

A prototype pulse modulator was completed and now is testing for final tune-up. Design of the low power rf unit and the control unit was started in early spring of 1988. A preliminarily designed L-band amplifier for klystron power tests will be fabricated until the end of this October. Most of the other components for the amplifier control are still being designed or planned at present.

As a result of five years operation of the rf system for the KEK 2.5 GeV electron linac, we confirmed to promote the study of software supporting operation and maintenance of pulse modulators, as well as improvements of the components. The control unit is specially planned to have an advanced control section for the new functions. Preliminary investigations for new intelligent control was already started.

Conventional control will be realized by an I/O control section using a high-performance industrial programmable controller.

The UHF amplifier system will not be discussed in this paper, however, it has the same construction as the L-band amplifier's.

Low Power Rf Unit

The low power rf unit amplifies an input signal up to 600 W maximum and suppress fluctuations of rf level and phase in the acceleration cavity. A diagram of the unit is illustrated in Fig. 1. The major components of the unit are a phase controller, a level controller, a timing and sequence controller, an rf monitor, and a klystron drive amplifier.

The phase controller adjusts phase of a reference rf signal (1296 MHz). The following level controller modulates and stabilizes amplitude of an rf wave. The pulsed rf wave is amplified by the klystron drive amplifier and transmitted to a klystron. Rf signals picked up from transmission lines or the cavity are returned to the phase controller and the level controller for feedback control. A beam monitor signal is fed to the both controllers for feedforward control of an rf wave in the cavity.

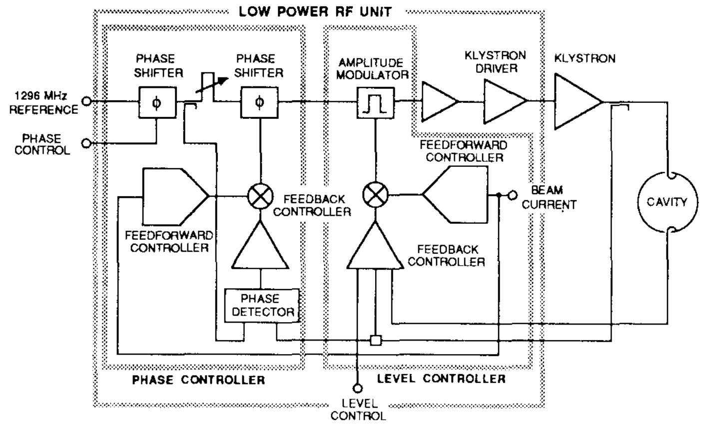

Fig. 1. Block diagram of the low power rf unit.

Components

(1) Phase controller:

A reference rf signal is fed to a first stage voltage-controlled phase shifter, which is adjustable to obtain optimum accelerating phase. A second stage phase shifter, a phase detector and a feedback controller construct a phase locked loop (PLL) in order to stabilize phase fluctuation. The phase detector compares rf signals from the primary phase shifter and one from the klystron. A feedforward controller is also equipped to correct fast phase variations prospectively.

The phase shifter is required to have a frequency response beyond 500 kHz and a phase range more than ±360°. The phase detector should be designed to realize characteristics of 20 dB dynamic range and response time shorter than 1 µs.

(2) Level controller:

The level controller consists of a voltage-controlled amplitude modulator, a feedback controller, and a feedforward controller. The feedback controller compares a cavity rf level and a reference voltage and feeds a control signal to the amplitude modulator so as to keep the cavity accelerating field constant. Fast fluctuation of an rf pulse shape, such as beam loading, is stabilized by the feedforward controller which generates a compensation signal according to a beam current, pulse width and pulse timing.

(3) Rf monitor:

Diodes in this monitor rectify following rf waves: input/output rf signals of the level controller, traveling/ reflected waves in a transmission line from the drive amplifier to the klystron, traveling/reflected waves in a waveguide from the klystron to the cavity, and a wave in the cavity. The rectified pulse signals are converted to DC signals by peak hold circuits and transferred to ADC's in the control unit. The DC levels are also compared with upper/lower limits to detect abnormal condition of the rf system; for example, discharge in waveguides or cavities.

This rf monitor should be fabricated to have linear dynamic range beyond 20 dB and response time shorter than 1 µs.

(4) Timing and sequence controller:

A timing generator receives a trigger signal from a master trigger generator and supplies timing pulses to the devices, for example, the amplitude modulator, sample/hold circuits, and a thyratron trigger circuit in the klystron pulse modulator. Delay and width of the pulses are controlled according to preset values. A sequence controller organizes local ON/OFF control and interlock sequence, and receives remote control signals from the control unit.

