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STEADY-STATE CHARACTERISTICS OF CARBON-PILE VOLTAGE REGULATORS



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D. G. Scorgie and D. H. Schaefer

Approved by:

Mr. N. W. Matthews, Head, Operational Equipment Branch
Dr. W. C. Hall, Superintendent, Electricity Division



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ABSTRACT

Measurements of regulator carbon-pile resistance as a function of operating coil voltage, heretofore unobtainable, have been made with recently developed equipment. The factors contributing to nonlinearities and errors in the regulator have been studied in detail, particularly where heating and hysteresis were concerned. A theoretical analysis is presented which explains the effects of magnetic hysteresis, carbon-pile hysteresis, ambient temperature, and localized heating of the carbon pile and operating coil. Study of the theoretical and experimental results reveals the important role played by carbon-pile power dissipation in determining steady-state operation. Although magnetic hysteresis in the regulator iron is extremely small, its effect is amplified many times by the variable air gap and its importance is far greater than had been anticipated. However, magnetic hysteresis is found to have the beneficial effect of permitting good regulation of large disturbances yet tending to stabilize the regulated system in the steady state.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

NRL Problem E03-04R
NR 423-040

STEADY-STATE CHARACTERISTICS OF CARBON-PILE VOLTAGE REGULATORS

INTRODUCTION

Attempts to measure the steady-state characteristics of carbon-pile voltage regulators have repeatedly been made and have ended in failure. The straight-forward method of measuring carbon-pile resistance vs operating coil voltage is to connect the operating coil of a regulator in series with a source of current and a variable resistance. This method fails, though, because upon increasing the voltage applied to the operating coil a point is reached where the carbon-pile resistance can no longer be controlled by manual adjustments.

It is not sufficient to attribute this result to a lack of sensitivity in controlling the voltage. Instead, the measurements reported upon here indicate that there exists an operating voltage above which the carbon-pile resistance jumps discontinuously to a high value. An electronic measuring circuit¹ which controls pile resistance directly has been used to circumvent this difficulty. With its use steady-state carbon-pile resistance vs operating coil voltage hysteresis loops have been obtained under several conditions with constant current flowing through the carbon pile. The first case uses carbon-pile currents of the order of milliamperes, and hence eliminates most of the heating effects within the pile. The other cases use current of the same order of magnitude as that which actually flows through a carbon pile in operation.

In an effort to evaluate the effects due to heating, hysteresis loops were taken at an elevated ambient temperature and low pile current, then again at room ambient temperature and high pile current. It was hoped to separate the effects caused by: (a) Expansion due to heating of the metallic parts of the regulator, and (b) resistance and pressure changes due to extremely high local temperatures within the carbon stack.

MEASUREMENT TECHNIQUE

The electronic measuring circuit is reproduced in Figure 1. It consists essentially of a dc amplifier with a cathode-follower matching stage to supply the large current for the regulator operating coil.

For the measurements in which small constant carbon-pile current flows, the input to the dc amplifier is connected across the series combination of the regulator carbon pile and the variable resistor, R_s . For measurements using high pile currents the Helipots and carbon-pile supply of

¹ Mills, R. L., "Dynamic Characteristics of Carbon-Pile Voltage Regulators," AIEE Technical Paper 50-213, October 1950

