A VERSATILE RF CONTROLLER*

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Abstract

The low level RF system developed for the new Bevatron local injector provides precise control and regulation of the RF phase and amplitude for three 200 MHz linac cavities. The main features of the system are:

- o Extensive use of inexpensive, off-the-shelf components
- o Ease of maintenance
- o Adaptability to a wide range of operation frequencies.

The system utilizes separate function, easily removed RF printed circuit cards interconnected via the edge connectors. Control and monitoring are available both locally and through the computer. This paper will describe these features as well as the few component changes that would be required to adapt the techniques to other operating frequencies.

Introduction

This is a third generation 200 MHz low level RF control chassis, designed to control and regulate the RF phase and amplitude of a single RF load while monitoring the phase and amplitude of two RF loads. The first chassis was a 23 MHz unit designed for the Wideroe type Linac [1] presently in service at the SuperHILAC. The second was a 70 MHz unit designed to control a buncher in the SuperHILAC injector system. Both chassis were indentical in construction and provided many desirable features. These chassis designs were used as a guideline for the 200 MHz version that is used in the upgrade Bevalac local injector [2].

Naturally, one would expect to incorporate the little improvements made to the first unit in the construction of the next, however, the very nature of dealing with 200 MHz has produced two very significant changes from the 23 MHz model:

1) Versatility - The 23 MHz model was limited to frequencies of 70 MHz and below by the component specifications and construction techniques. The 200 MHz model is presently limited by "off-the-shelf" components to frequencies of 250 MHz and below.
2) Maintenance - The 200 MHz model is more easily maintained due to reduced circuit complexity.

Construction

The chassis is constructed around a standard control logic chassis. Dedicated test points and controls are located throughout the system block diagram which is stenciled on the front panel above the control logic chassis. Access to the control logic cards is provided by a removable blank panel located below the system block diagram. Two color stenciling is used on the rear panel to identify each plug by channel as well as function and number. A blank panel located directly above the rear plug panel provides access to the power supply regulators and phase compensation cables.

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RF Signal Handling

Type "N" connectors are used on the rear panel to interface all the RF input and output signals while "SMA" connectors are used for the front panel RF monitor signals.

Semi-rigid, RG 402 coax, which are used throughout the bin are interfaced to the RF card striplines via a "Coax - Edge Card Interface Connector". These devices shield the RF loop antenna formed by the coax-stripline interface.

RF Card Construction

Etched, double sided ground plane construction is provided for the RF cards. The component side ground plane is removed where necessary to provide component connection to the stripline below. All component grounds interconnect the two ground planes.

Even though custom artwork is done for each card, all "D.C." signals in or out of the card are hand wired on the component side. This is done to prevent passing an artwork "wire" over a stripline, which could cause on board oscillations as well as introduce RF noise to the rest of the bin.

The impedance of striplines, discrete component attenuators, and all commercial RF devices is nominally 50 ohms.

All mixers, directional couplers, and power dividers/combiners are commercially available and of "half-crystal can" construction. For ease of maintenance, they are "plug-in" replaceable by virtue of the individual pin sockets that are soldered to the RF boards.

360° ø Detector

The RF reference input signal is +10 dbm at a fixed phase. While the unknown RF input is limited to +10 dbm maximum, satisfactory operation has been observed with this input <-10 dbm. These two RF input signals are monitored off board via the buffered, coupled ports of the input directional couplers.

The reference coupler output is sent to the buffered L.O. ports of two doubly balanced mixers via an "in-phase" power divider. While the "unknown" coupler output is sent to the buffered RF ports of the same two mixers, it is sent via a 0°/90° power divider.

The resultant D.C. mixer output voltages are then

$$V_{0^\circ} = k \sin \phi$$

$$V_{90^\circ} = k \cos \phi$$

where k is a value proportional to the unknown RF input voltage and ø is the phase difference between the two RF input signals.

The mixer output voltages are filtered to remove any RF harmonics and amplified by ultra low drift op-amps. Amplifier gains are set to produce an output voltage of ± 10v maximum, when the unknown RF signal is +10 dbm and ø is variable.

These two output voltages are the x,y components of the unknown RF signal and when displayed vectorially give an accurate account of amplitude as well as phase.

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360° Ref ø Shifter

The +10 dbm RF input signal is monitored off board by the buffered, coupled port of the input directional coupler.

