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Restrictive Loads Powered by Separate or by Common Electrical Sources

J. Appelbaum
Lewis Research Center
Cleveland, Ohio

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RESISTIVE LOADS POWERED BY SEPARATE OR BY COMMON ELECTRICAL SOURCES

J. Appelbaum*
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

In designing a multiple load electrical system, the designer may wish to compare the performance of two setups: a common electrical source powering all loads, or separate electrical sources powering individual loads. Three types of electrical sources: an ideal voltage source, an ideal current source, and solar cell source powering resistive loads were analyzed for their performances in separate and common source systems. A mathematical proof is given, for each case, indicating the merit of the separate or common source system. The main conclusions are: (1) identical resistive loads powered by electrical sources perform the same in both system setups, (2) nonidentical resistive loads powered by ideal voltage sources perform the same in both system setups; (3) nonidentical resistive loads powered by ideal current sources have higher performance in separate source systems and (4) nonidentical resistive loads powered by solar cells have higher performance in a common source system for a wide range of load resistances.

INTRODUCTION

Loads that are in close proximity to each other, or a multiple load system, may be powered by separate electrical source for each one, or alternatively, by a common electrical source for all the loads. The performance of all the loads in a common source system may be higher than the total performance of all these loads when powered by separate sources for a

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certain type of electrical sources, and lower for another type; or the performance may be the same for still another type of electrical sources. In a common source system there is an interaction between the loads such that one load may improve its operation on the expense of another load. In certain cases, it might be advantageous to disconnect a load from a common source system in order to improve the operation of another load. In general, the designer may wish to compare the performance of a common source/multiple load system design versus a separate source/individual load system design. The present study deals with three types of electrical sources: an ideal voltage source; an ideal current source; and a solar cell source. A mathematical proof is given that show the merit of the separate or common source system for the three types of electrical sources. Loads may be of the same or different types. The proof, in this paper, is given for resistive loads only. The electrical sources in the separate source system are of the same size; the common source is formed by paralleling the separate sources.

VOLTAGE SOURCES

The I-V characteristic of an ideal voltage source is shown in Fig. 1. A resistive load of value R_1 connected to a separate source is shown in Fig. 2(a).

The power delivered to R_1 is:

$$P_1 = V_o^2/R_1 \tag{1}$$

By varying the load resistance, the load power varies hyberbolically, i.e.,

$$P = V_o^2/R \propto \frac{1}{R} \tag{2}$$

This is shown in Fig. 3.

A second load of value R_2 connected again to a separate voltage source of the same size is shown in Fig. 2(b). The power delivered to R_2 is:

$$P_2 = V_o^2/R_2 \tag{3}$$

The total power delivered to both loads is:

$$P_s = P_1 + P_2 \tag{4}$$

where "s" stands for separate.

Now, these two resistive loads will be connected in parallel to a common source formed by the above sources as shown in Fig. 4 (the individual voltage sources are connected in parallel).

The equivalent load resistance is:

$$R_c = R_1R_2/(R_1 + R_2) \tag{5}$$

where "c" stands for common. The common source system load power P_c is:

$$P_c = V_o^2/R_c \tag{6}$$

For the particular case of identical loads, where $R_1 = R_2 = R$, we have for the separate source systems:

$$P_1 = P_2 = P = V_o^2/R \tag{7}$$

and

$$P_s = 2P \tag{8}$$

For the common source system, the load resistance (Eq. (5)) is $R_c = R/2$ and the load power is:

$$P_c = V_o^2/R_c = 2V_o^2/R = 2P \tag{9}$$

By comparing Eqs. (8) and (9) we see that for <u>identical</u> resistive loads the load powers are the same for both the separate and common source systems, i.e., $P_s = P_c$.

Now we shall examine the case of <u>nonidentical</u> resistive loads. We shall change the value of one load and keep the value of the other load constant, i.e.,

$$R_1 = R \quad \text{and} \quad R_2 = R + \Delta R \tag{10}$$

For the separate source systems we have:

$$P_1 = V_o^2/R \quad \text{and} \quad P_2 = V_o^2/(R + \Delta R) \tag{11}$$

and

$$P_s = P_1 + P_2 = V_o^2 \frac{2R + \Delta R}{R(R + \Delta R)} \tag{12}$$

For the common source system, the equivalent load resistance (Eq. (5)) is:

$$R_c = \frac{R(R + \Delta R)}{2R + \Delta R} \tag{13}$$

and the power delivered to the equivalent load is:

$$P_c = V_o^2/R_c = V_o^2 \frac{2R + \Delta R}{R(R + \Delta R)} \tag{14}$$

By comparing Eqs. (12) and (14), we see that also for <u>nonidentical resistive loads</u> the load powers are the same for both the separate and common source systems, i.e., $P_s = P_c$.

