ELECTRONIC PEAKERS*

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Summary. A reliable system has been designed and built for the variable phase generation of pulses for the firing of ignitrons. These ignitrons rectify the ac output of a motor generator set for application of dc power to the main magnets of the Alternating Gradient Synchrotron at Brookhaven National Laboratory. It is now possible to shift the phase of the ignitron firing so that the current in the main magnets either increases in a linear manner (rectify mode), decreases in a linear manner (invert mode), or stays constant at any desired level (flat-top mode). In addition time interval pulses can be applied to the electronic peakers so that the main magnet current can be made to be any combination of the rectify, flat-top and invert modes. The electronic peakers have been in operation for a little over a year without a single failure.

I. General Considerations

The main magnets of the Alternating Gradient Synchrotron are powered by a motor generator set consisting of a 5500 hp induction motor and a 30,000 kVA generator. In order to obtain the dc voltage required to drive the main magnets, the ac power is applied to twelve banks of ignitrons operated as phase controlled rectifiers.[1]

The firing of an ignitron is controlled by timing the injection of sufficient current into an ignitor rod immersed in its mercury pool cathode to cause the initiation of an arc. At the present time the required amount of ignitor rod current is obtained from a capacitor which is charged once each generator cycle to a thousand volts and then discharged by operation of a thyratron switch (called the firing thyratron) through a step down transformer. The transformer serves the very important function of isolating the 6000 volts appearing at the cathode of the ignitron from all the circuits associated with the firing thyratrons as well as increasing the current obtained through the discharge of the capacitor.

One of the principal objectives, then, of the twelve electronic peakers is to generate and deliver pulses at the proper time during a generator cycle to the grids of the firing thyratrons. Before the design and construction of the electronic peakers, these pulses were obtained by applying the ac generator twelve phase sine wave outputs to peaking transformers. The great disadvantage of the use of the peaking transformers was that the range of phase control of pulse generation was very narrow. As a matter of interest the name "electronic peakers" is derived from the original use of these transformers.

The use of the Alternating Gradient Synchrotron as a research tool requires that the main magnet current flow be one of the following modes for any arbitrary period of time whose duration is limited by the maximum ratings of the magnets and motor generator set:

A. Increase in a linear manner (rectify mode).

B. Stay constant (flat-top mode).

C. Decrease in a linear manner (invert mode).

The generation of any one of the three modes of operation depends on when the ignitron is fired during the generator cycle. For instance the application of a step function of positive voltage to an inductor from a voltage generator will result in mode A. In actual operation the firing of the ignitrons at the thirty degree point of the generator cycle causes a 6000 volt, positive voltage step to be applied to the main magnets. If at any time after the initiation of the rectify mode, it is desired to go into the flat-top mode of operation, then the angle of firing has to be switched to between 120^{o} and 150^{o}. The magnitude of applied positive voltage needed to achieve constant current flow is just the amount necessary to make up the IR drop in the magnets and busses. The fact that these drops vary for different duty cycles determines the exact point between 120^{o} and 150^{o} to fire the ignitrons. Finally, firing the ignitrons after the 180^{o} point results in a reversal of energy flow, which is to say that the energy stored in the magnetic field flows out of the main magnets into the ac generator now acting as a motor. The magnet current cycle is completed when there is no longer any energy in the main magnets. The voltage appearing at the magnets during an invert period is a negative step of 6000 volts magnitude.

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Therefore, another objective to be met by the electronic peakers is the capability of being switched in such a manner that any combination of the main magnet current flow modes can be achieved. The one described was rectify, flat-top, invert. Another combination which is in use is rectify, invert. Two other possibilities might be rectify, invert, flat-top, invert and rectify, flat-top, rectify, invert.

An installation like the AGS is a large complex structure which means that downtime is very expensive. Naturally, then, reliability of operation of the electronic peakers is essential. For this reason heavily derated semiconductor circuits were used. It was reliability, also, that dictated the decision that the firing pulse during the invert period be generated by the peaking transformers. When a situation of seven thousand amperes flowing in the main magnets exists, it becomes imperative that there be no possibility of failure to go into the invert mode of operation. It is extremely unlikely that any one invert peaking transformer will fail. It is considered almost impossible for any two to fail at the same time.