The coupler output signal is sent to two doubly balanced mixers via a power divider. The two equal RF signals are buffered and then modulated by the mixers.

The resultant RF mixer output voltages are proportional to the respective ± D.C. mixer input modulation voltages. It should be noted, a D.C. input sign change causes a 180° phase change in the mixer RF output voltage.

The ± D.C. modulation voltages are generated by the on board computer card and are the x,y components of the desired RF output phase.

The RF mixer outputs are buffered and then summed by a 0°/90° power divider/combiner to produce the phase shifted, albeit distorted and attenuated, output RF signals.

The output signal is then passed through another 0°/90° power divider/combiner. This device, with the normal outputs unterminated and the normally isolated port acting as the output port, serves as a filter to the distorted input.

The filtered signal is sent to the fixed gain, wide band amplifier via the associated input attenuator. This discrete component attenuator/amplifier combination compensates for all circuit losses.

The amplifier output signal is divided and sent off board as two +7 dbm, equally phased, RF signal.

180° Phase Detector

The RF reference input signal is +7 dbm, derived from the 360° ref. ø shifter, and the unknown RF input is limited to +10 dbm. Both RF input signals are monitored off board via the buffered, coupled ports of the input directional couplers.

The reference coupler output is buffered and sent to the L.O. port of a doubly balanced mixer, while the "unknown" coupler output is buffered and sent to the RF port.

The resultant D.C. mixer output voltage is then

$$V = k \sin \phi$$

where k is proportional to the unknown RF input voltage and ø is the phase difference between the two RF input signals.

The mixer output voltage is filtered to remove any RF harmonics and amplified by a wide bandwidth op-amp.

Maximum output is ~3°/volt with a 1 MHz bandwidth.

RF ø and Amplitude

This board derives its RF input signal from the "360° Ref. ø Shifter" at the +7 dbm level. Off board monitoring of the input signal is provided via the input directional coupler.

The coupler output is sent to a 360° ø shifter equivalent in design and function to the "360° Ref. ø Shifter". Again, the phase shifted RF output signal is distorted and sent to a 0°/90° power divider/combiner.

The normal outputs of the device are equally terminated in the reactance, ±J. The normally isolated port now provides a filtered RF output, that is phase variable as follows:

$$\phi = 2 \arctan (1/\pm J)$$

where $+J = X_L/50$ and $-J = X_C/50$

To vary ø at a 1 MHz rate, four matched varactor diodes were used to build two identical circuits each consisting of two series LC circuits in parallel.

This method, which can produce phase changes in excess of 360°, yields excellent phase linearity to the modulation (varactor) voltage over the 180° phase range with little change in insertion loss.

The "fast" ø modulator output is buffered, amplified and sent, via buffer, to a doubly balanced mixer. This mixer, which is used as a single quadrant, linear, RF modulator, is the system amplitude modulator.

The mixer output is buffered, amplified and sent off board via the output directional coupler at a maximum RF level of +10 dbm.

The output directional coupler provides buffered monitoring of the output signal via the coupled port.

Phase Compensation Cables

These three cables determine the absolute indicated values of the phase detectors.

Equally phased RF signals are applied to the phase reference and monitor plugs located on the chassis rear panel.

The indicated phase detector output is then set to 0° by trimming the length of the associated phase compensation cable.

Power Supplies

The chassis has no internal supply and requires external inputs of ± 24v and +12v. These voltage are generated by single supplies and distributed to each chassis. Each voltage, with its common, is brought in on a twisted pair through a single plug, fused, and sent to a series regulator. The over-voltage protected, regulator outputs provide chassis voltages of ± 15v and +5v. This technique virtually eliminates A.C. line noise and provides isolation between the chassis.

Internal Interlocks

There are two interlock chains in the chassis. One ensures all cards are installed, the other ensures all P.S. voltages are greater than 80% of rated value.

If any fault occurs, pulse permissive is removed and a relay is de-energized. The relay contacts are available on the chassis rear panel.

Low Level System Controls

The following controls are available either from the computer or the chassis front panel. The control point is determined on the chassis front panel by the switch labeled "Local/Computer" and all functions are controlled together.

- o RF Pulsing On
- o RF Phase Loop On
- o RF Pulse Width
- o RF Phase Reference
- o RF Gradient Reference - This is the RF peak detected value the load will assume provided the drive is not limited. This would be a closed loop condition.
- o RF Drive Limit - This control limits the absolute value of drive to the RF load. Operation in this mode would be an open loop condition.