An individual source in the common source system sees an equivalent load resistance of $2R_c$, i.e.,

$$2R_c = 2 \frac{R(R + \Delta R)}{2R + \Delta R)} = R + \frac{\Delta R}{2 + \Delta R/R} \tag{15}$$

The average resistance of R and $R + \Delta R$ is:

$$R_{av} = \frac{R + (R + \Delta R)}{2} = R + \frac{\Delta R}{2} \tag{16}$$

therefore:

$$2R_c < \frac{R + (R + \Delta R)}{2} \tag{17}$$

i.e., the equivalent resistance seen by an individual source in the common source system is less than the average resistance of two different loads connected individually to two separate source systems. This result will be used later.

CURRENT SOURCES

The I-V characteristic of an ideal current source is shown in Fig. 5. A resistive load of value R_1 connected to a separate source is shown in Fig. 6(a). The power delivered to R_1 is:

$$P_1 = I_o^2 R_1 \ . \tag{18}$$

By varying the load resistance, the load power varies linearily i.e.,

$$P = I_o^2 R \propto R \tag{19}$$

This is shown in Fig. 7.

A second load of value R_2 connected again to a separate current source of the same size is shown in Fig. 6(b). The power delivered to R_2 is:

$$P_2 = I_o^2 R_2 \tag{20}$$

The total power delivered to both loads is:

$$P_s = I_o^2 (R_1 + R_2) \tag{21}$$

Now, these two loads will be connected in parallel to a common source formed by the above sources as shown in Fig. 8 (the individual current sources are connected in parallel).

The common source system load power is:

$$P_c = (2I_o)^2 R_c \tag{22}$$

where R_c is given in Eq. (5).

For the particular case of identical loads where $R_1 = R_2 = R$, we have for the separate source systems $P_1 = P_2 = P = I_o^2 R$

and

$$P_s = 2I_o^2 R \tag{23}$$

For the common source systems $R_c = R/2$ and

$$P_c = (2I_o)^2 R_c = 2I_o^2 R \tag{24}$$

By comparing Eqs. (23) and (24), we see that for <u>identical resistive loads</u>, the load powers are the same for both the separate and common source systems, i.e., $P_S = P_C$

Now we shall examine the case of <u>nonidentical</u> resistive loads. We shall change the value of one load and keep the value of the other load constant, i.e.,

$$R_1 = R \quad \text{and} \quad R_2 = R + \Delta R$$

For the separate source systems we write:

$$P_1 = I_o^2 R \quad \text{and} \quad P_2 = I_o^2 (R + \Delta R)$$

and

$$P_s = P_1 + P_2 = I_o^2 (2R + \Delta R) \tag{25}$$

For the common source system, the equivalent load resistance is given in Eq. (5) and the power derived to the equivalent load is:

$$P_c = (2I_o)^2 R_c = I_o^2 \frac{4R^2 + 4R\,\Delta R}{2R + \Delta R} = I_o^2 \left(2R + \frac{2R\,\Delta R}{2R + \Delta R}\right) \tag{26}$$

In order to compare the performance of the two setups, Eqs. (25) and (26), we have to compare ΔR (Eq. (25)) with $2R\,\Delta R/(2R + \Delta R)$ (Eq. (26)). The value in Eq. (26)

$$\frac{2R\,\Delta R}{2R + \Delta R} = \frac{\Delta R}{1 + \Delta R/2R} \tag{27}$$

thus:

$$\Delta R > \frac{\Delta R}{1 + \Delta R/2R} \tag{28}$$

therefore $P_s > P_c$.

The conclusion is that for nonidentical resistive loads and for current sources, the total power of separate source system is higher than for a common source system.

SOLAR CELL SOURCE

The I-V characteristic of a solar cell array is shown in Fig. 9. Broadly speaking, the I-V characteristic may be divided into two ranges; range I where the solar cell behaves more likely as a current source, and range II where the solar cell behaves more likely as a voltage source.