(5) Klystron drive amplifier:
Since this amplifier is required to keep high reliability, high stability and easy maintenance over a long period, we decided to adopt a solid state amplifier. Table 1 gives fundamental specifications of the amplifier.

It is presumed that the specification of long pulse width in L-band frequency makes it difficult to realize a high power and linear L-band amplifier. Therefore we are planning two 300-W C-class amplifiers because it is not difficult to satisfy the specifications except for the variable output level. An rf signal from the level controller is divided by a 90°-hybrid. The both sine and cosine signals are fed to the amplifiers through voltage-controlled phase shifters ϕ and $-\phi$, respectively, as shown in Fig. 2. The two outputs of the amplifiers are again combined by a 90°-hybrid, so that an amplitude of the final output, which is vector sum of the rf waves, can be controlled according to the phase shift difference. Thus these phase shifters in this case work as an electronic amplitude modulator.

Table 1. Fundamental characteristics of the klystron drive amplifier.

Frequency	1296 MHz ± 5 MHz
Output power	0 to 600 W
Input power	1 mW
Pulse width	650 µs max.
Pulse repetition	50 pps max.
Pulse rise/fall time	< 5 µs
Pulse flatness	< ± 1 % (on flattop)
Output power stability	< ± 0.3 %
Phase flatness	< ± 1° (on flattop)
Phase stability	< ± 0.3°
Spurious	< -20 dB

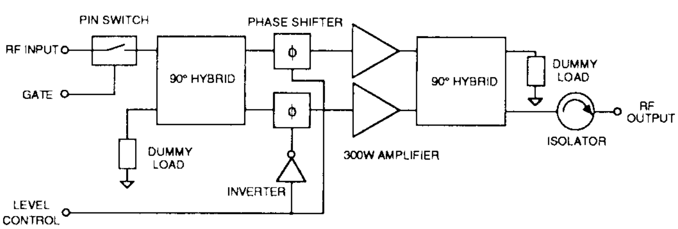

Fig. 2. Simplified schematic of the solid-state L-band amplifier.

Control of Rf Fluctuations

Fluctuations of an accelerating rf field are divided into two classes: The one is fast fluctuation of an rf pulse shape or phase appearing within one pulse, and the other is slow one of an rf level recognized over a long term. These kinds of fluctuation are suppressed by means of feedback control and feedforward control. The feedforward controller can communicate with a computer in the control unit and data in the controller can be refreshed, so that accuracy of stabilization comes the better, the more practiced.

Major sources of the fast fluctuations are beam loading, sag of a klystron output wave due to a pulse transformer. It is difficult to complete a stable feedback loop for a system which contains slow time constant devices. Feedforward control is effective to compensate beam loading, especially transient parts of it, because slow response (< 100 kHz) of an cavity, comparing to frequency spectrum of fluctuation of an rf envelope, prevents to construct a feedback control loop. On the contrary phase or amplitude variations on stationary part of beam loading can be corrected by supplementary compensation using feedback control. The sag of the rf pulse shape can be corrected by feedback control that compares the klystron output wave and a reference signal.

Temperature drift of devices and their circumstances gives slow fluctuations to an rf level. In the low power rf unit, the phase shifters, the amplitude modulators and the amplifier, which are composed of semiconductor devices, change phase and amplitude of their output rf waves in response to temperature variations. The feedback controller in Fig. 1 also reduce the thermal fluctuation of an rf wave.

Control Unit

Unexpected halt of operation in the KEK 2.5 GeV linac has been mainly caused by malfunction of the rf system, especially trouble of klystrons and pulse modulators. Halt time greatly depends on the time for troubleshooting and repair. This tells us that the most important things to maintain klystron amplifiers properly and minimize the halt time are how to detect a symptom of trouble quickly before failure and how to identify a troubled component.

Reliable control of the rf system depends on countermeasure of noise problems, as well as capability of components. For the new control system we decided to isolate the control unit from the controlled devices by optical fibers. Analog signal monitor cables and control cables, which are extracted from enclosures of the amplifier, are also presumed to spoil electrical environment by transmission of high-frequency noise through the cables. Therefore the amplifier system is planed to have no externally connected cables except optical fibers and power lines.

The above consideration results that the control unit is composed of an optically isolated I/O control section, which has functions of sequence control and remote control, and an advanced control section to help troubleshooters and operators. Figure 3 expresses block diagram of the control system for the L-band amplifier.

