TECH LETTER # 2

CONSTANT VOLTAGE/CONSTANT CURRENT REGULATED POWER SUPPLIES

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CONSTANT VOLTAGE/CONSTANT CURRENT REGULATED POWER SUPPLIES

I. CHARACTERISTICS OF CONSTANT VOLTAGE SUPPLIES

An ideal voltage source is defined as an electric source for which the output voltage is independent of the current being drawn from it. Thus, for any value of imposed load resistance the output voltage of an ideal voltage source remains constant.

Since it is possible that active devices (tubes, transistors, etc.) connected as part of the load device may cause the load current to vary with time, the ideal voltage source must have a zero source impedance at all frequencies (not just zero ohms at DC). Consider, for example, the case of a 30 volt DC constant voltage power supply having a source impedance of zero ohms at DC, but differing from the ideal voltage source in that it has a source impedance of 1 ohm at a frequency of 1 KC. Thus, if a load device "A" draws a steady current of 1 amp on which is superimposed a 1 KC sinusoidal current having peak excursions of plus and minus 500 milliamps, this "constant" voltage source will deliver an output which will vary sinusoidally between 29.5 and 30.5 volts at a 1 KC rate. Such a power supply would therefore not be suitable for most practical applications of regulated power supplies, where it is desired that the output voltage remain essentially constant.

In addition to the fact that this imperfect power supply fails to deliver a truly constant voltage to the load device "A", it should be noticed that the resulting variation in output voltage can be coupled into any other load device "B" which is connected to the same power supply. Such undesirable coupling can result in spurious or noisy performance of low level amplifier stages, or can result in oscillation of entire systems because of unintentional feedback from one circuit to another via the common impedance of the power supply terminals.

Of course, it is not possible to build a practical power supply having an ideal source impedance of zero ohms at all frequencies, and all power supplies are economic comprises between this ideal and the state of the art. On most of the specification sheets for H-Lab power supplies can be found charts showing power supply output impedance vs. frequency. From these charts it may be assumed that it is most difficult to build a constant voltage supply having a low output impedance over a band from DC into the megacycle region. The reasons for the general shape of this performance characteristic are made more evident when one considers the block diagram of a typical voltage regulated power supply.

As shown in Figure 1, a voltage regulated power supply consists basically of a conventional rectifier and filter followed by a feedback amplifier (consisting of a series regulating element used in conjunction with a comparison amplifier), a reference voltage, and an output capacitor. The comparison amplifier continuously controls the series transistor regulator so as to maintain the two comparison amplifier inputs exactly equal--thus the voltage across the output terminals is always held equal to the reference voltage. (The arrows in Figure 1 are not intended to show the direction of current flow; rather, these arrows indicate the direction of signal and power flow).

Without the feedback circuitry to the left of the dotted line of Figure 1, the output impedance of the power supply would be that of the output capacitor alone. Since it is desired that this output impedance be as low as possible, most voltage regulated power supply designs utilize a large electrolytic capacitor across the output terminals.

However, the impedance of any capacitor is not purely capacitive at all frequencies. Even the best capacitors have associated with them finite lead inductance and resistance. A typical impedance vs. frequency characteristic for an electrolytic capacitor is shown in Figure 2. This drawing shows the impedance vs. frequency characteristic (plotted on a log-log basis) of a 500μf capacitor, (actually used as an output capacitor on Models 855C and 865C). Both the asymptotic and actual impedance characteristics are shown in this figure.

The effect of the regulator circuit is to make the supply output impedance at each frequency lower than the impedance of the output capacitor by a factor equal to the loop gain* of the regulator feedback amplifier at that same frequency. Let us suppose therefore that the gain vs. frequency characteristic of the feedback amplifier is as given in Figure 3. Then out output impedance of the supply would be as shown in Figure 4. Notice that at low frequencies the output impedance is low primarily because of the high amplifier gain. At mid-frequencies, the output impedance of the supply is held to a reasonably low value because of the moderate amplifier gain remaining at these frequencies combined with the low impedance (resistance) of the output capacitor. At high frequencies (beyond the bandwidth of the feedback amplifier) the output impedance is inductive and is completely dependent upon the output capacitor (and the inductance of the leads connecting it to the output terminals).

In conjunction with Figures 3 and 4, it is worth noting that increasing the gain of the feedback amplifier will lower the output impedance of the supply, but that no finite amount of gain, however great, will be sufficient to cause the output impedance of this supply to equal zero ohms. Feedback analysis reveals that only by employing positive feedback to boost the loop gain of the negative feedback amplifier can zero output impedance be achieved! It fact, the positive feedback required is just that amount which would cause the feedback amplifier to oscillate if it were not confined within a negative feedback loop having overall stability In some H-Lab power supplies, this positive feedback is introduced at low frequencies and makes possible a zero output impedance over a narrow band of frequencies including DC. On such supplies the positive feedback control provides continuous adjustment of the polarity of the output impedance. Increasing the amount of positive feedback present in the amplifier will gradually decrease the output impedance of a voltage regulated supply and cause it to reach zero ohms. A further increase in the positive feedback will cause the output impedance to go negative (i.e. the output voltage will <u>rise</u> for an increase in load current). Thus, it is possible to achieve a power supply exhibiting a small negative output impedance, and to use this supply in conjunction with short lead lengths having an equal positive resistance--with the result that the impedance at the end of these leads will be zero ohms without remote sensing. Such a configuration does not commonly have significant practical applications, but does provide interesting food for thought.

*Actually by a factor of (1 + loop gain), but over nearly all of the frequency band of interest the loop gain is much larger than 1.

II. CHARACTERISTICS OF CONSTANT CURRENT SUPPLIES

An ideal current source is defined as an electrical source for which the current remains constant regardless of the value of output voltage demanded by the load. Most normal power supply applications require a constant voltage power supply. There are many special applications, however, for which the constant current source is more suitable. For example, the magnetic field of a focus coil or any electromagnet is proportional to the current through the coil. If a constant voltage power supply were placed across this coil, the current through this coil would change if the resistance of the coil were to change as a result of external temperature influences or self-heating effects, and the magnetic field surrouding this current would probably not be held as constant as originally desired. Other applications involving constant current power supplies include battery charging, battery discharging, and some special purpose semiconductor circuits.

Since it is possible that the load resistance connected to a constant current power supply may vary with time, the ideal constant current source must have an infinite source impedance at all frequencies. Consider the case of a 1 amp DC constant current source having an infinite source impedance at DC, but differing from the ideal constant current source in that it has a source impedance of 1000 ohms at 100 cps. Suppose now that the load resistance "A" fluctuates at a 100 cycle rate in such a manner that the load voltage varies sinusoidally between the limits of 10 and 30 volts. The ideal current source with infinite source impedance would be able to accomodate these demanded voltage changes (or as some manufacturers state it, would have the necessary voltage compliance) with no change in the current delivered. However, with a source impedance of 1000 ohms, this peak-to-peak load voltage change of 20 volts would result in a peak-to-peak current variation of 20 milliamperes from the 1000 ohm "constant current" source. Thus, such an imperfect power supply would fail to deliver a truly constant current to load device "A" or any other load device "B" connected in series with it. (Just as multiple loads are commonly connected in parallel for constant voltage supplies, constant current supplies must have their multiple load devices connected in series if all are to operate at the same value of current).