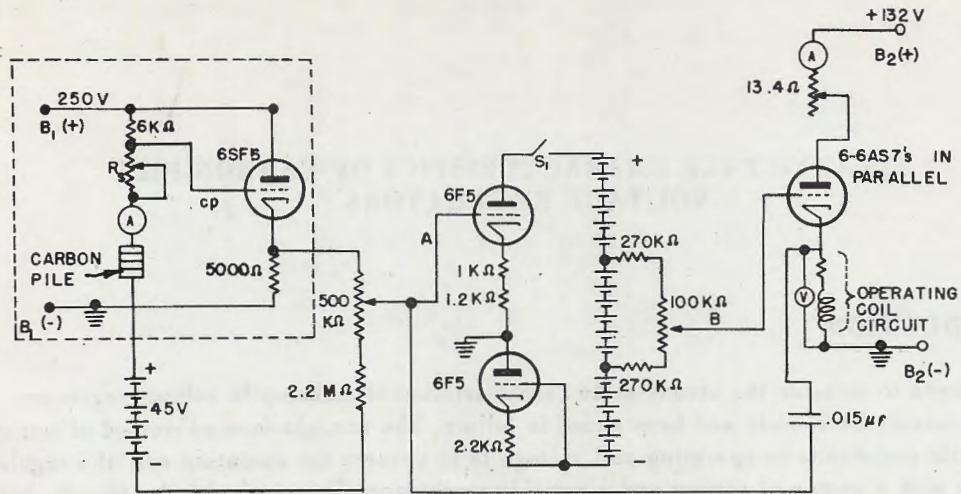


Figure 1a - Schematic diagram of regulator test circuit

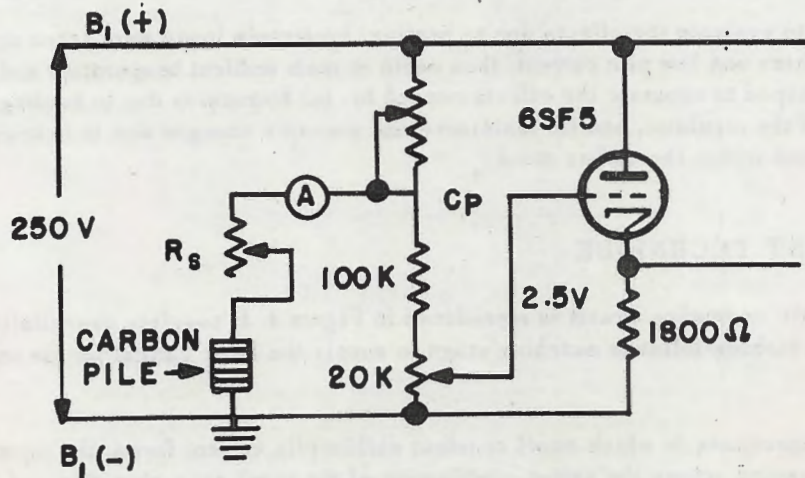


Figure 1b - Test circuit modification for high pile current

Figure 1a are replaced by the arrangement shown in Figure 1b. In both cases a closed, stable loop is formed which acts automatically to control the magnitude of the pile resistance.

The following sequence of steps puts the circuit into operation:

- (1) Set the resistances in series with the carbon pile at some resistance greater than any value to be measured in the regulator hysteresis loop.
- (2) Turn on the B supply and the filaments of the 6SF5. Set point CP at 2.5 volts. Set point A at ground potential.
- (3) Heat the 6F5 filaments. Close switch S, and set point B at ground potential.
- (4) Heat the 6AS7 filaments. Turn on the B_2 supply and allow a voltage of less than ten volts to be impressed across the operating coil circuit of the regulator.
- (5) Rebalance the whole circuit. Warm for an hour. Rebalance again.

The circuit is now ready for use. Up to a point just below the operating range of the regulator the operating coil voltage can be adjusted by varying the 6AS7 plate supply, and the circuit balanced by varying the series resistor (R_s in Figure 1a, b). Above that point, however, the regulator becomes extremely sensitive to voltage changes. Therefore from that point on the 6AS7 plate supply is left at a constant value while the series resistors are further decreased, allowing the electronic circuit automatically to increase the carbon-pile resistance. This eliminates minor hysteresis loops and assures control over the direction of each carbon-pile resistance change. During this time the circuit will become unbalanced, but the fluctuations in current through the carbon pile during each loop measurement are less than 5 percent. All resistances are calculated from ammeter and voltmeter readings.

When it is desired to extend the hysteresis loop to infinite pile resistance values, the pile resistance is first increased to the highest plotted value by the technique described above. Then, in parallel with the pile, a 70-ohm rheostat is connected, the resistance of which is slowly decreased. The action of the feedback loop is such that the carbon-pile resistance goes to infinity. Manually increasing the 6AS7 plate supply assures complete opening of the pile. From the time the 70-ohm rheostat is connected the carbon-pile current is of course not held constant. All of these operations are done in reverse to obtain the decreasing portion of the hysteresis loop.