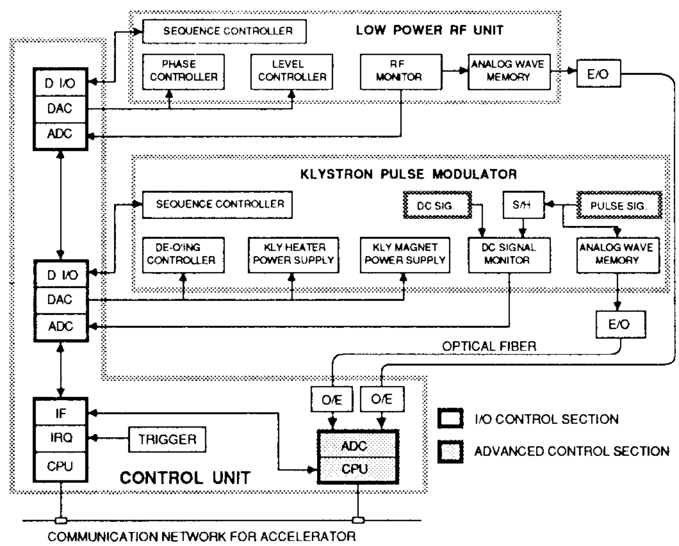

Fig. 3. L-band amplifier control system.

I/O control section

This section treats following signals: interlock status, DC monitor signals, reference voltages, and digital control outputs.

The low power rf unit and the pulse modulator have slave control stations, respectively, which consist of digital I/O's, DAC's and ADC's. The digital I/O's read out interlock signals and give the ON/OFF control signals. The DAC's output the reference voltages to set operational values for the controllers. The ADC's digitize DC monitor signals. A master station having a CPU communicates with the slaves through an optical fiber to avoid noise problems. The master also has another communication control unit for the remote control, an interrupt request (IRQ) unit to receive a klystron trigger pulse and an interface unit for the advanced control section. Table 2 gives the input/output signals concerning the control.

Usually this control section repeats checking itself. When the trigger pulse excites the interrupt circuit, a signal processing routine starts its action following the interrupt halt of the checking program. At first ADC-start command is send to all

ADC's. Next, digital signals expressing the interlock status are collected quickly. After the end of the AD-conversion, data of ADC's are transferred to the master. The collected interlock status and digital values are compared with normal status and standard/limit values, respectively. If the amplifier system is judged to be abnormal, the system will be controlled immediately according to the symptoms. The all actions following one interrupt trigger should be completed within 20 ms which is the time interval between the triggers. The checking program runs at intervals between the interrupt processing routines.

Also this control section receives remote control commands ordered by the central control system. Major remote control functions for the low power rf unit and the pulse modulator are follows: ON/OFF control of switches and relays, UP/DOWN or setting control of the reference values, and readout of tables of the interlock status and the digitized signal levels.

Table 2. Input/output signals and control lines of the control unit.

Interlock signals	> 70 points
Analog DC signals	32 points
Analog pulse signals	> 12 points
Digital outputs	> 10 points
Reference signals	> 5 points
Master-slave communication line in the I/O control system	Optical line (> 1 Mbps)
Remote control network	undecided

Advanced control section

This section will be designed to help troubleshooters and operators actively when the amplifier breaks down or must be operated in spite of some trouble of itself. At present, following functions have been considered.

(1) Automatic recording of operational history

When operational parameters or status are changed, this control section records them automatically in its own file.

(2) Supervision of a klystron

The section keeps data of a klystron and also measures its some characteristics automatically, such as cathode emission or output power vs. input power, according to requests.

(3) Storage of the last monitored data

Large FIFO resisters will be prepared for storage of the last data of pulse waveforms or DC levels on every pulse, so that a troubleshooter can replay the events just before a fault. Storage time depending capacity of the resisters will be longer than 1 second.

(4) Support of troubleshooting

The section executes so-called trouble diagnosis based on the operational history, the klystron characteristics and data in the FIFO resister. Thus a troubleshooter can repair the amplifier referring to results of the diagnosis.

(5) Support of operation

In a case of conditioning of klystrons or cavities, operators are required to trim the amplifier carefully watching monitor signals. Though their rich experience enables it, such kinds of uneasy operation impose heavy load on them. This section executes a part or the whole of these operations.

The above-mentioned functions require the advanced control section composed of a high-performance CPU, waveform digitizers to analyze the monitored pulses, and a communication unit connected with a optical network line for linac control. Now application of expert system is discussed to realize the advanced functions (4) and (5). Since this kind of software is quite heavy for a computer system, careful consideration should be paid to determine a CPU, an operating system and a bus-standard.