The approximate I-V characteristic equation of the solar cell array source, neglecting the shunt resistance, is given by:

$$I = I_{ph} - I_o\left\{\exp\left[\Lambda\ (V + IR_s)\right] - 1\right\} \tag{29}$$

where I_{ph} is the photocurrent, I_o is the reverse saturation current, R_s is the series resistance, $\Lambda = q/AKT$, and $V = IR$ for resistive loads. The source terminal current and voltage are I and V, respectively.

The I-V equation of N_p such sources connected in parallel and N_s such sources connected in series, which form a larger array, is given by:

$$I_c = N_p I_{ph} - N_p I_o\left\{\exp\left[\frac{\Lambda}{N_s} V_c + I_c \frac{N_s}{N_p} R_s\right] - 1\right\} \tag{30}$$

where I_c and V_c are the larger array (or common) terminal current and voltage, respectively. A resistive load of value R_c which is connected to a common solar cell array is seen by an individual source in the common array with a resistance value of:

$$R = R_c\ N_p/N_s \tag{31}$$

For the case where $N_p = N_s = 1$, we have $I_c = I$, $V_c = V$, $R_c = R$ and Eq. (29) applies.

Resistive loads R_1 and R_2 connected to identical separate solar cell array sources are shown in Fig. 10. The load currents are, respectively:

$$I_1 = I_{ph} - I_o\left\{\exp\left[\Lambda I_1(R_1 + R_s)\right] - 1\right\} \tag{32}$$

$$I_2 = I_{ph} - I_o\left\{\exp\left[\Lambda I_2(R_2 + R_s)\right] - 1\right\} \tag{33}$$

Now, let these two loads be connected in parallel to a common solar cell array source ($N_s = 1$, $N_p = 2$) formed by two identical solar cell sources, as shown in Fig. 11. The equivalent load resistance is given by Eq. 5, and the common load current I_c is:

$$I_c = 2I_{ph} - 2I_o\left\{\exp\left[\Lambda I_c(R_c + R_s/2)\right] - 1\right\} \tag{34}$$

For a particular case of <u>identical loads</u> where $R_1 = R_2 = R$, the load current of a separate source system is:

$$I = I_{ph} - I_o\left\{\exp\left[\Lambda I(R + R_s)\right] - 1\right\} \tag{35}$$

and the load power is:

$$P = I^2 R \tag{36}$$

The total power of two such systems is:

$$P_s = 2P = 2I^2 R \tag{37}$$

Now, for the common source system we have:

$$I_c = 2I = 2I_{ph} - 2I_o\left\{\exp\left[\Lambda 2I(R/2 + R_s/2)\right] - 1\right\}$$

or

$$I_c = 2\left\{I_{ph} - I_o\left\{\exp\left[\Lambda I(R + R_s)\right] - 1\right\}\right\} \tag{38}$$

and

$$P_c = I_c^2 R_c = 2I^2 R = 2P \tag{39}$$

comparing with Eq. (37) we get: $P_s = P_c$.

The result shows that for identical resistive loads, the load powers are the same for both the separate and common source systems.

A criterion for comparing the load performance of the solar cell array systems may be the "energy utilization" defined by:

$$\eta^e = \int_T P(T)dT \bigg/ \int_T P_m(T)dT \tag{40}$$

where the numerator is the input energy to the loads by the array, and the demoninator is the maximum available energy that the array can supply; P is the array output power, and P_m is its maximum output power; both are functions of the solar insolation, T is time.

For a given array size and insolation profile the $\int P_m \, dT$ = constant independently whether the cells are utilized or not. The energy utilization of the two separate source system (Eq. (37)) is:

$$\eta_s^e = \int P_s \, dT \bigg/ 2 \int P_m \, dT = \int P \, dT \bigg/ \int P_m \, dT \tag{41}$$

and the energy utilization of the common source system (Eq. (39)) is:

$$\eta_c^e = \int P_c \, dT \bigg/ 2 \int P_m \, dT = \int P \, dT \bigg/ \int P_m \, dT \tag{42}$$

where P_m is the peak power of an individual solar cell array source.

The results show that identical resistive loads which are connected to separate solar cell sources perform the same as if they are connected in parallel to a common solar cell source of the appropriate size.

