FIELD CONTROL TYPE CURRENT REGULATOR FOR ELECTROMAGNETS*

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Summary

A system is described for regulating current in electromagnets of more than 1 H inductance and requiring more than 50 kW of power. Current stability of better than 1 part in 50,000 has been realized using this system with the main magnet coils of the Argonne 60-inch cyclotron. Design is based on the classical approach in which current through the generator load is controlled by the current through its field rather than the presently popular use of series transistor design. It incorporates advantages of developments in the fields of feedback control and solid state devices to provide a simple, reliable and flexible system. During startup, to minimize overshoot and consequent hysteresis effects, a voltage loop is used for control. For precise, long term regulation, a current loop is added in which the current through the magnet is controlled by a pre-set current reference signal or a magnetic field reference signal obtained from a nuclear magnetic resonance probe.

Introduction

A field control type current regulator, in which the current through the generator load is controlled by the current though windings of the generator field, has been traditionally used for the control of large electromagnets. The conflicting requirements of regulation, stability, ripple, operational flexibility and simplicity challenge the ingenuity of the designer as evidenced by the variety of solutions found in the literature prior to 1959.[1-8]

The current through the load can also be controlled by means of a control element placed in series with the load. This control element is normally a vacuum tube, or a transistor, in which the output current is controlled by a small control signal. Power transistors are particularly suited for this purpose because they can pass large currents at relatively small collector to emitter voltages. Because the collector current, and thus the load current, is practically independent of the collector to emitter voltage, ripple voltage and small variations in the load supply voltage are not reflected in the load current thus providing an effective filtering action. Finally, the small time constant of transistors relative to the large time constant of electromagnets makes it readily possible to obtain large loop gain and a correspondingly high degree of regulation. The simplification in design of high current regulators obtained by using transistors in series with the load, is reflected in the popularity of this method as evidenced by the literature beginning with the classic paper of Garwin, et. al.[9-11] This simplification, however, is obtained at the expense of added complexity, reduced reliability and higher cost.

In large number of applications, particularly where iron core magnets are used, a current regulation of 1 part in 10,000 is satisfactory. Regulation to this degree, or higher, can be readily obtained by means of the field control type current regulator. The field control type regulator is considerably more simple and more reliable than the series transistor type and costs less. This is made possible because the large number, usually more than 50, of power transistors and the associated hardware necessary for mounting, fusing and cooling is eliminated. The design of the field type current regulators, generally, is more difficult due to presence of several, usually 3 or more, closely spaced time constants whose values may range from 0.1 to 20 seconds. However, by taking advantage of the developments in the control field theory and the availability of the frequency response measuring equipment, the suitable phase correction networks can be incorporated into the field type regulator that make the high loop gains and the correspondingly high degree of regulation possible.

This paper describes a field type current regulator developed at Argonne National Laboratory to regulate the current in the main magnet coils of the 60 inch cyclotron.

System Description

The functional block diagram of the field control type current regulator is shown in Fig. 1. The current is supplied by a 300 kW, 1000 A, dc generator driven by a synchronous motor. Its field is excited by a 5 kW amplidyne whose field current is controlled by an amplified error signal.

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For operational flexibility two main feedback loops are used, a voltage loop and a current loop. To minimize the overshoot and the consequent hysteresis effects during the startup, only a voltage loop is used. This loop consists of the generator, amplidyne and the power amplifier connected to form an operational amplifier whose output voltage is proportional to its input from a voltage reference. The voltage regulation of this loop is approximately 1 part in 500. Under these conditions, the magnet current depends primarily on the reference voltage setting, the loop gain and the resistance stability of the magnet windings. The response of this loop is relatively fast, thus the variations in the output voltage are corrected before they can produce the corresponding variations in the output current. For precise, long term regulation a current loop is added to the voltage loop. The loops are combined in an operational amplifier-current summing junction to minimize the possible interaction between the two loops. Under these conditions, the current through the magnet windings is controlled in response to either the pre-set current reference signal or the reference signal obtained from an NMR probe. For control in response to the preset current reference signal, the voltage developed across a series sensing resistor is compared with a known reference voltage and the resulting difference error voltage is amplified. In this design, the NMR sensor is used continuously for sensing magnetic field level, but only occasionally for control.

Construction and Operation Features

The solid state electronic components of the regulator are mounted in the plug-in units for ease of servicing. They are mounted on a single 19 inch rack chassis 12 inches high and 18 inches deep as shown in Fig. 2. The desired mode of control is selected by a mode control switch, while the precise value of current, to 5 digits, is pre-set by means of a direct reading Kelvin-Varley type potentiometer. Variables such as generator voltage and current, and outputs of error and power amplifiers are indicated by individual panel meters. The current sensing resistor consists of a 4 inch wide by 13 inch long manganin strip immersed in an oil bath thermostated at 40° C.