LINEAR THEORY OF REGULATOR OPERATION

The dotted curves of Figure 2 are several force-vs-displacement curves for the regulator magnet at constant operating coil ampere-turns. The voltage across the operating coil circuit is $R_c I$ where R_c is the total circuit resistance. Hysteresis is ignored in these curves but will be discussed later. Two additional curves are superimposed on the magnet curves in Figure 2. The first is the force-vs-deflection characteristic of the spring. The second, although misnamed, is called the carbon-pile characteristic,² and is constructed by adding the carbon pile and

² Kouwenhoven, W. B., and Thaler, G. H., "Analysis and Redesign of a Carbon-Pile Voltage Regulator for Aircraft Generators," *AIEE Transactions* 67, Pt II, p. 1197-1203, 1948

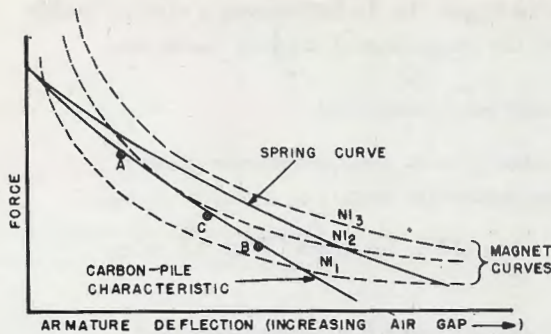


Figure 2a - Force-deflection characteristics with pile screw tightened

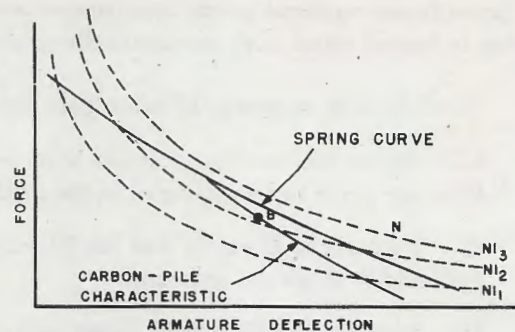


Figure 2b - Force-deflection characteristics with pile screw loosened

spring forces at each deflection. Therefore the net force on the carbon pile is given by the difference between the latter two curves, and a deflection to the left corresponds to an increase of carbon-pile resistance. Loosening the pile screw corresponds graphically to moving the origin of the carbon-pile characteristic to the right along the spring curve. Figure 2b shows a carbon-pile characteristic for a regulator with its pile screw further out than Figure 2a.

Provided system stability criteria are satisfied,³ the only requirement for a regulator to operate at a specific point is that the algebraic sum of the spring, magnet, and carbon-pile forces be zero. Any point of intersection of a magnet and carbon-pile characteristic satisfies this condition, and the operating voltage will be determined by which magnet curve is selected. It can be seen from Figure 2a that for low carbon-pile resistances the armature must be far to the right and the carbon-pile characteristic intersects a low NI magnet curve. As the resistance is increased, points of equilibrium are found at higher NI magnet curves until the curve marked NI₂ is intersected. From then on, points of equilibrium for still higher resistances are found at lower NI magnet curves. In other words, it would be expected that for increasing carbon-pile resistance the operating coil voltage would increase to a maximum of $R_c I_2$ then decrease. Both the ascending and descending portions of Curve A of Figure 8 show such a situation. Similar arguments applied to Figure 2b show that no maximum voltage would be expected. Curve B of Figure 8 was measured on the same regulator as curve A, but with the pile screw loosened.

According to linear theory, perfect regulation would be afforded by parallelism between the magnet and carbon-pile characteristic curves. Linear stability criteria demand, however, that the magnitude of the slope of the carbon-pile curve be greater than that of the magnet curve at a point of stable operation. This is equivalent to saying that generator terminal voltage must drop with load for any stable regulated generator. Since we know this to be false, in practice

³ Scorgie, D. G., "Transient Analysis of Voltage-Regulated Aircraft DC Systems," AIEE Tech-Technical Paper 50-208, October 1950

nonlinearities must exist, and their nature has been experimentally investigated in the section which follows.

EXPERIMENTAL RESULTS

The experiments performed were intended to determine the manner in which performance differs from the idealized picture given above. A standard 28-volt dc regulator with disc-type spring was used for all measurements. The various adjustments of the regulator are noted on the graphs.