As in the case of the constant voltage power supply, it is not possible to build an ideal constant current source. Also, it will be shown in the following discussion that some of the design requirements for an ideal constant current source conflict with corresponding requirements for a constant voltage source. Thus, a supply which is to be built to operate as both a constant voltage and constant current source will not usually be of optimum design for both modes of operation.

As is revealed by an examination of Figure 5, the block diagram of a constant current regulated power supply resembles in many respects the block diagram of a constant voltage regulated power supply. However, instead of comparing the reference voltage with the output voltage , the comparison amplifier of a constant current power supply compares the reference voltage with an IR drop caused by the output current flowing through a fixed resistor. The action of the feedback loop is such as to adjust the conductance of the series regulating element so as to maintain the IR drop across the series monitoring resistor constant and equal to the reference voltage, thereby holding the output current to some constant value.

In a constant current power supply, output impedance without feedback consists of the output capacitor in parallel with the current monitoring resistor (assuming that the impedance looking back into the series transistors in conjunction with the rectifier is negligibly small compared to the current monitoring resistance). The effect of the regulator circuit on the constant current output impedance is to multiple the effective value of the monitoring resistor by the value of loop gain* at each frequency--this increased resistance still remaining in parallel with the actual output capacitance. Since the output capacitor presents a low impedance as a function of frequency across these output terminals, a large electrolytic capacitor is detrimental for high performance constant current sources. Let us suppose that the impedance vs. frequency characteristic of the output electrolytic is as given in Figure 6 and that the gain vs. frequency characteristic of the feedback amplifier is as given in Figure 7. Then the output impedance of the supply would be as shown in Figure 8. At low frequencies the output impedance is high because of the high amplifier gain and the fact that the output electrolytic has a relatively high impedance at these frequencies. At mid-frequencies the output impedance drops because the loop gain drops and the output electrolytic impedance is also lower at these frequencies. At high frequencies the output impedance is inductive and is not enhanced by the feedback amplifier since this amplifier no longer has gain at such high frequencies.

Note that Figures 6 and 8 are based on the use of a 50µf output capacitor while Figures 7 and 8 are based on the use of a 1 ohm monitoring resistor. Either a large output capacitor (as would normally be desired for constant voltage operation) or a smaller monitoring resistor (as would be necessary to avoid excessive dissipation in a precision resistor on high current supplies) would result in a lower output impedance or a reduction in the bandwidth of the high impedance characteristic.

Increasing the gain of the feedback amplifier will increase the output impedance of a constant current supply (assuming the output impedance is not limited by a low value of impedance due to the output capacitor). No finite amount of gain, however great, will be sufficient to cause the output impedance of the supply to be infinite. By employing positive feedback within the negative feedback amplifier of a constant current power supply, a perfect constant current source would be achieved at DC. As in the case of a constant voltage supply, the amount of positive feedback required for perfect performance is that which would cause the feedback amplifier to oscillate if it were not confined within a negative feedback loop having overall stability. Because of overall stability considerations, it is not practical to introduce the benefits obtained by positive feedback except over a narrow band of frequencies including DC.

Thus, it is possible to build a constant current power supply having nearly perfect performance at DC and extremely low frequencies, but it is very difficult to approximate an ideal current source at mid and high frequencies, especially if one includes a large electrolytic across the output terminals.

Why, then, on constant current supplies should the output electrolytic be included? Several reasons exist:

1. The inclusion of such a capacitor reduces the output ripple in both constant voltage and constant current operation.

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* As before, the multiplier is actually (1 + loop gain), but 1 is negligibly small compared with the loop gain at most frequencies of interest.

2. A large output capacitor helps insure that the overall loop will not oscillate regardless of the phase angle of the load impedance attached across the supply output terminals.

III. EVOLUTION OF CONSTANT VOLTAGE/CONSTANT CURRENT SUPPLIES

It is desirable for many reasons to limit the maximum instantaneous current which the series transistors can pass to some predetermined value. The reasons for wanting to do this include a desire to protect the series transistors themselves from damage due to excessive heating, and the desire to be able to charge a large load capacitor without blowing a fuse or circuit breaker on the power supply. Consequently, the protection circuit for many power supplies limits the maximum output current under any load condition to some non-adjustable value. This approach is followed, for example, on H-Lab Model 801C power supply.

If a supply is being used at considerably less than its maximum output current rating, it is possible that, although the supply may be adequately protected under any overload conditions, the load circuit still receives no protection, since the limiting value of current is much higher than the normal load current. Consequently, it becomes desirable from a user's standpoint to make the current limiting point adjustable so that this current limit can be set for the exact value which will provide maximum protection to the load device as well as providing adequate protection to the power supply itself under all operating conditions.

The next evolutionary step is the realization that such an adjustable protection circuit constitutes a rudimentary adjustable constant current power supply. Admittedly, when used in the current limit region, a constant voltage supply with an adjustable current limit may have constant current regulation of the order of 5 or even 10 per cent (which is grossly inexact when compared to the regulation capabilities of the supply as a constant voltage source). Nevertheless, the distinction between operating in the overload region of a constant voltage supply with current limiting and operating in the constant current region of a Constant Voltage/Constant Current power supply is a difference only in the degree of regulation available in the current limit or "constant current" region of operation--the nature of performance being the same in both instances.

Therefore, the next natural developmental step is the improvement of the regulation of the power supply while in the constant current "limiting" mode so that the supply can be equally billed as a constant voltage or constant current source. It is worthwhile at this point to note the great flexibility which this type of Constant Voltage/Constant Current supply affords.

Figure 9 is the block diagram of such a CV/CC power supply with automatic crossover between the two modes of operation. The disconnect diodes are arranged in the circuit so that when the supply is in constant voltage operation, the upper diode is forward biased (or shorted) while the lower diode is reverse biased (or opened); conversely, when the supply is in constant current operation, the upper diode is reverse biased and the lower diode is forward biased. Thus, the series transistor regulator is only called upon to respond to either the constant voltage comparison amplifier or the constant current amplifier, and the effectiveness of one amplifier is not diluted by the shunt presence of the other.

Figure 10 reveals that this supply is capable of constant voltage operation with a continuously variable current limit, or of constant current operation with a continuously variable voltage limit. Note that the same output terminals are used for both constant voltage and constant current operation. Whether the supply is in constant voltage or constant current operation at any instant depends upon the relationship between the DC load resistance and the "critical" value of load resistance R_C--defined as the ratio of the front panel voltage control setting to the front panel current control setting. The disconnect diodes make possible a sharp transition between these two modes of operation.