Now, let us examine the case where the solar cell array sources are not identical in their sizes and compare again the performances of the systems with separate and common sources. In order to load each source identically, the load resistances are of proportional values. Assuming a load resistance of value R is connected to the above mentioned solar cell source, Eq. (29), and another load resistance of value R/N_p is connected to a second source of N_p times larger than the first one (Fig. 12), the load currents of the separate sources are:

$$I_1 = I = I_{ph} - I_o \left\{ \exp\left[\Lambda I(R + R_s)\right] - 1 \right\} \tag{43}$$

and (Eqs. (30) and (31))

$$I_2 = N_p I = N_p I_{ph} - N_p I_o \left\{ \exp\left[\Lambda N_p I(R/N_p + R_s/N_p)\right] - 1 \right\}$$

or

$$I_2 = N_p I = N_p I_{ph} - N_p I_o \left\{ \exp\left[\Lambda I(R + R_s)\right] - 1 \right\} \tag{44}$$

The powers of the separate source systems are:

$$P_1 = P = I^2 R \quad \text{and} \quad P_2 = (N_p I)^2 R/N_p = N_p P \tag{45}$$

The total power is:

$$P_s = P_1 + P_2 = (1 + N_p)P \tag{46}$$

and the energy utilization is:

$$\eta_s^e = \int P_s \, dT \bigg/ \int P_m (1 + N_p) dT = \int P \, dT \bigg/ \int P_m \, dT \tag{47}$$

For the common source system, the common current is:

$$I_c = (1 + N_p)I \tag{48}$$

or (Eq. (30)):

$$I_c = (1 + N_p)I = (1 + N_p)I_{ph} - (1 + N_p)I_o \left\{ \exp\left[\Lambda(1 + N_p)I\left(\frac{R}{1 + N_p} + \frac{R_s}{1 + N_p}\right)\right] - 1 \right\}$$

or

$$I_c = (1 + N_p)I = (1 + N_p)I_{ph} - (1 + N_p)I_o \left\{ \exp\left[\Lambda I(R + R_s)\right] - 1 \right\} \tag{49}$$

The power of the common source system (where $R_c = R/(1 + N_p)$) is:

$$P_c = \left[(1 + N_p)I\right]^2 R_c = (1 + N_p)I^2 R = (1 + N_p)P \tag{50}$$

and the energy utilization is:

$$\eta_c^e = \int P_c \, dT \bigg/ \int P_m(1 + N_p)dT = \int P \, dT \bigg/ \int P_m \, dT \tag{51}$$

By comparing Eqs. (47) and (51), we see that resistive loads of proportional sizes which are connected to solar cell array sources of proportional sizes perform the same whether they are connected to separate or to common sources.

We shall now analyze the performance of <u>nonidentical</u> resistive loads once powered by two identical separate solar cell array sources, and the second time powered by a common source formed by the above two sources that are connected in parallel, Figs. 10 and 11. The resistive loads are, for example, R_m and R_1 in range I, Fig. 9, (current source range), and R_m and R_2 in range II (voltage source range), where R_m is the load resistance corresponding to the maximum power point P_m of the solar cell array source. We examine first an extreme case in range I for $R_1 = 0$ and R_m. For the separate source system $P_1 = 0$, $P_m = I_m^2 R_m$ and $P_s = P_1 + P_m = P_m$, therefore, the energy utilization of both separate systems is:

$$\eta_c^e = \int P_s \, dT \bigg/ 2 \int P_m \, dT = 50 \text{ percent} \tag{52}$$

For the common source system $P_c = 0$ since R_1 short circuits R_m, i.e., $\eta_c^e = 0$, therefore $\eta_s^e > \eta_c^e$.

Another extreme case is in range II for $R_2 = \infty$ and R_m. For the separate source system we have $P_m = I_m^2 R_m$ and $P_2 = 0$, therefore:

$$\eta_s^e = \int P_s \, dT \bigg/ 2 \int P_m \, dT = 50 \text{ percent} \tag{53}$$

For the common source system, $P_2 = 0$ and R_m is now powered by a double size source, therefore $P_c > P_m$ and,

$$\eta_c^e = \int P_c \, dT \Big/ 2 \int P_m \, dT > \eta_s^e \tag{54}$$

We have mentioned three distinct cases:

(1) $R_1 = R_2 = R_m$ (identical loads whether optimal or nonoptimal), where both the separate and the common solar cell source systems have the same energy utilization;

(2) $R_1 = 0$ and R_m, where the separate source systems have a higher energy utilization than the common source system; and

(3) For R_m and large R_2, where the common source system has a higher energy utilization than the separate source systems.

