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COMPARISON AND OPTIMIZATION OF ALTERNATIVE
ENERGY SOURCES FOR CATHODIC PROTECTION

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INTRODUCTION

To date the majority of cathodic protection systems utilize either sacrificial anode or impressed current systems relying upon AC to DC rectifiers powered from the conventional electric power grid. In remote locations however, many alternative energy sources have been used with varying degrees of success. As the cost of conventionally derived electric power increases as a result of increasing fuel costs and as we move further from inhabited areas in the search for petrochemical reserves, the use of alternative energy sources becomes more viable as cathodic protection energy sources. Unfortunately, as everybody realizes the equipment necessary to convert this energy to electricity is not necessarily inexpensive.

This paper is intended to establish an approximate cost per watt to convert the various alternative energy sources to electrical energy as compared to the powering of conventional cathodic protection systems from the electrical grid. This cost per watt should only be used as a guide in seeking the viability of a particular source. The main objective of this paper is to describe how to optimize the use of these relatively expensive systems to ensure all available power is used efficiently.

THE PRICE OF POWER

The cost of power is a complex function of availablility of the energy source, competitive demand for that particular source, and thermodynamic efficiency in converting the source energy to the form required. Table No. 1 depicts the full range of costs per kilowatt hour of energy derived from various energy sources. The values shown on this table are presented to show approximate relative costs only, as the cost of energy varies over wide ranges. Even today, the fossil fuels and their derivatives such as fuel oil, natural gas, coal and gasoline seem to be the least expensive. If a source of energy is conveniently packaged, the price is also affected as witnessed by the high cost of the energy stored in a flashlight battery. It should also be noted that whereas fossil fuels are the most economical in providing heat, other energy sources may be very competitive if

the energy is to be used in other forms rather than heat because of the thermodynamic limitations of converting heat to work. It should be noted at this point that it is difficult to directly compare alternative energy sources on a cost per watt of installed capacity or kilowatt hour of output since many factors will affect the end cost. If alternative energy sources are contemplated for a particular installation it is, therefore, imperative to establish the design criteria before comparing the actual costs.

COST OF USING ALTERNATIVE ENERGY SOURCES FOR CATHODIC PROTECTION

Table No. 2 lists average equipment costs for the conversion of various alternative energy sources used to supply electricity for cathodic protection. This list is not meant to be exhaustive as other devices can and should be examined before proceeding with a installation.

The use of alternative energy sources is usually thought of as the last resort in providing electrical power for cathodic protection and is not considered until the conventional cathodic protection systems are ruled out due to the cost of installation. As can be seen from Table No. 2 and Figure No. 1 it is possible that the alternative energy sources are price competitive even though the structure being protected is not remote from the electrical grid.

Figure No. 1 indicates the distance from the conventional electric power at which the alternative energy sources are price competitive. The significant observation from this figure is the importance of the amount of power actually required at the site.

In summary, the equipment necessary to produce electrical energy for cathodic protection from the alternative energy sources is usually expensive in itself however, even in 1979 many of these devices can be competitive and should be studied before finalizing the cathodic protection system design.

OPTIMIZATION OF ALTERNATIVE ENERGY SOURCES FOR CATHODIC PROTECTION

Optimization in the use of alternative energy sources to produce electricity in many instances allows these power sources to compete with the conventionally powered cathodic protection systems. The company utilizing these alternative energy sources must pay a relatively high cost per installed watt for the capability of these units. It is therefore imperative that all possible power capability is totally utilized for the cathodic protection of the structure. If a 10 watt photovoltaic system costs $2000.00, utilization of only 5 watts of this source means the designer has wasted $1000.00 in capital expenditure.

Unlike some of the other end uses of alternative energy sources, a cathodic protection system presents a variable load due to seasonally fluctuating groundbed resistances and changing current requirements on the cathodes themselves. In spite of these variables the system must be able to provide the maximum average current output, utilizing minimum power.

Figure No. 2 shows a typical arrangement of a unit for the conversion of the source energy to electricity to be used for cathodic

protection. The battery storage in some cases is not required, however, the output power of the entire unit has a definite design limitation. As an example, in this paper we will deal with a source capable of producing 10 watts output at 10 volts, 24 hours per day. This example has been used to simplify the calculations necessary to evaluate various optimization techniques.

As with any power source providing electrical energy there is an optimum load that will provide the maximum power transfer. As can be seen from Figure No. 3 which shows the power and current output versus groundbed resistance for our example there is an area referred to as the safe operating area. This area covers a range of groundbed resistances versus power output and is the only region in which the system can operate continuously. Any groundbed resistance less than rated will result in a excessive current output, exceeding the continuous power rating of the device. Any groundbed resistance greater than 10 ohms results in poor utilization of the equipment.