If the load resistance is greater than this critical load resistance, the supply will be in constant voltage operation; if the load resistance is less than this critical load resistance, the supply will be in constant current operation. An example using numbers will perhaps make this even clearer. Let us suppose that on the front panel of a CV/CC power supply we have set the voltage control for 20 volts and the current control for 1 amp. With no load resistor attached to the supply terminals the output voltage will be 20 volts. With a high load resistance attached, the output voltage will remain at 20 volts and the output current will start increasing from zero. As the load resistance is decreased the output current will increase, with the output voltage remaining constant at 20 volts--until the load resistor value is reduced to 20 ohms. For further decreases in load resistance, the output current will remain constant at 1 amp and the output voltage will drop by exactly the right amount to maintain a constant current of 1 amp through the load resistance provided. Finally, with the load resistor set equal to zero ohms , the output current will still be 1 amp and the output voltage will equal zero volts. The previous sequence will occur in reverse as the load resistor is slowly increased from a short circuit to a value equivalent to an open circuit.

All of the comments made thus far pertain to CV/CC power supplies of Type I. These are CV/CC power supplies possessing the automatic crossover feature; the value of load resistance compared with the ratio of the voltage and current control settings alone determines whether the supply is in constant voltage or constant current operation. Supplies of this type include Models 510A, 520A, 810B, 814A, 855C, 865C. A second type of CV/CC supply will now be described. This second type of CV/CC power supply makes it possible to get around one of the inherent limitations of CV/CC Type II supplies.

Notice that in CV/CC automatic crossover supplies, the large electrolytic existing across the output terminals (as a result of design requirements for good constant voltage performance) still remains across the output terminals in constant current operation. Thus, while this type of power supply is a high impedance source in constant current operation at DC, still it does not have a high impedance over a wide band of frequencies, as would be required to approach the characteristics of an ideal current source. Fortunately, most applications involving constant current power supplies require a high impedance source at DC without also requiring a high impedance at higher frequencies. Nevertheless, there are requirements for constant current sources with characteristics more nearly approaching the ideal than can be realized with an automatic crossover type of CV/CC power supply. These requirements can often be met using an H-Lab CV/CC Type II power supply.

IV. CONSTANT VOLTAGE/CONSTANT CURRENT--TYPE II POWER SUPPLIES

CV/CC Type II power supplies models employ plug-in printed wiring card inserts to determine whether the supply is in constant voltage or constant current operation. In constant voltage operation, these supplies (including Models 808A, 809A, and 881A) still possess a continuously variable current limiting control for optimum protection of the load device. However, regulation performance of this type of supply when current limited in the constant voltage mode is not extremely accurate. Instead, when more tightly regulated constant current operation is desired, a new card is inserted in these supplies. In fact, with each CV/CC Type II instrument is furnished a choice of two constant current cards. The first of these cards is labeled "Constant Current--DC." This card permits operation of the supply in the constant current mode with an output impedance high at DC and low at other frequencies. The constant current impedance performance of this supply is therefore no better than that of the CV/CC Type I supply, but the use of the constant current DC card permits high performance constant current operation with minimum output ripple. When a higher output impedance at frequencies other than DC is required, a "Constant Current--AC" card can be inserted. This card in effect removes the major portion of the output capacitor from the circuit, and thereby permits the higher output impedance at AC. The disadvantage of this type of operation is that the output ripple of the supply in constant current operation will be increased by a factor of 2 to 5 as compared with "Constant Current--DC" operation. Note also that in the CV/CC Type II supplies, there is no continuously variable voltage limit in constant current operation to provide adjustable protection for the load device in the event that the load resistance increases and causes an output voltage which is higher than desired.

V. AUTOMATIC BATTERY CHARGING APPLICATIONS

There exists a large market potential for CV/CC supplies for use as automatic, unattended battery chargers. Many different types of cells (including "Nicad" silver, lead-acid, etc.) are repeatedly discharged in use in industry and require recharging for further use. Such recharging applications are widely found in the missile industry as well as in other defense work. Since the cost of the individual cells may be quite high, it is very important that these cells be charged in a non-destructive manner. The manufacturer usually recommends charging at a constant current rate until the final value of charge voltage has been reached. Using a normal voltage-regulated power supply, this means that an attendant must continually readjust the output voltage of this supply to be slightly higher than that of the cell being charged so as to keep the cell from being overheated during the charging process. A normal constant current power supply also has disadvantages in this type of application since, if unattended, it might cause the cell to be charged to excessive voltage with resulting gassing or destruction. Also, the more inexpensive constant current supplies frequently do not have ripple specifications sufficiently low to avoid AC heating of the cell.

CV/CC power supplies are ideally suited to battery charging applications; supplies of either Type I or Type II may be used in such applications. (Type II supplies when used as battery chargers should use the constant voltage insert; the current limiting control in most cases will provide a constant current which is sufficiently well regulated for battery charging.) The procedure for charging batteries using CV/CC supplies is:

1. With no load on the supply, set the voltage control so that the front panel voltmeter displays the final voltage to which it is desired to charge the batteries.

2. Short the output terminals of the supply and set the current control to a value equal to the desired charging rate (as shown on the front panel ammeter).

3. Place the battery across the power supply terminals--and forget it!

4. Step four is accomplished in a completely automatic fashion. The initially uncharged battery will be "pumped up" at the predetermined constant current rate until its output voltage equals that of the voltage setting previously made with the power supply terminals open. At this point the battery charging action will cease and the power supply will revert to constant voltage operation. No further current will flow into the battery except for whatever trickle charge may be required to offset internal leakage current, thereby holding the battery to the desired final value of voltage.

VI. AUTOMATIC BATTERY DISCHARGING APPLICATIONS

In some applications it is desired to have a device which will automatically discharge batteries at a constant current rate. All H-Lab supplies capable of constant current operation can be used for this application. The current rating of the supply to be used must be equal to or greater than the highest contemplated steady state current discharge rate, and the voltage rating of the supply must be equal to or greater than the maximum undischarged battery voltage being contemplated.

It is not possible to place the battery directly across the power supply terminals for discharge purposes since, in order to accomplish discharge, the battery would have to be placed across the output terminals with a reverse polarity. This reverse polarity would then tend to place a reverse voltage across the output electrolytic used on any H-Lab power supply, with the result that the diode normally placed across the electrolytic to prevent such reverse voltage would conduct at a high rate (probably in excess of the desired discharge rate). More importantly, the placement of a large reverse voltage across the output terminals of an H-Lab power supply would in most cases have detrimental effects upon the performance (and existence!) of the power supply.