II. System Design

A block diagram of one of twelve identical phases is shown in Fig. 1. The output of the 30,000 kVA generator is not in synchronism with the line. This is a consequence of using an induction motor as a driver. The frequency from the generator varies from approximately 55 cps. to 58.5 cps. However, the firing of the ignitrons has to be in synchronism with the output of the motor generator set. Therefore, all operations are timed by using machine cycles as reference signals. For instance in another piece of equipment there are generated rectify, flat-top, and invert interval pulses consisting of any arbitrary number of generator output cycles. Also it is logical for the electronic peakers to process the generator output in such a way that the variable phase generation of firing pulses is achieved. The waveform of the signal from the generator is highly distorted and with an amplitude which varies with loading. First, it becomes necessary to filter out the higher harmonics, a process which is not too difficult because of the discrete character of the unwanted frequencies. Second, the effect of the varying amplitude on the phase of the firing pulse has to be obviated. This is done by applying the filtered signal, now consisting of the fundamental frequency of the ac generator to a zero crossing, limiting circuit. This results in acquiring a square wave whose half period durations are independent of the change in amplitude. The next step is the generation of a linear sawtooth of voltage for one-half of the period of the square wave. The existence of a linear relationship between voltage and time transforms the problem from one of selecting different times to one of selecting different levels of voltage. A voltage comparator which puts out a single pulse of 100 microseconds duration when a desired voltage level is reached was used to perform this type of operation. In addition the voltage comparator was designed so that different reference voltages could be switched in as desired. As explained previously the electronic peakers generate the pulses only for the rectify and flat-top modes and the peaking transformers generate the pulses for the invert mode. This led to the use of rectify and flat-top switches for the changing of the reference voltages in the comparator. It also led to the need for a gated amplifier so that transmission of rectify and flat-top pulses from the electronic peakers could be inhibited during the invert mode.

The invert pulse appears at the grid of the firing thyratron during all modes of operation. Its presence there is highly desirable for safety of operation. It does nothing during the rectify or flat-top periods since the capacitor which the thyratron discharges in igniting an arc in the ignitron is charged only once per cycle. This means that only the first pulse to appear on the grid of the firing thyratron has any effect. The gated amplifier is enabled during the rectify, flat-top periods, thereby allowing the transmission of pulses which arrive ahead of the invert pulses. During the invert period the gated amplifier is inhibited and only the invert pulse appears on the thyratrons grid.

III. Circuit Design

A. Low-Pass Filter

The circuit diagram of the electronic peakers is shown in Fig. 2. The filtering is simplified because of the discrete frequencies involved and because the frequency of the distorted ac generator output changes only by approximately 5% as the induction motor is loaded. The filter is a conventional LC half-section which is coupled to the generator through two transformers. The one shown on the circuit diagram is the only one built into the equipment.

B. Squaring Circuits

The squaring of the filtered signal is done by a Schmitt trigger biased to detect the zero voltage crossing. The loop gain has been reduced to approximately five so that the hysteresis effects inherent in this type of regenerative feedback would not be excessive. The two half periods of the square wave equalled each other to within 1%. The output is taken from the emitter of Q2 because the low output impedance is desirable.

C. Sawtooth Generator

This circuit is a bootstrapped sweep generator that is activated by the switching pulse derived from the Schmitt trigger. Q5 is the switch which controls the start and stop of the sweep. Sufficient current is injected into the base to hold it in the saturation region for one half of the period, thereby shunting C2 to ground. For the next half period Q5 is shut off and sweep action occurs due to the charging of C2 through the resistors in the collector. Bootstrapping is used to linearize the sweep.

D. Variable Voltage Comparator

The voltage comparator used is of the multiar type. This selection was made because of the great sensitivity of voltage indication that can be obtained with this kind of circuit. In this case a voltage sensitivity of 10 millivolts has been achieved. This is not difficult to do since the sensitivity can be increased by increasing the forward gain of the amplifier which is made up of Q10 and Q11. A multiar configuration looks like a blocking oscillator, but there are some important differences in its manner of functioning. For instance Q10, Q11 are biased in their active region and yet without the application of the sweep voltage, there would be no pulse output. This is due to the fact the feedback loop is broken by the back biased diode D1. With the application of a gradually increasing forward bias, the resistance of the diode will decrease until the loop gain becomes one, regeneration occurs, and an output pulse will result. This illustrates the importance of having a diode with a gradual turn on characteristic.