In general, efforts are made to minimize the groundbed resistance, however, if for some reason the groundbed resistance is less than calculated a resistor can be placed in series with the load in order to limit the current output to rated value and subsequently the power output of the device. This technique is used in some cases with sacrificial anodes and quite often with distributed groundbeds energized by a conventionally powered rectifier. This method of limiting output is only valid if the cost of the power wasted is small. However, as can be seen from Figure No. 4 and Table No. 3 when we are dealing with a power converter that has a high capital cost the waste becomes very costly.

For instance in Table No. 3 if the device again is rated for a 10 volt output at 10 watts and the groundbed resistance is 1 ohm then a series resistor of 9 ohms is required. This results in a total current output of 1 amp. with only 1 watt of power being delivered to the groundbed giving an efficiency of only 10%. Assuming a cost of approximately $2000.00 for a photovoltaic system, then the above example shows that only $200.00 of that $2000.00 investment is utilized.

In the example, the optimum load to which 100% power is delivered is a groundbed with a resistance of 10 ohms. Unfortunately, in designing the majority of cathodic protection systems, it is difficult to predict all of the exact parameters necessary to optimize the design. Because many parameters can change with time, then a significant decrease in efficiency can result in systems previously optimized at 100% operating efficiency.

In view of the foregoing it is imperative that some method be established to effectively match the source to load resistances. This matching can be accomplished by the use of a transistor type regulator. Figure No. 5 shows a typical transistor controlled matching unit. As transistors and semi-conductors are considered to be efficient in themselves any use of these devices is sometimes assumed to be efficient

as well. Unfortunately, this is not the case. Again referring to Figure No. 5 the output of the alternative power source conversion unit is easily controlled by changing the value of the resistor referred to a R bias.

However, if analyzed in detail it will be realized that there is some voltage drop between the collector and the emitter of the power transistor. The current flow through the series circuit of the transistor and the groundbed multiplied by the actual voltage across this transistor is equal to a power loss. In this particular case, the transistor is working simply as a voltage controlled resistor and wastes considerable power. Referring to Table No. 4 it can be seen that the same efficiencies are recorded as per Table No. 3 utilizing a simple series resistance. The only advantage of the transistor control is that it provides a variable control, using a low wattage potentiometer. It can be shown that there is however more power lost due to the operation of the transistor than would be lost using the series resistor in the previous example.

What type of system can be utilized to ensure the maximum use of the available power, assuming neither resistor nor conventional transistor regulator systems are acceptable from a power wastage point of view? Consider the task of dimming a light bulb. We have seen that both the series resistor and the transistor control are wasteful of power. The alternative is to interrupt the flow of current to the bulb using a switching device such that the average power is reduced as we increase the duration of the interruptions. A basic schematic of this type of concept is shown in Figure #6.

Note that when the switch is closed the voltage across the switch is zero and when the switch is open the current through the switch is zero. Thus the power dissipated in the switch is always zero and this circuit is highly efficient.

A circuit to accomplish this switching in an automatic manner has several names, however for the purposes of the paper it will be called a DC-to-DC converter. DC-to-DC power supplies play a significant part in the conventional power supply market. They feature good regulation (even during brown outs), overload protection and high efficiency. As can be seen from Figure No. 6 the load is in fact connected for a period of time directly across the power source. In order to minimize the power output of the device it is also turned off completely for a period of time. As a result the voltage output pattern is a square wave as shown in Figure No. 7. The important thing to realize is that the average value of the output voltage is proportionate to the duty cycle. This duty cycle is the ratio of the "ON" time ($\mathcal{T}$) of the switch to the total period (T) of operation. Table No. 5 shows various groundbed resistances and the average output current. It should be noted that as long as the resistance is less than the previously defined optimum (10 ohm) the output of the entire system is 100% efficient. The efficiency of this device drops if the load resistance is too high for the voltage capabilities of power source.

It is imperative that the voltage value be over-designed to ensure a DC-to-DC converter can be utilized at a high operating efficiency over a wide range of load resistances. As shown in Figures No. 7 and No. 8 the output waveform of the device will be a square wave with an average value as defined in Table No. 5. This square wave output contains harmonics which do not aid in the cathodic protection of the structure and can interfere with nearby communication equipment. As a result this waveform is filtered with a suitable inductance as shown in Figure No. 9. The resulting current waveform will be as shown in Figure No. 10. It is still possible to obtain operating

efficiencies in the order of 90 to 95% even with the filtered output. As an example Figure No. 11 shows a block diagram of a typical DC-to-DC converter.