Other controls available only at the chassis are:

- o Phase Offset - This control sets the phase correction loop in the center of its range. This feature is meant to compensate for any amplifier tune, position, or other system drift. It is assumed that these changes are long term and do not require daily adjustment.

- o Internal Drive Limit - This control provides the system with a fixed limit which prevents accidental overdrive either via computer or front panel input.

Pulse Control and Timing Center for System

The injector system typically runs a 1 ms RF pulse at a 2 PPS rate. During the off time, the intermediate power amplifier is biased off and the plate voltage for the final power amplifier is removed via the hard tube modulator.

To prevent "gradient control loop" saturation, the bias and plate voltages are turned on ~ 100μ sec prior to the RF. These three pulses are generated from the chassis input pulse via the pulsing on/off controls and may be "crowbared" by any of three fault conditions.

The IPA and HTM systems each generate a fault condition while the third fault is internally generated by excessive gradient loop error. This fault may be disabled for purposes of cavity conditioning or manual operation.

External Strobes

There are two pulses that occur prior to the completion of a normal machine on pulse. These strobes are used to "read" the system operating parameters and the frequency control loop errors. If a fault condition occurs during the normal on pulse, these strobes are not generated.

Analog Monitoring

To ensure the integrity of the feedback systems, analog monitoring of the gradient and phase of each RF load is done independently of the feedback monitoring.

Tank ø is determined by the "360° RF ø Detector" card which outputs the information in x,y format. These monitored values are sent to the on board computer card where they are processed and outputed as a linear D.C. value proportional to phase.

In addition to these RF gradient and phase values, the respective modulation and error signals for each loop are monitored.

Access to the aforementioned analog operating parameters is provided by the bin to the computer, the complete system multiplexer, and the front panel.

16 Channels of Boolean Monitoring

Additional to the two Boolean command channels, there are 16 Boolean functions that are monitored in parallel by the computer and by LED's placed on the front panel block diagram. These include:

- o The permissive, command, and status conditions for each Boolean command
- o Three channels for the RF drive control mode (Auto, drive limit or internal limit)
- o Three channels for the fault indicators
- o Reduced pulse width indicator
- o Gradient loop error in excess of 1%
- o Phase loop error in excess of 1°
- o Phase loop offset conditions in excess of ± 60°

I/O Interface

Several techniques for handling I/O signals are used to reduce the effect of noise in the system.

TTL pulses and strobes are transmitted and received differentally over twisted pair shielded, terminated cables. By definition, the cable pair condition "1, 1" or "0, 0" is not valid.

All analog signals are intended for differential reception. To this end, the analog outputs are isolated by 100 ohms in both the signal and common lines. Again, transmission is over twisted pair, shielded cables, which, in some cases, are terminated at the receiver.

Boolean I/O signals pose another problem as the computer interface is not intended for differential signals. For this application two 9 channel opto-isolator cards are used. These cards are universal in that the wiring to the card is fixed while the transmit or receive function is determined by component placement on the card. These cards provide D.C. isolation between the computer and bin common.

Other Operating Frequencies

Adapting the RF boards to other operating frequencies, requires changing the six 0°/90° power dividers/combiners and modifying the LC circuits mentioned under the heading "RF ø and Amplitude".

The 0°/90° power divider/combiner is a resonant device that should be chosen for center frequency, bandwidth, and/or best operation.

The 200 MHz RF cards can use either the 180 MHz or the 250 MHz combiners, however, the 180 MHz devices were chosen for the slight improvement in operation.

The initial LC networks were calculated by an iterative process using a computer. Advertised values for the varactor capacitance versus bias voltage were entered into the data base. The slope Δø/Δ bias was then evaluated for various values of L. Tests on the final design showed good correlation with the calculations.

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References

[1] J. Fugitt, et al., "A Simplified R.F. Power System for Wideroe - Type Linacs", Particle Accelerator Conference, Washington D.C., March 11-13, 1981, p. 2955.

[2] J. Staples, et al., "Heavy Ion Upgrade of the Bevatron Local Injector", Proceedings of the 1984 Linear Accelerator Conference, Seeheim, Germany (May 7-11, 1984), p. 377.