One circuit configuration useful for discharging batteries in a constant current fashion using H-Lab power supplies is shown in Figure 11. The resistor R must be chosen so that its IR drop is always greater than the battery voltage. The net resulting voltage across the power supply terminal is therefore of normal polarity. Consequently, resistor R must be chosen to be greater than or equal to E_B/I where

E_B = the battery voltage, and

I = the constant current discharge rate.

Now let

E_S Max = the maximum rated supply voltage

E_B Max = the maximum battery voltage

E_B Min = the minimum battery voltage (zero if battery is to be fully discharged)

I Max = the highest discharge current contemplated, and

I Min = the lowest discharge current contemplated.

Having selected a value of resistor R, the minimum discharge current times this resistance will equal the maximum battery voltage which can be discharged (for a smaller I, a reverse polarity will appear at the supply output terminals),

$$I_{Min}R = E_B \text{ Max}$$

and the maximum discharge current times this resistance will equal the sum of the maximum rated supply voltage plus the minimum battery voltage at end of discharge (for a greater I, the supply would be called upon to deliver more than maximum rated output voltage when the battery voltage had been sufficiently dropped by discharge action).

$$I_{Max}R = E_{S\ Max} + E_{B\ Min}$$

Dividing the latter equation by the former

$$\frac{I_{Max}}{I_{Min}} = \frac{E_{S\ Max} + E_{B\ Min}}{E_{B\ Max}}$$

Thus, the range of values of programming current possible with no change in the value of R increases with higher supply voltage rating and higher minimum values of discharged battery voltages, but decreases with higher initial battery voltages (at start of discharge).

Where discharge of the battery down to zero volts is contemplated, by substituting $E_{B\ Min} = 0$ it can be seen that the previous relationship reduces to:

$$\frac{I_{Max}}{I_{Min}} = \frac{E_{S\ Max}}{E_{B\ Max}}$$

A simplified set of criteria for selecting the necessary power supply and resistor R are:

1. Select a constant current supply whose output voltage and current ratings are each at least as large as the maximum battery voltage and maximum desired discharge current.

2. Select a resistor R equal to or greater than the maximum battery voltage divided by the intended value of discharge current.

At first, the use of a large power resistor in such applications may seem objectionable, but it is worth noting that the energy contained in the battery to be discharged must be dissipated somehwere, and it is better to dissipate this energy in a resistor which is external to the power supply than in the power supply itself.

Since the requirement that the output voltage of the supply be greater than the maximum battery voltage is brought about by the fact that the supply output voltage must be greater than the IR drop across the power resistor R, which in turn must be greater than the highest battery voltage, it can be seen that the degree to which the power supply voltage must be greater than the highest battery voltage is dependent upon the tolerance of the power resistor used in series with the battery being discharged.

A second method of discharging a battery at a constant current rate is shown in Figure 12. Like the previous method, the power supply and battery are placed in series across a resistor R. Unlike the previous method, the supply required operates as a constant voltage source and is of such a design that when its positive programming and sensing terminals are returned to the positive output terminal of the battery, the total output E will be held constant at a value determined by the voltage control on the power supply. As the battery voltage falls with discharge, the supply voltage automatically rises by an equal amount maintaining the total voltage E across the resistor R constant and thereby assuring a constant current discharge rate. The power supply must have a current rating equal to or greater than the intended discharge rate, and a voltage rating equal or greater than the maximum downward change in battery voltage which will accompany its discharge. The value of resistor R must be made equal to the voltage E divided by the intended discharge current.

Since not all supplies will operate in the manner necessary for the proper operation of the discharge circuit of Figure 12, the factory should be consulted with reference to specific applications. In general, however, most H-Lab constant voltage supplies which have remote programming and remote sensing can be adapted to this type of battery discharge.

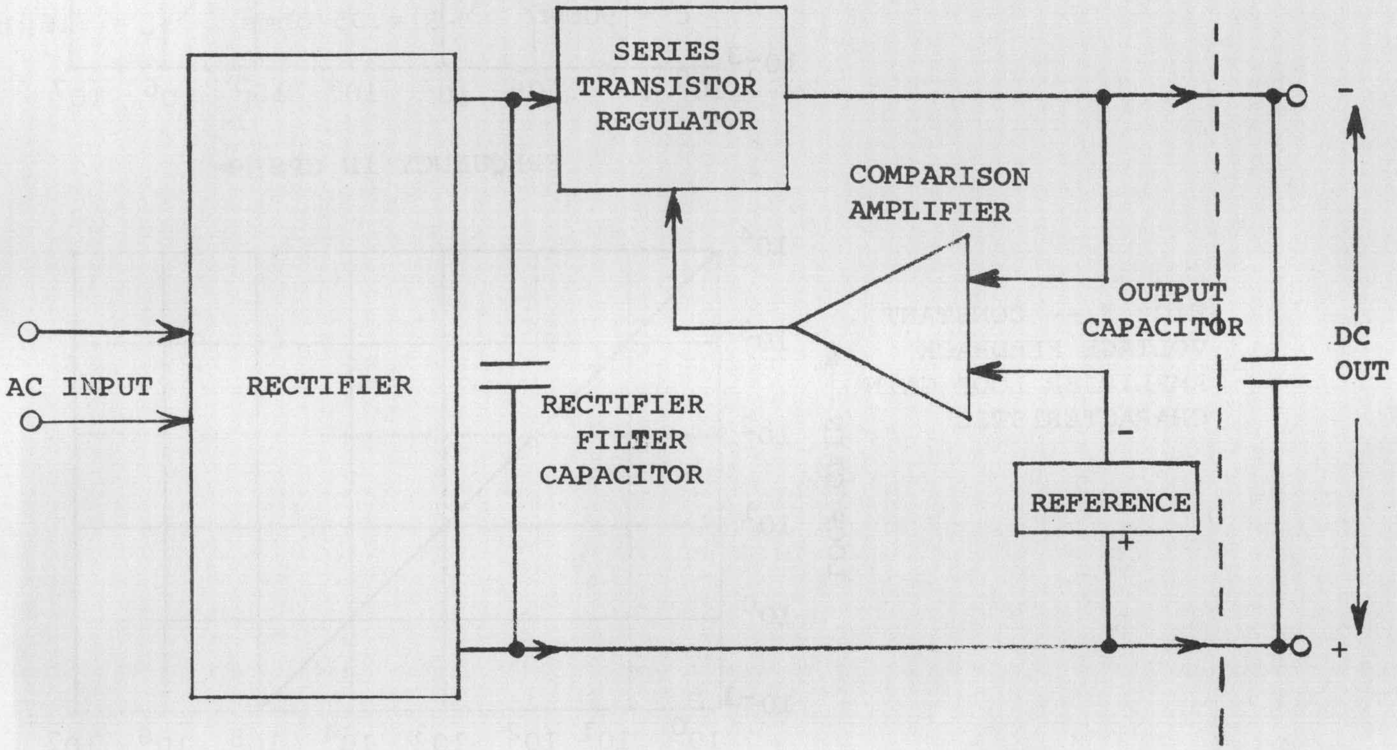


FIG. 1 -- BLOCK DIAGRAM OF A VOLTAGE REGULATED SUPPLY.