These three cases are shown in Fig. 13 by the circles. Connecting the circles by the solid line describes the energy utilization of the common source system η_c^e, and by the dashed line describes the separate source systems η_s^e. Two possible trajectories of η_s^e are shown in Fig 13 in range I. In one case, the energy utilization of separate source systems is always higher than for the common source system; in the second case, up to point "a" the separate source systems have a higher energy utilization, but between points "a" and "b" the common source system has a higher energy utilization. In range II, the common source system is always superior ($\eta_c^e > \eta_s^e$). The assumed variation of the solid and dashed lines will now be verified.

Let us assume that there exists an electrical source of a special type that behaves like a current source, in range I, where the power P increases linearily with increasing of the resistance R (Fig. 7); and behaves such that P decreases linearily with increasing R, in range II, as shown in Fig. 14.

In range I, the power of the load R_m is $P(R_m)$ and that of load R_1 is $P(R_1)$. If a load resistance is of value $(R_m + R_1)/2$, then two such identical loads will produce the same power as the two different loads of values R_m and R_1. But, if a load resistance is of a vlaue R_I that is less than the average of R_m and R_1, i.e.,

$$R_I < (R_m + R_1)/2 \qquad (55)$$

then:

$$2P(R_I) < P(R_m) + P(R_1) \qquad (56)$$

For a load resistance in range II of value

$$R_{II} < (R_m + R_2)/2 \qquad (57)$$

the inverse is true, i.e.,:

$$2P(R_{II}) > P(R_m) + P(R_2) \qquad (58)$$

Now, recalling the result obtained for the equivalent resistance seen by an individual source in a common source system, Eq. (17), the conclusion is that in range I, the load power of a common source system is lower than the sum of the load powers of the separate source systems. In range II, the load power of a common source system is higher than the sum of the load powers of the separate source systems. Indeed, the variation of the load power with resistance for a solar cell array source is similar to Fig. 14, excluding the vicinity of the maximum power point, as described in Fig. 15. The size of the solar cell array is 1400 W_p, 176 V open circuit voltage and 13.613 A short circuit current. This concludes the proof for the lower performance of resistive loads in the current range, and the higher performance of resistive loads in the voltage range in a common solar cell source system, as assumed in Fig. 13.

An actual comparison of resistive load performances of separate and common solar cell array sources based on energy utilization is shown in

Fig. 16. The size of the separate solar cell array sources is the one that is mentioned above, and the common source is of double size, i.e., 2800 W_p, 176 V and 27.23 A.

The optimal load resistance R_m from the viewpoint of maximum energy utilization is 13.5 Ω and was kept constant; the second load resistance was varied from 0 to 30 Ω. The dashed line, η_s^e, describes the energy utilization of the two separate source systems, and the solid line, η_c^e, describes the energy utilization of the common source system. In this case, if the value of one load resistance is taken as 13.5 Ω, and the value of the other load resistance chosen from the range between 4.85 Ω and any higher value, the result would be of higher performance for the common source system. Obviously, when $R_1 = R_2 = 13.5$ Ω, both setups perform the same as was proven for identical loads. Another case is illustrated in Fig. 17 where one load resistance of 5 Ω was kept constant and the second load resistance was varied. In this case, the energy utilization of the separate source systems, η_s^e, is higher than for the common source system, η_c^e, in the current source range as was assumed in Fig. 13, as for one of the possible trajectories. In range II, the common source system has always a higher energy utilization (again, compare the predicted Fig. 13, and the actual results, Figs. 16 and 17).

CONCLUSIONS

In designing a multiple load electrical system, the designer may wish to compare the performance of separate source systems with a common source system. Three types of electrical sources (a voltage source, a current source and a solar cell source) powering resistive loads were treated with mathematical proofs. The conclusions are:

1. Identical resistive loads powered by electrical sources perform the same for both the separate and common source systems.

2. Nonidentical resistive loads powered by ideal voltage sources perform the same for both the separate and common source systems.

3. Nonidentical resistive loads powered by ideal current sources have higher performance for separate source systems than for a common source system.

4. Nonidentical resistive loads powered by solar cells have higher performance, in the voltage source range, for a common source system. In the current source range, the loads have a higher performance for the separate source systems. In general, the common source system has a higher performance than the separate source systems for a wide range of load resistances, including the range of good system designs.

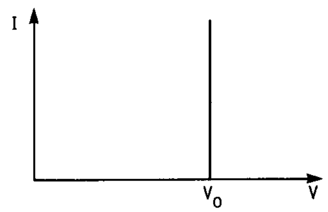


FIGURE 1. - IDEAL VOLTAGE SOURCE V_0.