Design Objectives

1) Regulated current range 100 to 600 amperes.

2) Stabilization to 1 part in 20,000 against 10% change in line voltage and generator output voltage. This, assumed variation in the generator output could be caused by change in gain of the generator, amplidyne or the power amplifier.

3) Stabilization to 1 part in 20,000 against 5% change in the resistance of the magnet windings.

According to the theory of current regulators[12-14], the fractional current variation due to generator output voltage changes is given by:

$$\frac{\Delta I}{I} = \frac{R_L}{R_L + (1 + \mu) R_S} \quad \frac{\Delta E}{E_L} \qquad (1)$$

where R_L is the load resistance, μ is the open loop gain and R_S is the current sensing resistance in series with the load. ΔE is the change in generator voltage and E_L is the voltage across the load.

The change in load resistance, such as caused by heating of the magnet windings also affects the current regulation. The fractional change of current due to this change is:

$$\frac{\Delta I}{I} = \left[\frac{\Delta R_L}{R_L + (1 + \mu) R_S}\right]^2 \frac{E}{E_L} \qquad (2)$$

where E is the nominal value of the generator voltage.

From these expressions it follows that for good regulation (small value of $\Delta I/I$) the open loop gain μ and the resistance R_S of the current sensing resistor have to be large. Using the expression (1), the value of open loop gain necessary to stabilize the current to 1 part in 20,000 against 10% changes in the generator output voltage was calculated to be approximately 0.8×10^6 (110 dB). Substituting the values of μ and $\Delta I/I$ into expression (2) shows that this value of gain can compensate for approximately 6% change in load resistance. Actually, the resistance of the magnet windings is kept relatively constant by means of cooling water whose temperature is maintained within 1° F.

Closed Loop Considerations

It has been pointed out, in equation (1), that for good regulation a high value of open loop gain is necessary. However, it is well known that a dynamic instability or oscillation may occur in a feedback amplifier containing two or more time constants. This oscillation will occur at a frequency at which the phase of the output signal has shifted 180 degrees with respect to the input, while the amplitude of the output voltage is still equal to or larger than that of the input signal.

The current regulating system described contains four major time constants and would definitely be unstable even at low values of loop gain. These time constants and their approximate values are as follows:

1.	The amplidyne control field	0.65 seconds
2.	The amplidyne quadrature axis	0.17 seconds
3.	The generator field	0.25 seconds
4.	The magnet	17.50 seconds

To utilize the high value of gain necessary for a specified degree of current regulation, the gain of the system has to decrease with frequency until at the frequency crossover (frequency at which the phase shift is 180 degrees) is less than unity. Several different methods, commonly referred to as "stabilization techniques", are used in this design. The control field time constant of the amplidyne is made negligible by operating the control windings from a high impedance source consisting of a transistor operating in the common emitter configuration. To compensate for the effects of the amplidyne quadrature axis time constants, the quadrature current rate signal is fed back negatively to the amplidyne "anti-hunt" windings. This feedback is accomplished by connecting the primary winding of a "stabilizing transformer" to the amplidyne output terminals and the secondary winding of the same transformer to the "anti-hunt" windings of the amplidyne. The "stabilizing transformer" was specially designed for this purpose and has been used in the field of industrial control since 1947.[15] Its output voltage is proportional to the rate of change of its input current, and when this voltage is fed back negatively it then decreases the gain and phase shift with frequency. In this respect, the results are similar to those obtained by placing a phase lead network in the forward path; however, at low frequencies, 10 cycles/second and below, and in low impedance circuits, the large values of capacity that are required in the RC lead network make the latter impractical. The effect of the generator field time constant is decreased by including it within a feedback loop from the generator voltage output to the power amplifier input.

To compensate for the magnet time constant, approximately 17 seconds, another current rate feedback is used. This feedback signal is obtained from a secondary winding around one pole of the magnet, which results in a form of a stabilizing transformer. After passing through a low pass filter, the secondary winding signal is fed back negatively to the input of the power amplifier. The effectiveness of this stabilizing transformer is demonstrated by the fact that with the secondary winding disconnected the maximum regulator loop gain possible is approximately 50, while with the secondary connected, the allowable loop gain is over 1000.