FIG. 2 -- IMPEDANCE OF A 500µf OUTPUT CAPACITOR.

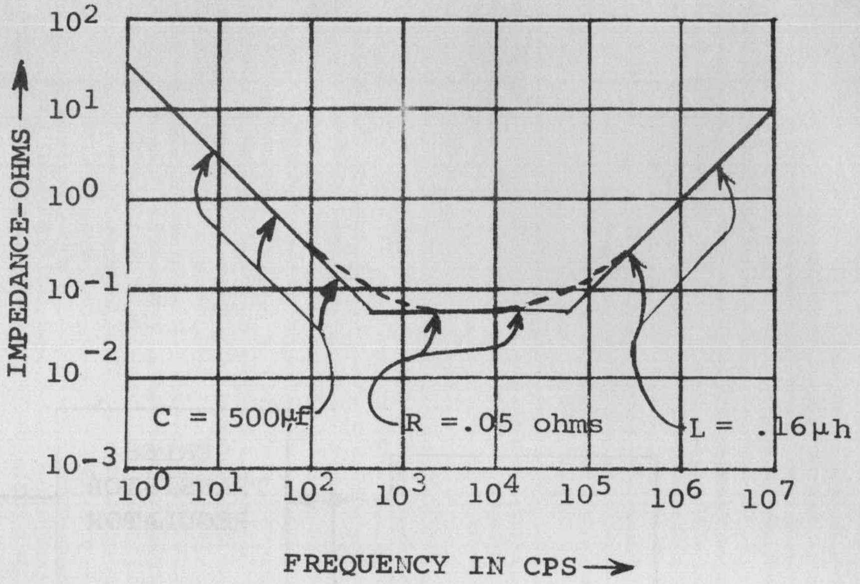


FIG. 3 -- CONSTANT VOLTAGE FEEDBACK AMPLIFIER LOOP GAIN CHARACTERISTIC

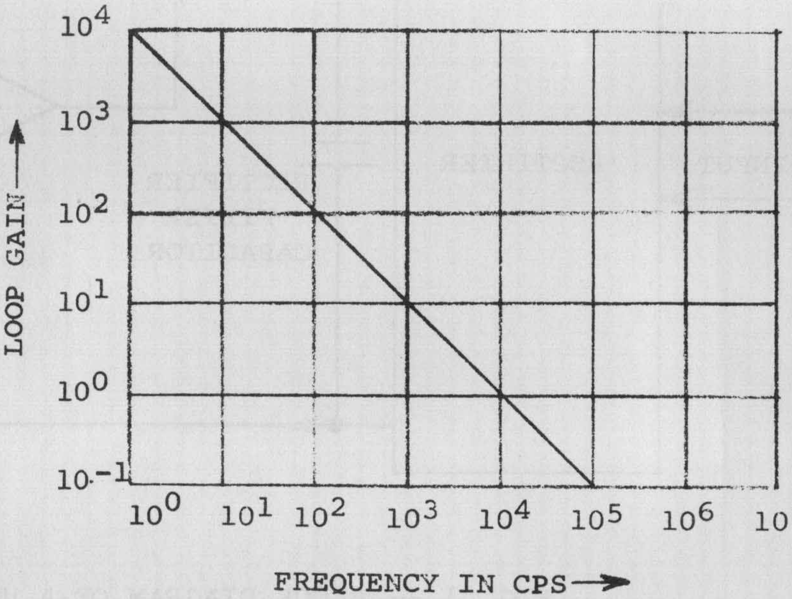
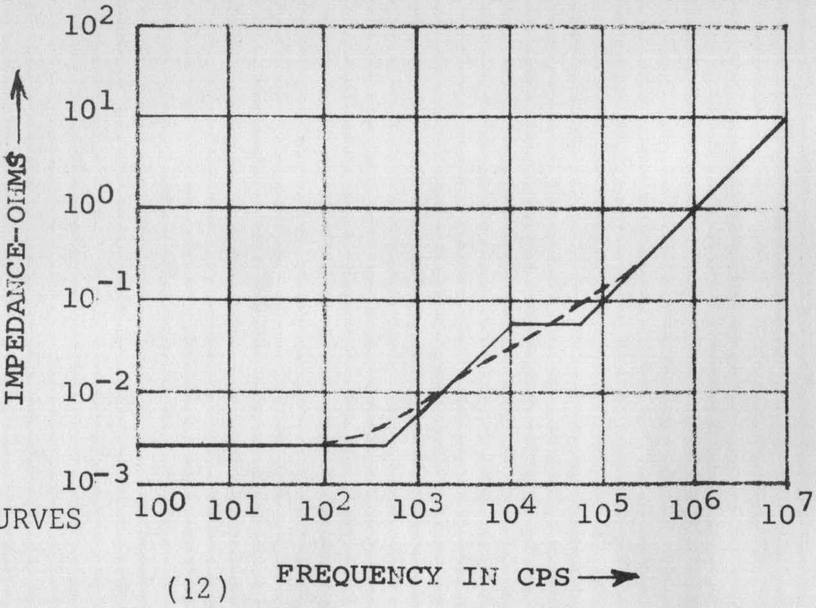


FIG. 4 -- RESULTING OVERALL OUTOUT IMPEDANCE OF CONSTANT VOLTAGE SUPPLY.