Another important difference in the functioning of the circuit results from the requirement that only one pulse be generated when the reference voltage is exceeded. This is accomplished in the multiar by applying a positive going sweep voltage so that Q11 is maintained in a cutoff condition after pulse generation. As long as Q11 is shut off, the feedback loop is broken and regeneration cannot occur. The multiar is ready for operation once more after retrace of the sweep. During retrace, the generation of a pulse due to the transistors being driven back into their active regions is prevented by shunting the multiar transformer with the diode D2.

The reference voltage against which the sweep is compared is the magnitude of the back bias of D1. As discussed previously this back bias has to be variable so that the phase of generation of the firing pulses can be changed. This is accomplished by the injection of a variable current bias into the emitter of Q9. If there is no current flowing in Q9 in the absence of the sweep, then the voltage, common to Q7's collector and D1's anode, is -24 volts. The cathode of D1 is at approximately -4.5 volts. For this bias the sawtooth of current injected into Q9's emitter will cause a pulse to be generated at approximately 180°, a firing angle which will result in zero transfer of energy into the main magnets. An increase in the amount of bias current flowing in the transistor makes the collector voltage more positive, reduces the back bias, and will advance the angle of pulse generation so that more energy will be transferred into the magnets. In other words decreasing the diode back bias allows the sweep voltage applied to the D1 anode to reach the fixed cathode level of -4.5 volts sooner.

E. Switches

It was decided to use separate switching circuits for the rectify and flat-top biases so that there could be independent adjustment of phase of pulse generation for the two modes. The circuit in each case is almost identical. Aside from some different resistor values, the only difference in the two switches is the fact that the rectify bias voltage is derived from the power supply and in the flat-top case it is derived from an automatically varying error voltage obtained from a closed loop system designed to keep the slope of the current change in the magnets at any desired magnitude. Transistor Q12 (the rectify switch) is biased into saturation when it is desired that no rectify mode bias be transmitted. This condition causes a zero voltage to be at the emitter of Q13. Therefore the result is there is no component of current flowing in Q9 which is due to rectify mode bias. When Q12 is driven into its cutoff region, its collector resistance is so high as to represent an open circuit. In this situation the voltage appearing at the emitter of Q13 will be a value determined by the voltage divider connected to its base. This bias voltage is changed to a bias current by the very simple process of applying it to a resistor large enough to swamp out the input resistance of Q9. This takes advantage of the fact that the input resistance of Q9 is very low when looking into its emitter. Actually Q9 is acting as an adder in that any desired bias current is added to the linear current sawtooths. The greater the amount of bias current added, the sooner the firing pulse is generated.

It is highly undesirable for the rectify and flat-top biases to appear at the same time since this occurrence would upset proper phase of firing pulse generation. The rectify and flat-top mode interval pulses are complements of each other which precludes the simultaneous appearance of both biases.

IV. Construction

All the stages with the exceptions of the power amplifier and the transformer, low pass filter combination, were built on plug-in cards. In order to facilitate repairs in the event of trouble, appropriate test points were made readily available and spare cards were built. Thus, it becomes quite simple to isolate the faulty phase and replace the troublesome card with a spare. As of the middle February 1965 when this was written there had been no failures since installation of the equipment which was in January of 1964.

V. Acknowledgement

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References

[1] G.K. Green and E.E. Shelton , "Magnet, Part VI - Power Supply", Rev. Sci. Instr., 24, pp. 762-769; September, 1953.

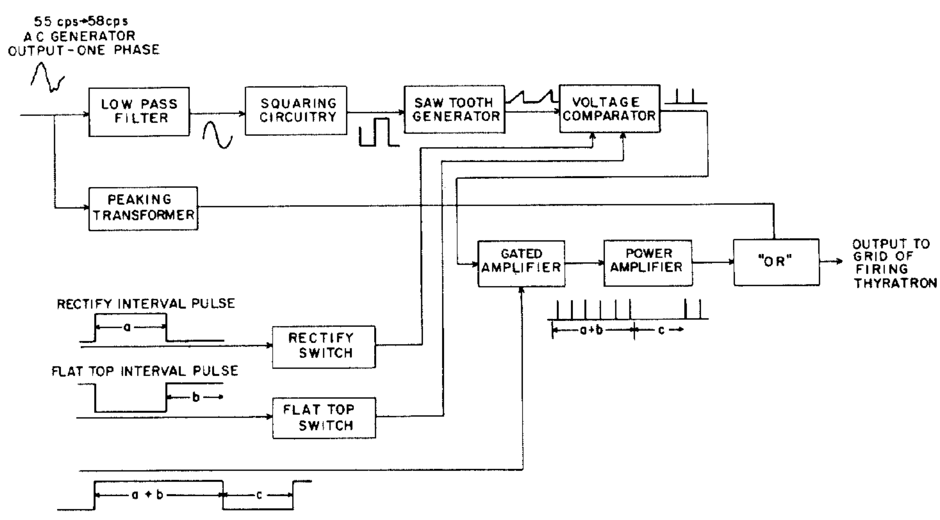

Fig. 1. System Diagram.