Constant Temperature Data

For the series of tests in Figures 3, 4, and 5, the temperatures in the regulator were held constant during the measurement of each loop. All were run with less than 0.1 watt power dissipation in the carbon pile, so that the variable heating was all due to operating coil current and thus very nearly constant. Figure 3 shows major hysteresis loops A, B, C, and D for which the maximum carbon pile resistances were infinity, 50 ohms, 30 ohms and 10 ohms, respectively. If, after each loop, the voltage is lowered to the neighborhood of 15 volts the rising portion of the loop can then be reproduced very accurately. If, however, the base carbon-pile resistance was never reached, the rising portion of the next loop was in some cases not reproduced. This effect is shown in Figure 4, Curve A, the descending portion of which is identical with curve A of Figure 3. From the graphs it can be seen that hysteresis alone can account for variations of up to 1.5 volts in the operating coil voltage for a given resistance.

Further constant temperature curves were taken but this time at elevated ambient temperatures. Carbon-pile current remained of the order of milliamperes and the ambient temperature was raised. As a result, operating coil voltages were higher than before, as shown in Figure 5. Only the rising portions of the curves are reproduced, and are compared in Figure 5 with the corresponding curves at room ambient temperature.

High Pile Current Data

The remainder of the tests were run with pile currents of either one, two, or three amperes. The ambient temperature was regulated in such a manner as to hold resistance of the operating coil circuit at a constant value for all tests. Figure 6 shows rising portions of four curves taken on a regulator adjusted for no drop upon application of full generator load. Figure 7 shows the same four curves measured on a regulator adjusted for a half-volt drop upon application of full load. It can be seen that larger currents in the pile lower the operating coil voltage for a given resistance in Figure 6 while the opposite effect is shown for the lower parts of the 2- and 3-ampere curves of Figure 7.

Effect of Regulator Adjustment

Figure 8 shows experimental results obtained from the regulator under two conditions of adjustment. For curve A the regulator was adjusted for zero regulation at 27.7 volts. The

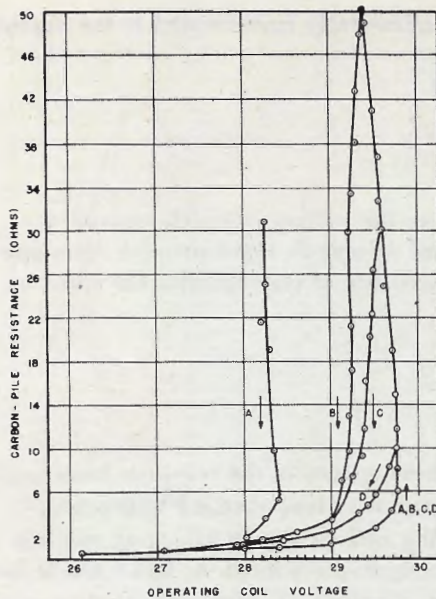


Figure 3 - Regulator hysteresis loops with low carbon-pile current (0.033 amps). Regulator adjusted for 27.8 volts, no drop upon application of load.

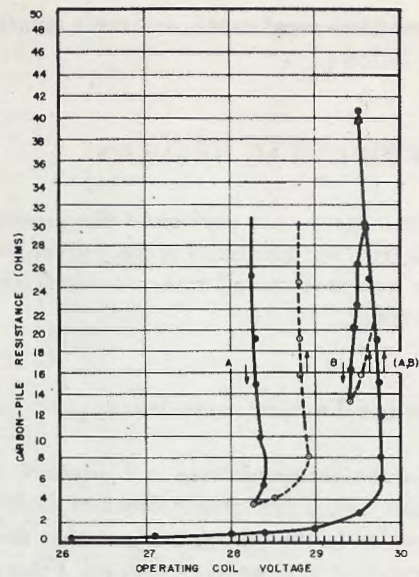


Figure 4 - Minor hysteresis loops with low carbon-pile current (0.033 amps). Regulator adjusted for 27.8 volts, no drop upon application of load.