———ASYMPTOTIC CURVES
------ACTUAL CURVES

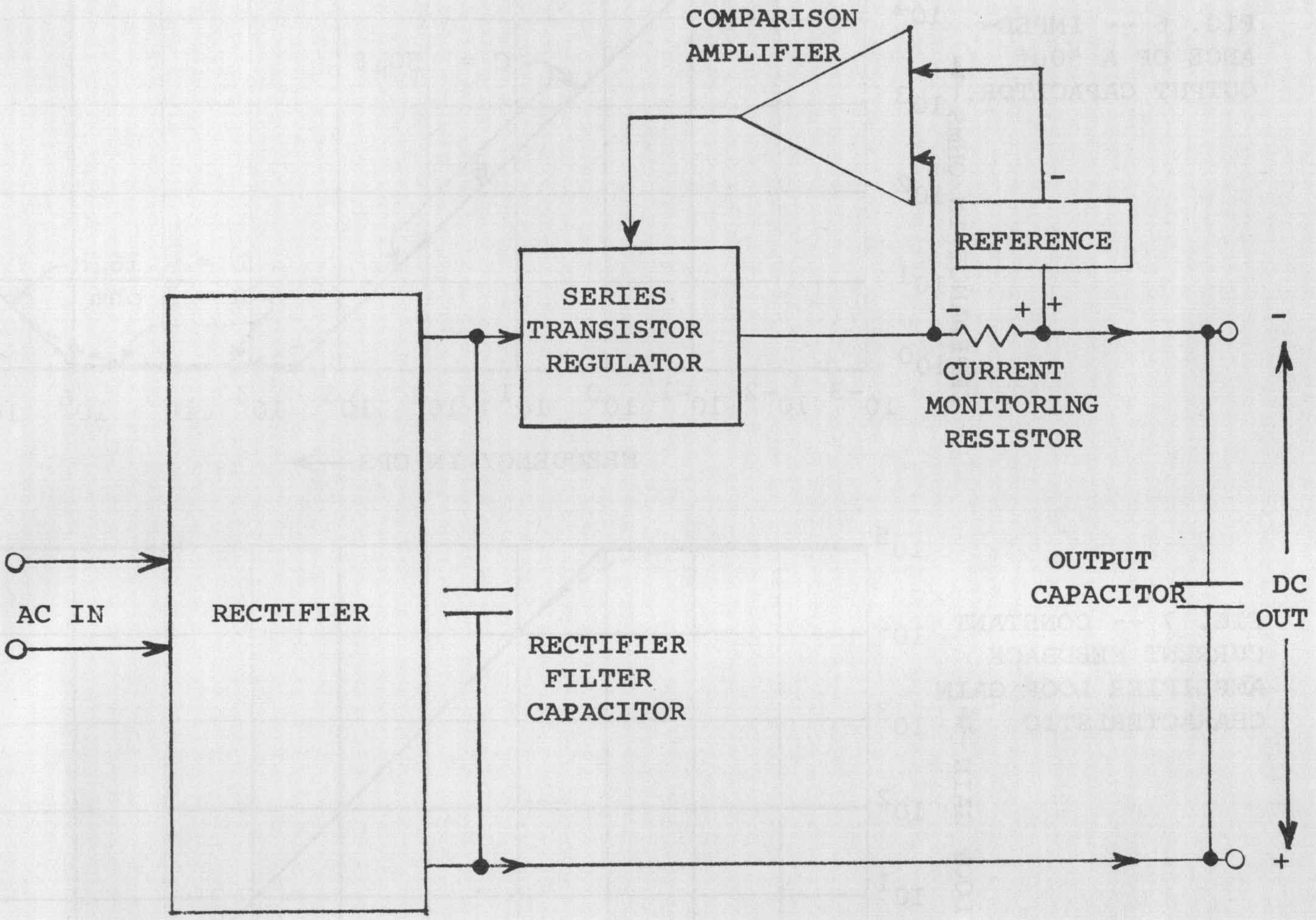


FIG. 5 -- BLOCK DIAGRAM OF A CURRENT REGULATED POWER SUPPLY.

FIG. 6 -- IMPEDANCE OF A 50μf OUTPUT CAPACITOR.