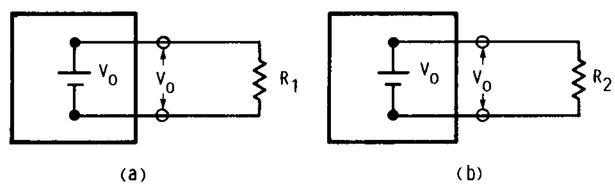


FIGURE 2. - RESISTIVE LOADS R_1 AND R_2 CONNECTED TO IDENTICAL IDEAL VOLTAGE SOURCES.

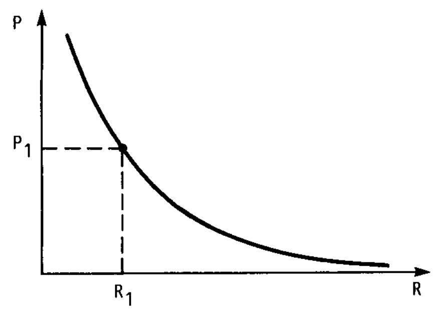


FIGURE 3. - VARIATION OF LOAD POWER WITH RESISTANCE FOR AN IDEAL VOLTAGE SOURCE.

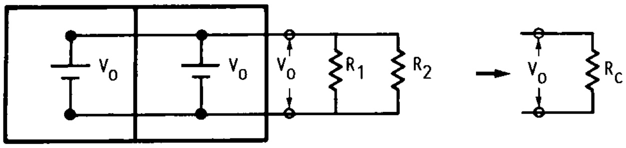


FIGURE 4. - COMMON VOLTAGE SOURCE SYSTEM.

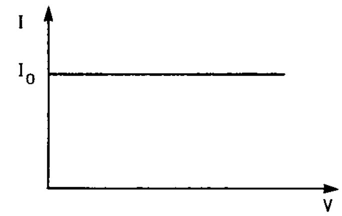
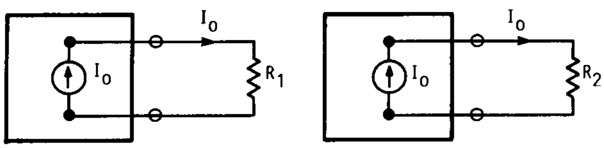


FIGURE 5. - IDEAL CURRENT SOURCE I_0.



(a) (b)

FIGURE 6. - RESISTANCES R_1 AND R_2 CONNECTED TO IDENTICAL IDEAL CURRENT SOURCES.

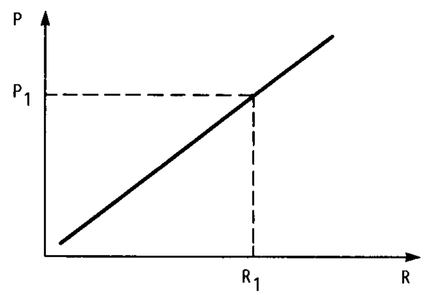


FIGURE 7. - VARIATION OF LOAD POWER WITH RESISTANCE FOR AN IDEAL VOLTAGE SOURCE.

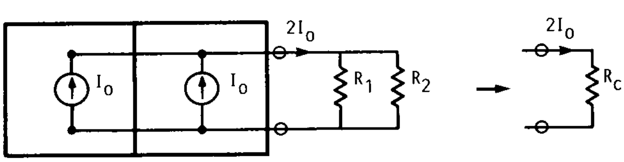


FIGURE 8. - COMMON CURRENT SOURCE SYSTEM.

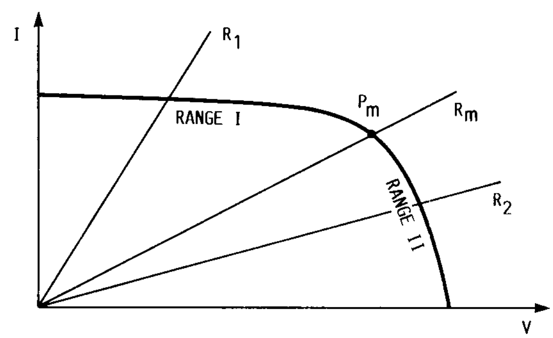
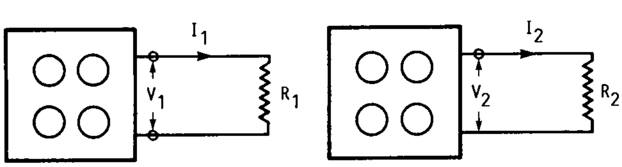


FIGURE 9. - I-V CHARACTERISTIC OF A SOLAR CELL ARRAY AND RESISTIVE LOADS.