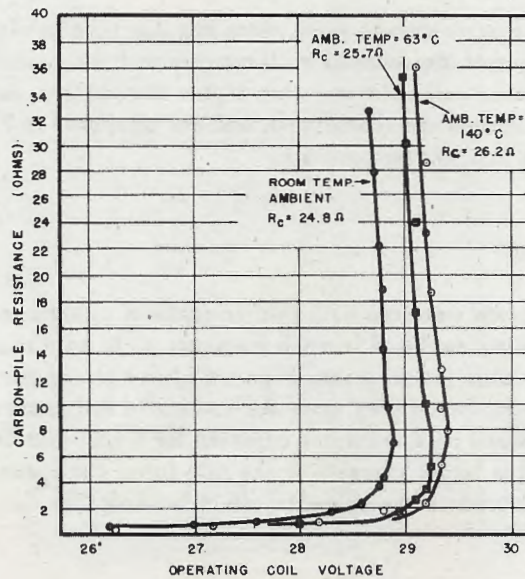


Figure 5 - Ascending portions of loops for various ambient temperatures, 21-ma pile current. Regulator adjusted for 27.35 volts, no drop upon application of load.

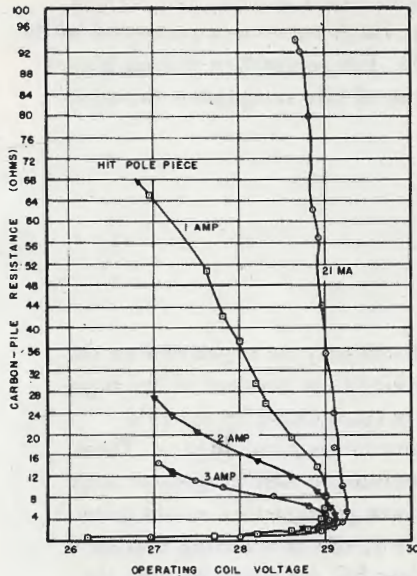


Figure 6 - Ascending portions of loops with various pile currents. Regulator adjusted for 27.3V. Zero drop upon application of load. Operating coil resistance $\approx 25.8 \Omega$.

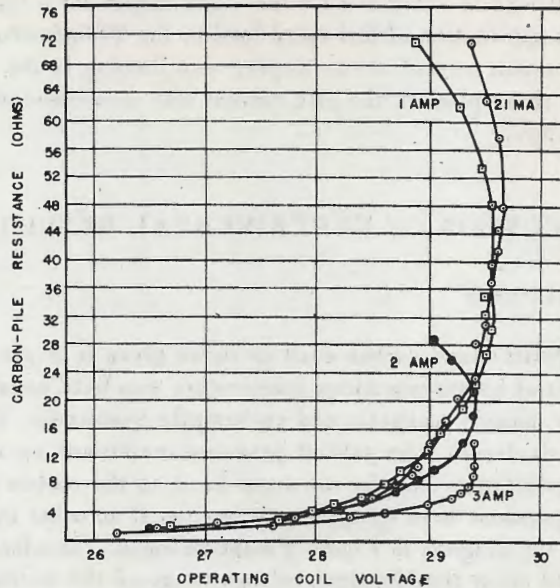


Figure 7 - Ascending portions of loops with various pile currents. Regulator adjusted for 27.3V. Half-volt drop upon application of load. Operating coil resistance $\approx 25.9 \Omega$.

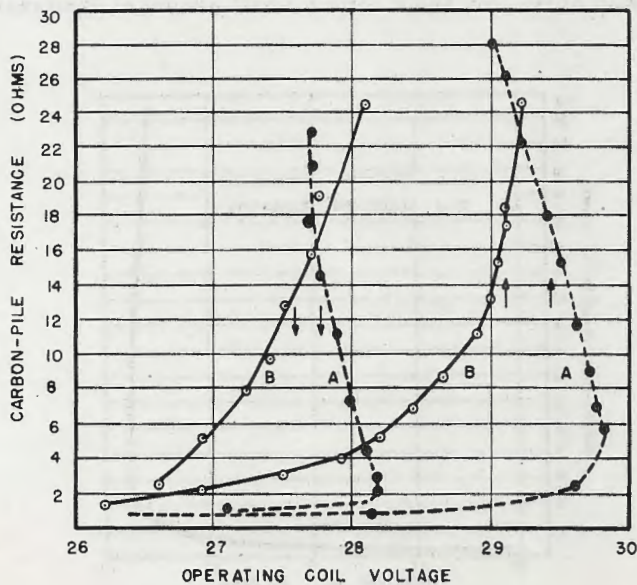


Figure 8 - Effect of regulator adjustment. Curve A - Adjustment for zero regulation. Curve B - Adjustment for half-volt regulation. Regulator adjusted for 27.7 volts - no load. One ampere carbon pile current.

conditions in curve B were the same except for a readjustment to obtain a ½-volt regulation upon application of full rated load to the 200-ampere generator. Each curve was measured while a constant current of one ampere was flowing in the carbon pile. For resistance values higher than those plotted, the pile current was decreased and the value of pile resistance raised to infinity.