It was mentioned previously that often in cathodic protection systems several variables can change the effective load resistance. To overcome the variation in load resistance it is possible to automate the system so that it always supplies the maximum power available at the source. Figure No. 12 is a block diagram of a typical automatic constant power output system. This circuit will always supply the maximum power available to the load.

As has been discussed in several other papers [2,3,4] concerning alternative energy sources that produce electricity for cathodic protection that the choice of the anode material is very important. Figure No. 13 a typical cathodic protection system and the equivalent electrical schematic of the circuit. The polarized potential of the structure and the anode tend to decrease the current output from the power source. Table No. 6 indicates the cathodic protection current discharged by various anode systems when powered by a nominal 10 volt, 10 watt power source. As can be seen, the use of a very electro-negative anode material such as magnesium or zinc will increase the apparent output power and hence efficiency to more than 100%. It is imperative that the anode is not an electro-positive material in order to keep the output efficiency of the power source high. Further, not only is the nominal corrosion potential of the anode important, the ideal anode should also resist polarization such that its potential does not change with a change in anode current density. Polarization of an anode can be minimized by installing a groundbed with a large surface area.

The other important factor mentioned in previous papers [2,3,4] on cathodic protection using alternative energy sources is the resistance of the groundbed. It is imperative to attain the mimimum resistance possible. Minimization of this resistance results in a higher current output for a fixed power output of the device. Figure No. 14 is a schematic of a distributed groundbed adjacent to a structure to be protected. In this figure R_1 is defined as the longitudinal resistance of the wire connecting the individual anodes and R_S is the resistance of the anode to the structure to the protected. Increasing the number of anodes beyond a certain number will not result in a corresponding reduction in resistance.

It is important to realize that there is a finite characteristic impedance of a grounding system defined as R_0 which equals the square root of the resistance of the wire connecting the anodes (R_1) multiplied by the resistance of an anode to the structure (R_S). As shown on the graph the resistance will eventually reach a valve Ro and no matter how many additional anodes are installed the resistance will not be lowered. The solution to this problem is to either feed the groundbed from a multiple run of header cable of low resistance or to use a number of small cathodic protection stations as opposed to one large unit. A change to small multiple stations will also result in a better distribution of current to the structure to be protected.

Conclusions

1. The use of alternative energy source electric converters for cathodic protection can be price competitive with rectifiers powered from the conventional power grid.

2. Resistor power controllers can be very cost inefficient if utilized to match the energy converter resistance to the groundbed resistance.

3. DC-to-DC converters can be utilized to load match with very high operating efficiencies.

4. The groundbed anode material should be as electronegative as possible.

5. The groundbed should be constructed of a material which minimizes anodic polarization.

6. The resistance of the groundbed should be .the minimum possible.

References

1. Stanley W. Angrist "Direct Energy Conversion"
   Published by Allyn and Bacon

2. Larry E. Beil, Ted Canfield "Solar Energy:"
   A Reality for Cathodic Protection Pipeline Industry April 1977

3. George Menzler, Tom Wilkinson, Warren Rustad
   "Solar Energy For Dependable Cathodic Protection"
   presented at Corrosion 1976

4. Thomas Lewicki "Solar Power for Cathodic Protection"
   Air Force Civil Engineering Centre

TABLE I

Costs of various energy sources (as taken from
Direct Energy Conversion by Angrist.)

SOURCE OF ENERGY	CENTS/ KWH
Fuel Oil	0.4 — 0.6
Natural Gas Wood Coal	0.4 — 0.7
Gasoline	0.87 — 0.93
Electricity (central station)	1.5 — 2.5
Sugar Bread Butter	10.0
Martini ($4\frac{27}{32}$ parts gin to $1\frac{5}{32}$ parts vermouth)	503
Flashlight Battery	1000
Caviar	1240

TABLE 2 Equipment costs for various cathodic protection power sources

POWER SOURCE	CONDITION	COST / WATT ($)	AVERAGE VALUE USED FOR COMPARISON ($)
Photovoltaic (Solar collector only)	cost/peak watt	15—30	25
Photovoltaic c/w battery system	cost/continuous watt—Arizona	150—175	160
Photovoltaic c/w battery system	cost/continuous watt—Toronto, Canada	275—400	350
Magnesium Anode	cost/continuous watt—3,000 Ω—CM soil	500—600	550
Thermo Electric	cost/continuous watt	50—150	75
Wind Generator c/w tower and battery system	average wind speed 19 Kmph (12 mph)	80—120	100
Conventionial power grid c/w Rectifier cost		0.50—2.00	1.00
(Overhead Poleline costs)	cost/Km $12,500		