(a) (b)

FIGURE 10. - RESISTIVE LOADS R_1 AND R_2 CONNECTED TO IDENTICAL SOLAR CELL SOURCES.

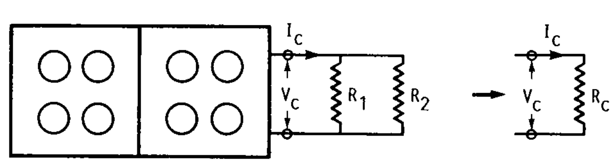


FIGURE 11. - COMMON SOLAR CELL SOURCE SYSTEM.

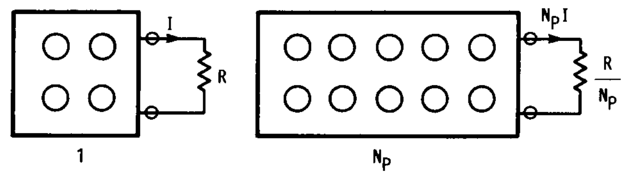


FIGURE 12. - RESISTIVE LOADS R AND R/N_P CONNECTED TO PROPORTIONAL SIZE OF SOLAR CELL SOURCES.

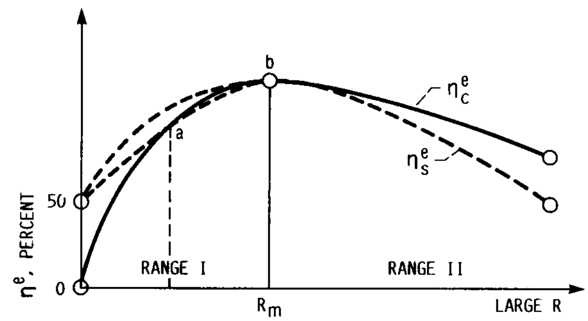


FIGURE 13. - ENERGY UTILIZATION OF SEPARATE AND COMMON SOURCE SYSTEM IN THREE EXTREME CASES $R_1 = R_2 = R_m$; $R_1 = 0$ AND R_m; R_m AND LARGE R_2.

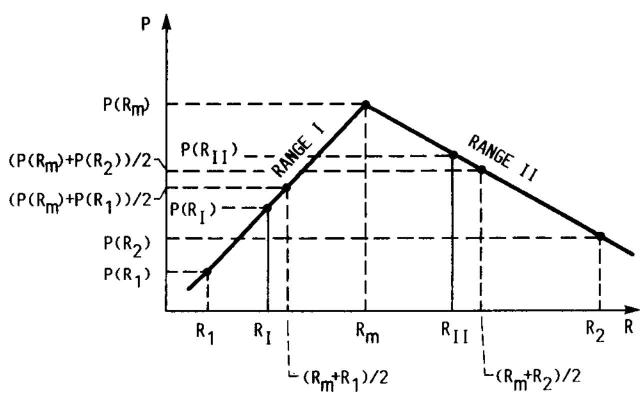


FIGURE 14. - AN ASSUMED ELECTRICAL SOURCE WHERE ITS POWER IS LINEARLY DEPENDENT WITH RESISTANCE.

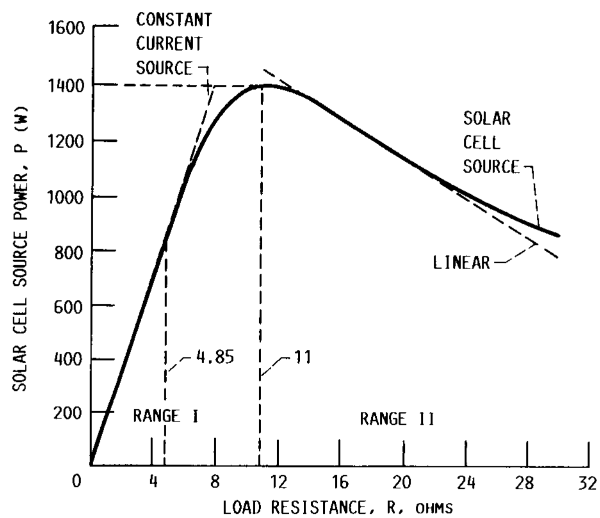


FIGURE 15. - VARIATION OF SOLAR CELL SOURCE POWER WITH LOAD RESISTANCE.