DISCUSSION OF EXPERIMENTAL RESULTS

Hysteresis

Multivalued curves such as those given in Figures 3 and 4 can only be explained on the basis of hysteresis since temperature was held constant. Two kinds are present in the regulator, namely magnetic and carbon-pile hysteresis. The latter is recognized by the pile manufacturers, who publish pressure-resistance hysteresis loops in their catalogues. Their loops indicate that for the same force on the carbon pile the resistance will be greater upon compression than upon decompression. If no other hysteresis were present this would mean that the diagram in Figure 2 must be valid. Therefore, in Figure 3, the descending portion would cover the identical voltage range as the ascending portion, but for every voltage the resistance would be higher. The result would be a curve such as shown in Figure 9, which was calculated from the manufacturer's curves for the particular pile. For all practical purposes, Figure 9 shows the effect of carbon-pile hysteresis to be negligible.

Figures 3 and 4 must then be explained on the basis of magnetic hysteresis. In all cases the pull of the magnet is proportional to the square of the flux across the air gap; and, of course, the flux-vs- H_1 relationship of the iron has a certain small amount of hysteresis.

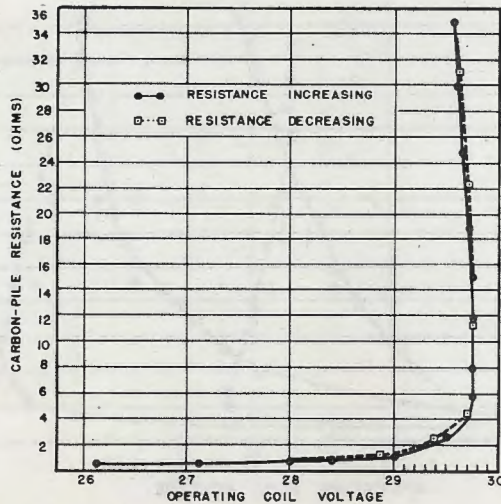


Figure 9 - Effect of carbon-pile hysteresis

We are directly concerned, however, not with the ϕ -vs- H_1 relationship but with the relationship between flux, ϕ , and total ampere-turns, NI. H_1 is a function of both ampere-turns and air gap, and since the air gap varies inversely with flux, the relative width of the loop ϕ vs NI will be enormously greater than that of ϕ vs H_1 . The clearest generality which can be made is that armature motion toward the pole piece always indicates an increase of flux. Therefore, flux and carbon-pile resistance increase together and decrease together. As a result, a single constant NI curve (Figure 2) will move to a region of greater magnet force (therefore flux) for a given pile resistance when the resistance is being decreased. It is not particularly necessary to know whether it is an air-gap change or a current change which is determining the hysteresis. However, the hysteresis effect due to change of air gap is held responsible for the regulator behavior near the peaks in Figure 3, because the coil current is decreasing monotonically through this region.

Let us think of the magnet curves of Figure 2 as representing, at each point, the force on the armature while approaching the pole piece. They will then represent the minimum force on the armature for a given current. The hysteresis effect indicates that for displacements away from the pole piece each magnet force curve will be higher for a given current. In other words for displacements away from the pole piece less current is needed for the same magnet force. In terms of carbon-pile resistance this means that less operating coil current is required for a given resistance when the resistance is decreasing.

Heating Effects

In Figure 5 the increase in terminal voltage observed upon raising the ambient temperature was only one-third as great as the increase that would be caused only by a change in resistance of the operating coil circuit. In symbols

$$\Delta E_t \cong \frac{\Delta R_c}{3} I_c$$

where

ΔE_t = change in regulated voltage

ΔR_c = change in operating coil resistance

I_c = operating coil current.