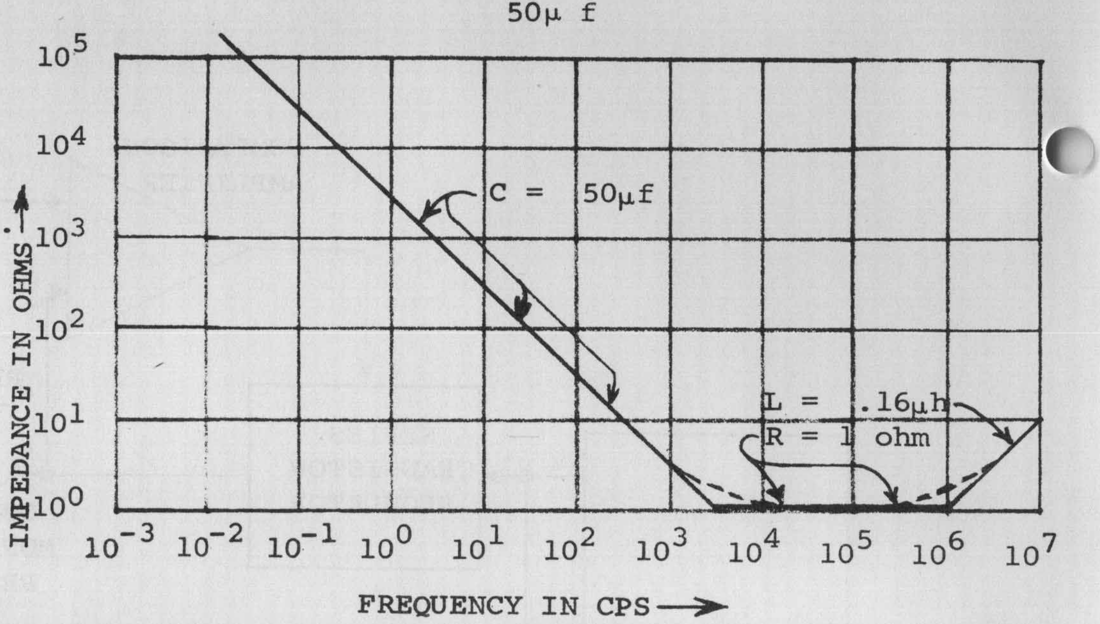


FIG. 7 -- CONSTANT CURRENT FEEDBACK AMPLIFIER LOOP GAIN CHARACTERISTIC

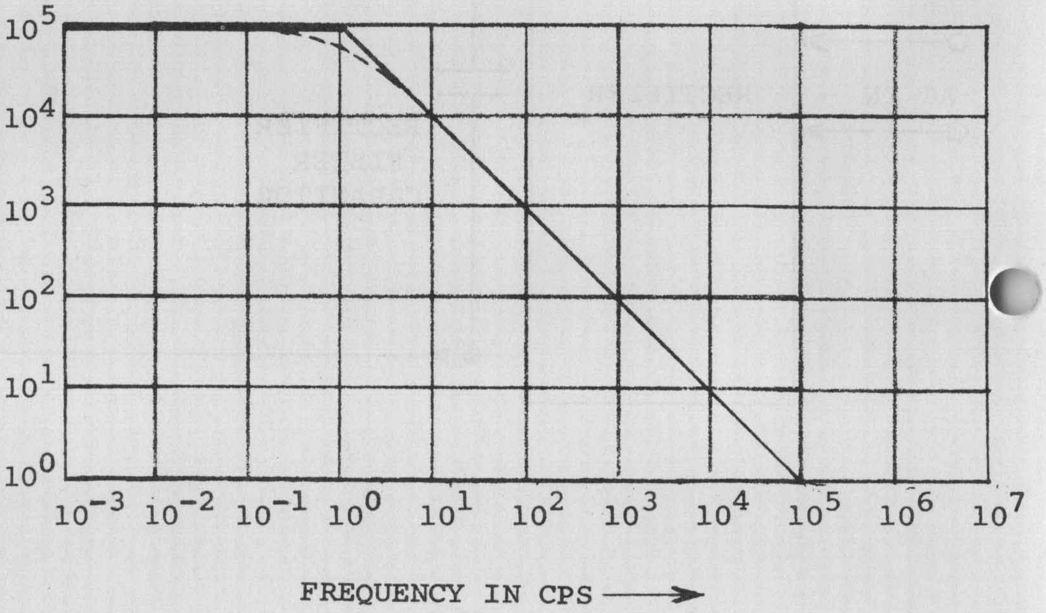
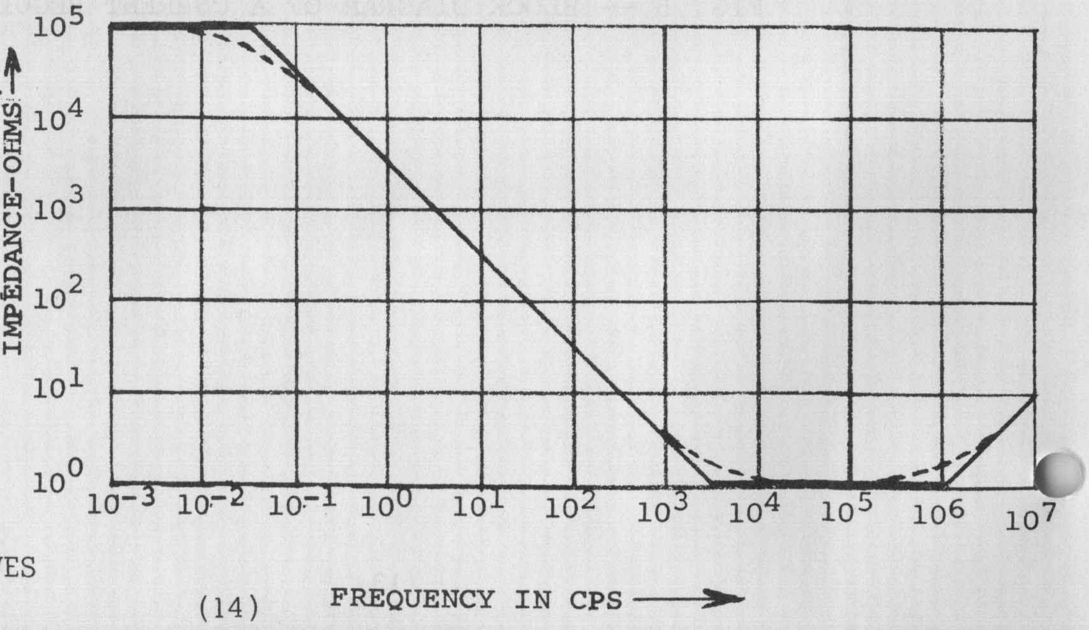


FIG. 8 -- RESULTING OVERALL OUTPUT IMPEDANCE OF CONSTANT CURRENT SUPPLY (ASSUMING CURRENT MONITORING RESISTANCE OF 1 OHM).



——— ASYMPTOTIC CURVES

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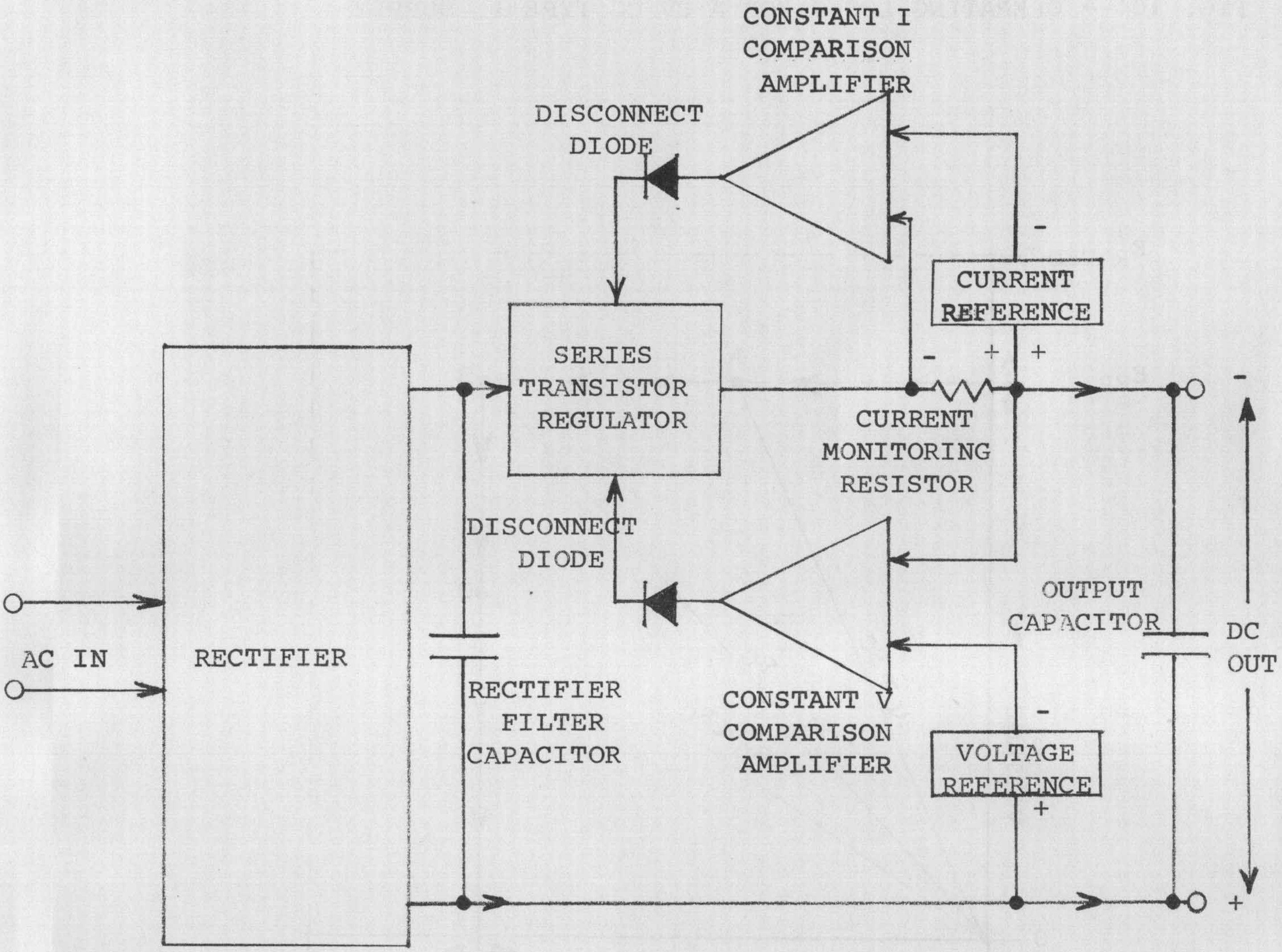
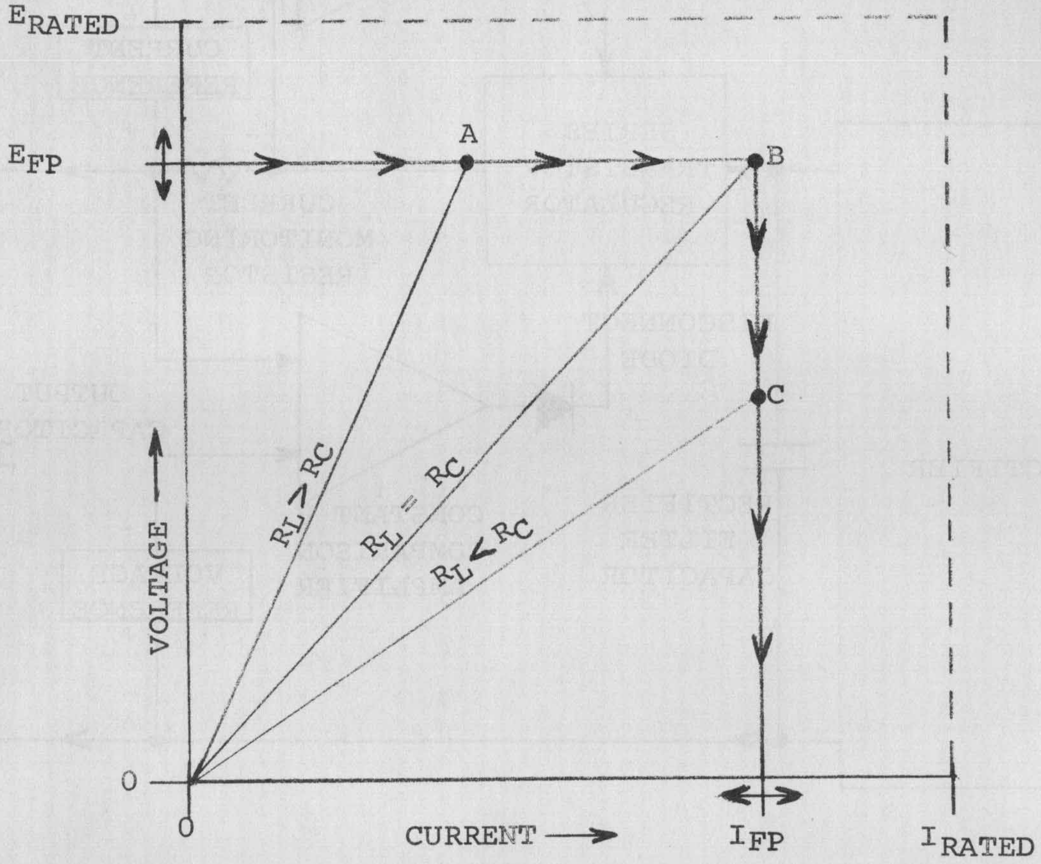