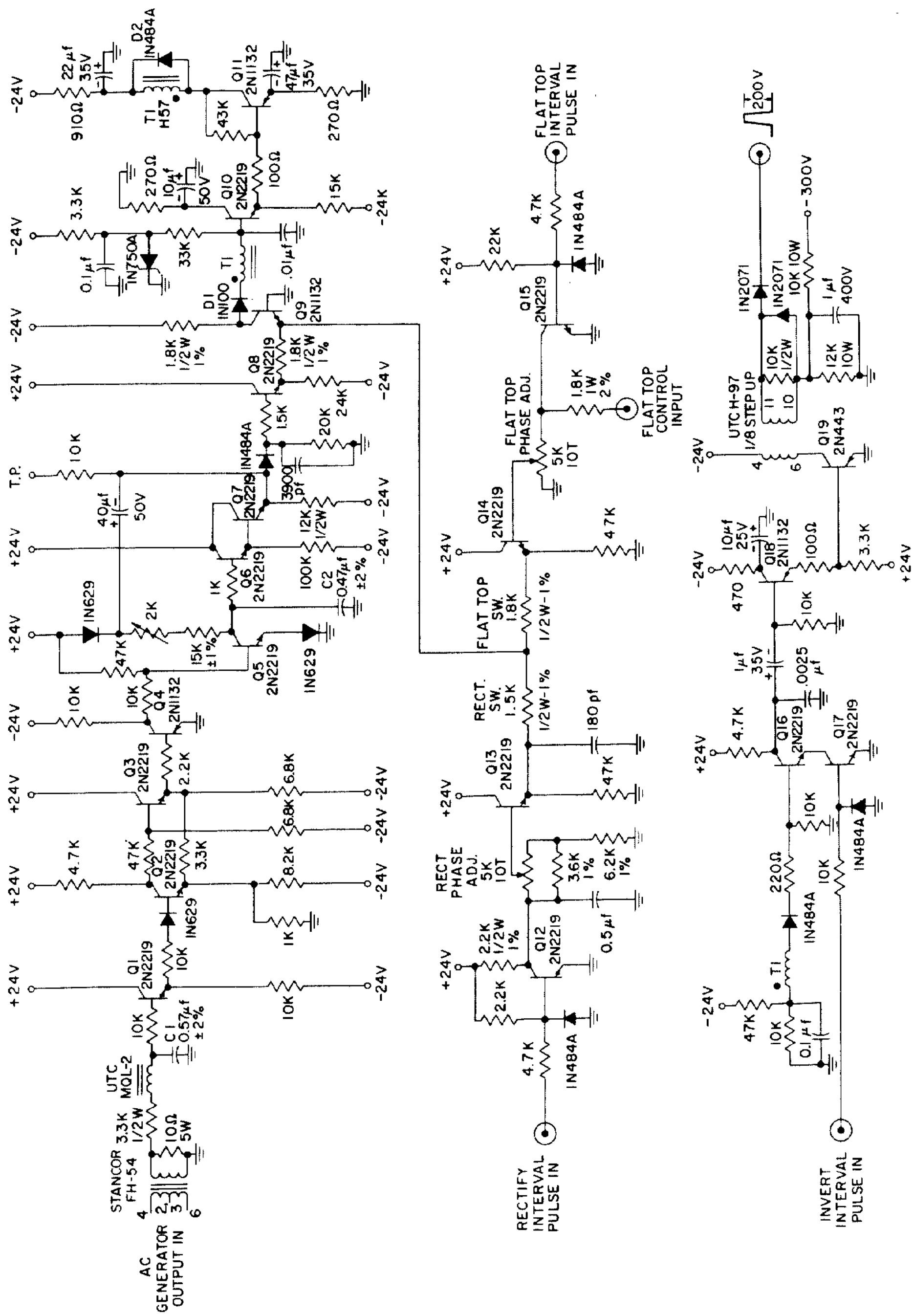

Fig. 2. Circuit diagram of electronic peakers.