This can be explained by the fact that the regulator under test has temperature compensators that alter the magnetic circuit. Here these compensators balanced out the effect of two-thirds of the operating coil resistance change.

The data shown in Figures 6 and 7 were taken with ambient temperature held such that the operating coil resistance was approximately the same for all runs. This was done primarily to eliminate the effect of changes in the magnetic compensator during the tests. Since the magnetic

compensator and the operating coil occupy the same physical region, their temperatures probably remain constant if the operating coil resistance is constant.

High current in the carbon pile has two results, namely a thermal expansion of the carbon, and a decrease in its resistivity. Measurements with a thermocouple placed in the space at the center of a carbon pile indicate that the temperature rises about 200°C under normal operation. Temperatures in the pile itself must increase a great deal more. The resulting decrease in the resistivity of the carbon must be compensated for by lowering the pile pressure, or in other words operating closer to the pole piece.

A two-inch length of carbon will expand slightly more than 0.001 inch for each 100°C temperature rise, which is significant when considering the operation of a practical regulator. Therefore for a fixed regulator armature position, pile pressure is increased by higher temperatures, and Figure 2 is changed by lowering the carbon-pile characteristic curve. In order to restore the original carbon-pile resistance the regulator armature must again move toward the pole piece. Therefore thermally caused changes of both carbon resistivity and length result in the regulator operating with smaller air gap. It follows that if the temperature increases slightly the regulated voltage will decrease if the magnet and carbon pile characteristics are related as at point A, Figure 2a, and will increase if they are related as at Point B, Figures 2a and 2b.

Examine Figures 6 and 7 in the light of the preceding two paragraphs. The data of Figure 6 were taken with the regulator adjusted for zero drop with load, corresponding to a point near C of Figure 2. As pile power dissipation increases, the changes of carbon resistivity and length make it necessary to operate at smaller air gap in order to obtain the same resistance, so that the operation moves to the vicinity of point A, Figure 2, which is a region of decreasing voltage. This change in operating point for the same resistance is well illustrated in Figure 6 where, on the one-ampere curve, the regulator armature struck the pole piece. With low power dissipation the resistance was raised to 100 ohms without the armature striking the pole piece. With one-ampere pile current, however, the armature struck the pole piece at 70 ohms. A general lowering of the carbon pile characteristic results from pile heat, as mentioned above, and this effect manifests itself in a slightly smaller maximum voltage for the high current curves.

Data for Figure 7 were taken with an adjustment for ½-volt regulation, corresponding at low pile resistances to a region near B of Figure 2. In this instance pile heating causes operation for a given resistance at smaller air gap, therefore higher voltage. For high pile resistance, however, the regulator operates near A of Figure 2, and heating of the pile causes a lowering of the voltage. Again in Figure 7 the maximum voltage is slightly lower for the high pile current data. Not too much faith should be placed in the latter small variations, since the curves are reproducible to only about ±0.1 volt.

RELATION TO TRANSIENT CONSIDERATIONS

In previous reports^{4, 5} linear theory has been successfully used to predict the transient characteristics of carbon pile regulators. It will be recalled that in the vicinity of some initial operating point the steady-state relationship between carbon-pile resistance and operating coil

⁴ Mills, *op. cit.*

⁵ Scorgie, *op. cit.*

voltage was assumed to be a straight line of slope K_r . In the linear theory good steady-state regulation depends upon K_r being a large positive number, but if K_r becomes too large or negative the system becomes unstable. The upward portion of Figures 3 and 4 seems to show regions of instability according to the above criteria (i.e. negative K_r). The minor loop, curve B of Figure 4, however, shows the average slope angle decreases for small disturbances, thereby allowing system stability.