FIG. 9 -- BLOCK DIAGRAM OF A CONSTANT/VOLTAGE CONSTANT CURRENT POWER SUPPLY WITH AUTOMATIC CROSSOVER (CV/CC TYPE I).

FIG. 10 -- OPERATING LOCUS FOR A CV/CC TYPE I. SUPPLY



$R_C = \dfrac{E_{FP}}{I_{FP}}$ = "CRITICAL" Load Resistance at which transition between Constant Voltage and Constant Current Operation occurs.

E_{FP} = Front Panel Voltage Control Setting (Adjustable)

I_{FP} = Front Panel Current Control Setting (Adjustable)

A = Typical Operating Point for $R_L > R_C$ (Supply is in Constant Voltage Operation)

B = Operating Point for $R_L = R_C$ (Supply is in transition between Constant Voltage and Constant Current Operation)

C = Typical Operating Point for $R_L < R_C$ (Supply is in Constant Current Operation.

→ = locus of operating points traversed as R_L decreases from ∞ to 0; this same locus with direction of arrows reversed is traversed as R_L increases from 0 to ∞.

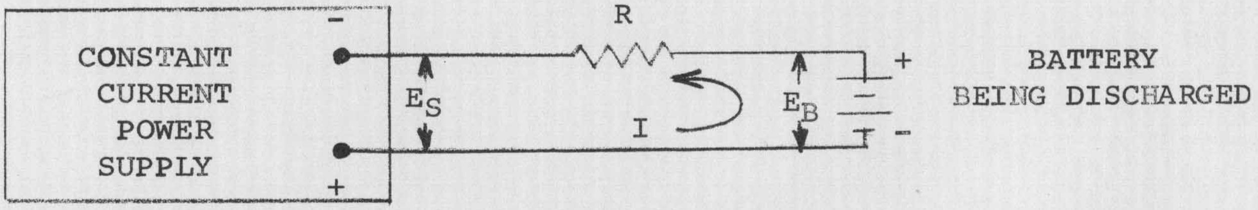


FIG. 11 __ CIRCUIT FOR CONSTANT CURRENT BATTERY DISCHARGING.

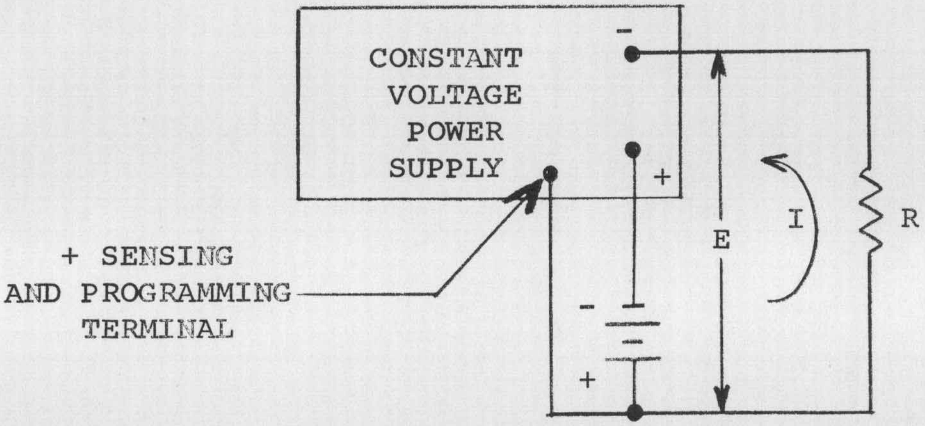


FIG. 12 -- ALTERNATE CIRCUIT FOR CONSTANT CURRENT BATTERY DISCHARGING.