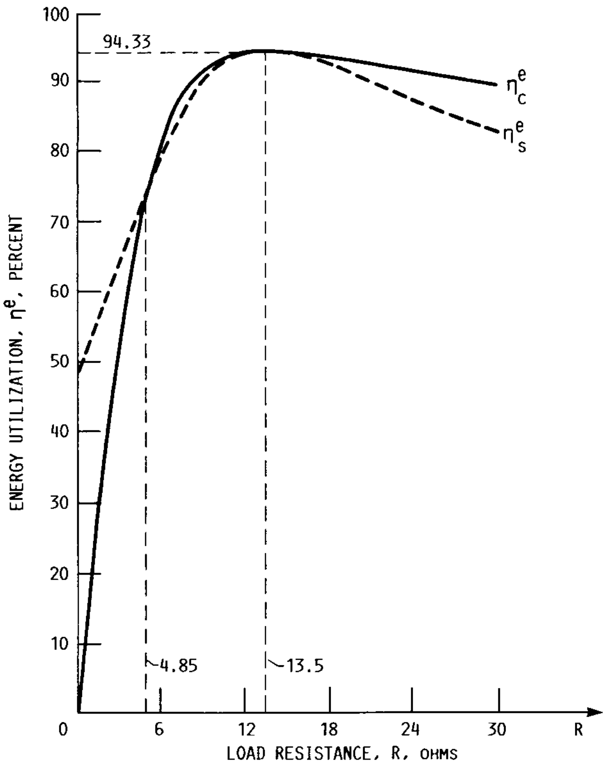


FIGURE 16. - ENERGY UTILIZATION OF SEPARATE AND COMMON SOURCE SYSTEMS FOR RESISTIVE LOADS; $R_1 = 13.5\ \Omega$ = CONSTANT.

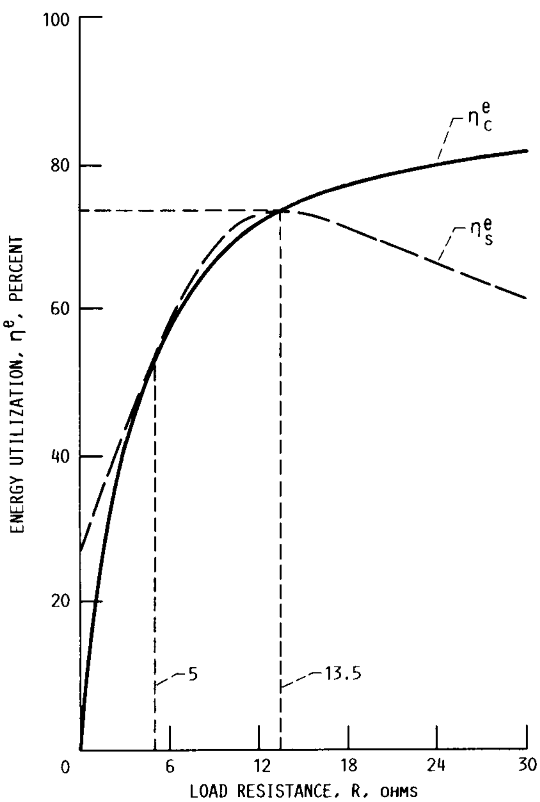


FIGURE 17. - ENERGY UTILIZATION OF SEPARATE AND COMMON SOURCE SYSTEMS FOR RESISTIVE LOADS; $R_1 = 5\ \Omega$ = CONSTANT.

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16. Abstract
In designing a multiple load electrical system, the designer may wish to compare the performance of two setups: a common electrical source powering all loads, or separate electrical sources powering individual loads. Three types of electrical sources: an ideal voltage source, an ideal current source, and solar cell source powering resistive loads were analyzed for their performances in separate and common source systems. A mathematical proof is given, for each case, indicating the merit of the separate or common source system. The main conclusions are: (1) identical resistive loads powered by electrical sources perform the same in both system setups, (2) nonidentical resistive loads powered by ideal voltage sources perform the same in both system setups; (3) nonidentical resistive loads powered by ideal current sources have higher performance in separate source systems and (4) nonidentical resistive loads powered by solar cells have higher performance in a common source system for a wide range of load resistances.

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