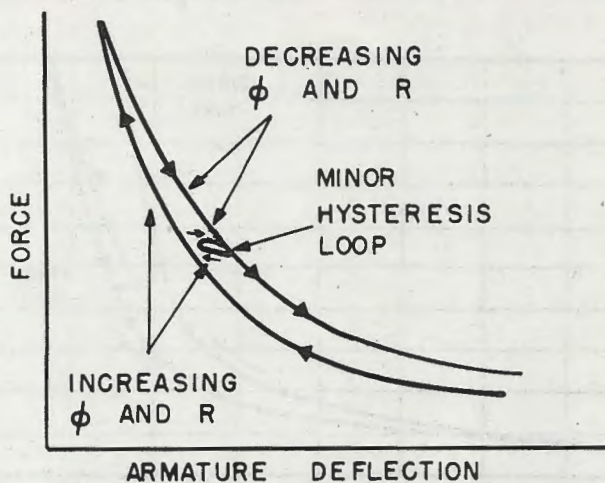


Figure 10 - Constant-NI magnet curve

This can be explained in terms of a force-deflection diagram. Figure 10 shows the position of one constant-NI magnet curve both when the carbon-pile resistance is being increased and when it is being decreased. As stated in the section of hysteresis effects, for displacements away from the pole piece (decreasing resistances) each such magnet curve will be higher. From the results of a previous report⁶ it follows that if the slope of the magnet curve is nearly as great or greater than the slope of the carbon-pile characteristic, then K_r is very large or minus and the system is unstable. Therefore all points to the left of such a position as C of Figure 2a should be points of instability. However, small excursions from an operating point will occur along a minor hysteresis loop such as drawn in Figure 10. The effective slope of the magnet curve is thus seen to be reduced, allowing stability. The effect of magnetic hysteresis in the regulator then is to allow perfect regulation and even voltage rises for large disturbances and yet have a stable system, a combination not possible with a linear system.

Introduction of a large transient disturbance, such as might completely open the pile, will drive the regulator iron onto a new portion of its major hysteresis loop where it then operates around minor hysteresis loops for further small disturbances. Curve A of Figure 4 illustrates this effect. By bringing a loaded generator gradually up to speed one can keep the regulator on its rising portion and observe the abnormally high regulated voltage. If the generator load

⁶ *Ibid.*

is then cycled the carbon pile will completely open during transient load removals and subsequent operation of the regulator will be on or near the descending portion of the curves of Figure 8.

Application of load will not then normally close the pile far enough to return the regulator to the region of high regulated voltage. Figure 11 serves to illustrate this point. There the hysteresis loops are those followed in an actual case by a regulator controlling a generator to which full load was applied. The regulator was adjusted to give $\frac{1}{2}$ -volt drop with load.

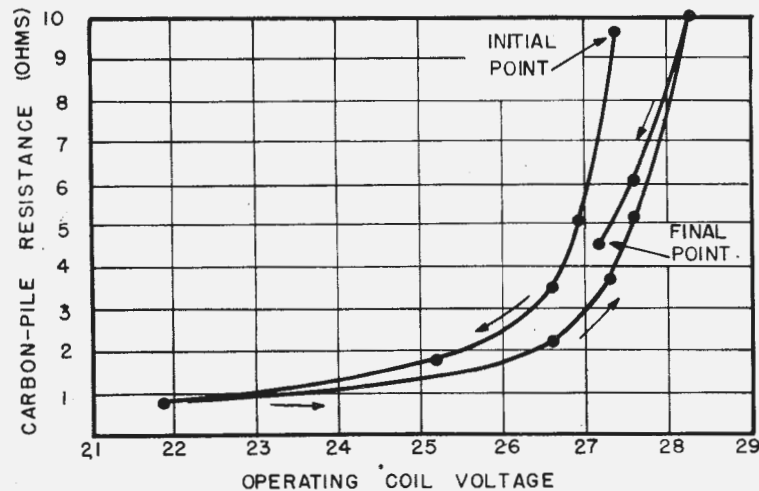


Figure 11 - Simulated regulator performance upon application of load (carbon-pile current 1 ampere)

However, heating effects were not taken into account, as a constant carbon-pile current of one ampere was used in obtaining the hysteresis measurements.

SUMMARY

The use of a feedback electronic control circuit permits measurement of steady-state carbon-pile regulator characteristics throughout the complete operating range. Measurements obtained using such a circuit reveal the part played by magnetic hysteresis in determining regulator performance. The effects of ambient temperature and carbon-pile power dissipation have also been studied and the latter is found to be of greater relative importance. Magnetic hysteresis is found to have the beneficial effect of permitting good regulation of large disturbances, yet tending to stabilize the regulated system in the steady state.

* * *