Performance

The operation of the current regulator over a period of 6 months indicates that the design objectives have been achieved. Several methods of measuring have been used to evaluate the regulator's performance. The primary method is by means of a precision potentiometer, Leeds & Northrup K-3, reading potential across the current sensing resistor, with a sensitive electronic null indicator and a strip chart recorder on the output of the null indicator. Using this setup, recordings have been made at high and low chart speeds to indicate the short and long term stability. Representative samples of these recordings are shown in Figs. 3 and 4. The high speed chart (3 in/min) indicates the short term stability of 1 part in 80,000. The long term regulation shown on the slow chart speed (3 in/hr), is approximately 1 part in 70,000. A nuclear magnetic resonance NMR indicator has been used continuously for monitoring the magnetic field stability, and thus the performance of the current regulator. However, because of the low Q of the NMR probe used, the resolution of this indicator is less than 1 part in 50,000. According to this method the current regulation is better than 1 part in 50,000, but the exact determination is limited by the resolution of the probe. Finally, the recording of the cyclotron beam current is another measure of the regulator performance, and according to this, the regulator performance is satisfactory.

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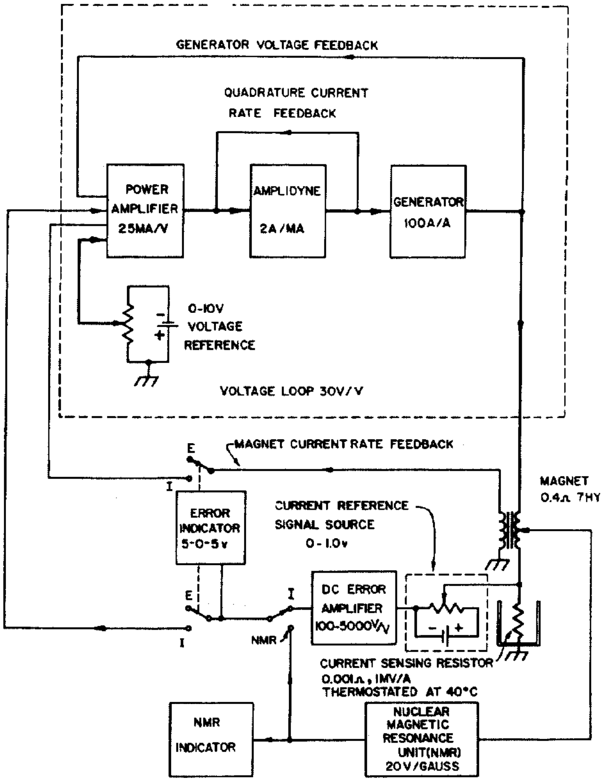

Fig. 1. Functional block diagram of the field control type current regulator.

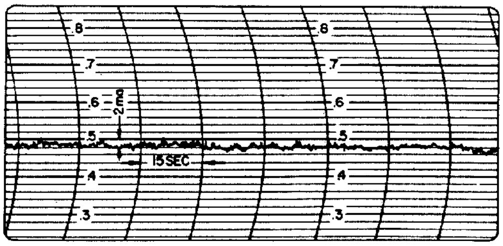

Fig. 3. Recording showing the short term regulation current level = 386.25 A.

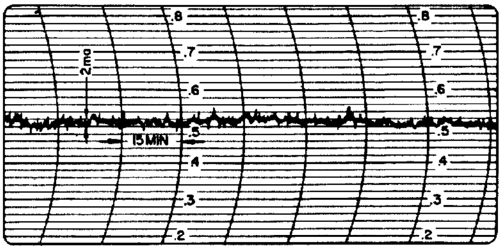

Fig. 4. Recording showing the long term regulation current level = 386.25 A.

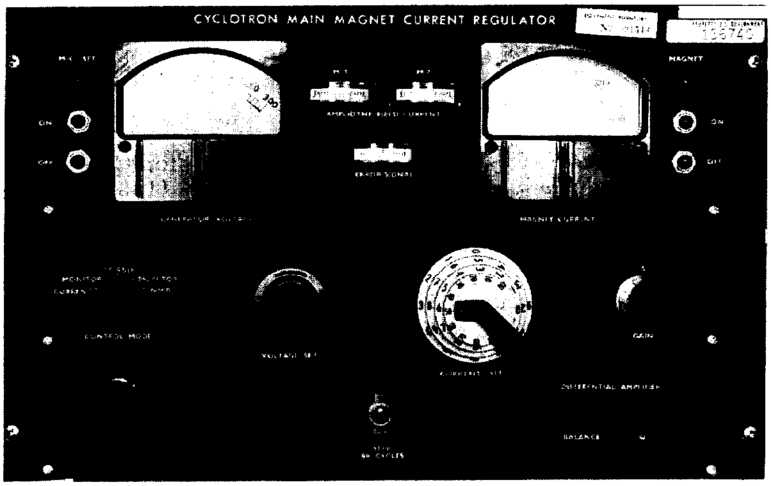

Fig. 2. Front panel of the current regulator for ANL 60 inch cyclotron.