TABLE 3

Operating efficiency vs. groundbed resistance for resistor control

R_L (Ω)	REQUIRED R_I (Ω)	I (amps)	P_L (output power to load) (watts)	Efficiency (%)
1	9	1	1	10
2	8	1	2	20
5	5	1	5	50
10	0	1	10	100
15	0	0.66	6.5	66
20	0	0.50	5	50
25	0	0.40	4	40

TABLE 4

Groundbed resistance vs. operating efficiency for Transistor control

R_L (Ω)	V_L volts	I (amps)	P_L (watts)	Efficiency (%)
1	1	1	1	10
2	2	1	2	20
5	5	1	5	50
10	10	1	10	100
15	10	0.66	6.6	66
20	10	0.50	5.0	50
25	10	0.25	2.5	25

TABLE 5
Groundbed resistance vs. operating efficiency for circuit in figure 6

R_L (Ω)	I max. (amps)	DUTY CYCLE	I_L (D.C. amps)	P_L (watts)	Efficiency (%)
1	10	0.316	3.16	10	100
2	5	0.446	2.23	10	100
5	2	0.705	1.41	10	100
10	1	1.0	1	10	100
15	0.66	1.0	0.66	6.6	66
20	0.50	1.0	0.50	5.0	50
25	0.25	1.0	0.25	2.5	25

TABLE 6

Groundbed material vs. operating efficiency for figure 13

ANODE MATERIAL	ANODE POT. with ref. to Cu:CuSo$_4$ (v)	STRUCTURE POT. with reference to Cu:CuSo$_4$ (v)	Vo (V)	R$_L$ (V)	I (amps)	P$_L$ (watts)	Efficiency (%)
Magnesium	−1.75	−1.0	10	10	1.07	11.45	114.5
Zinc	−1.10	−1.0	10	10	1.01	10.2	102
Steel	−0.50	−1.0	10	10	0.95	9.025	90.25
Graphite	−0.30	−1.0	10	10	0.930	8.65	86.5
Platinum	0.0	−1.0	10	10	0.900	8.1	81.0
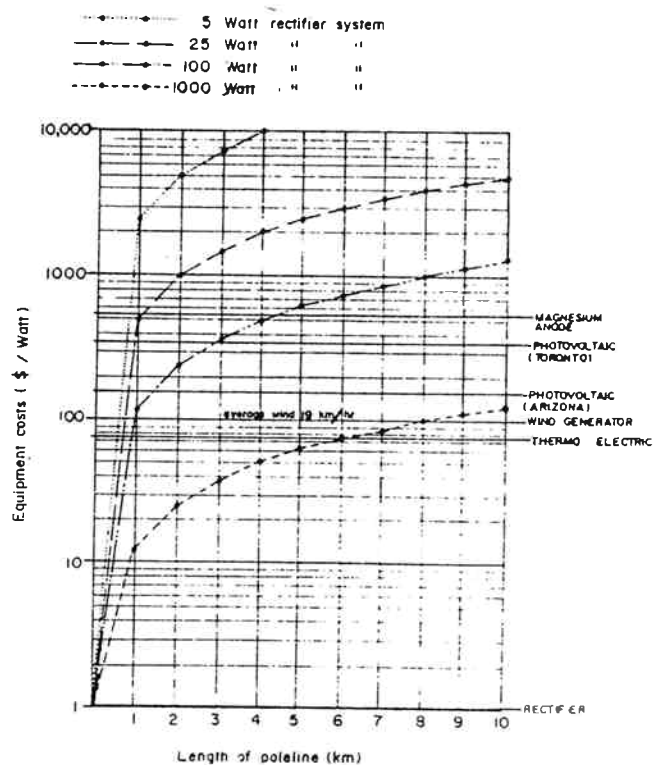
FIGURE 1 - Equipment costs per watt vs length of pole line.
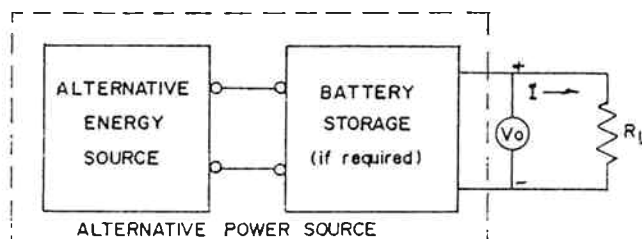
$P_{out} = I^2 R_L = V_o I$ where P_{out} is average Power output (watts)
I is current output (amps)
R$_L$ is groundbed resistance (ohms)
Vo is output voltage (volts)

FIGURE 2 - Typical arrangement of an alternative energy source used for cathodic protection.
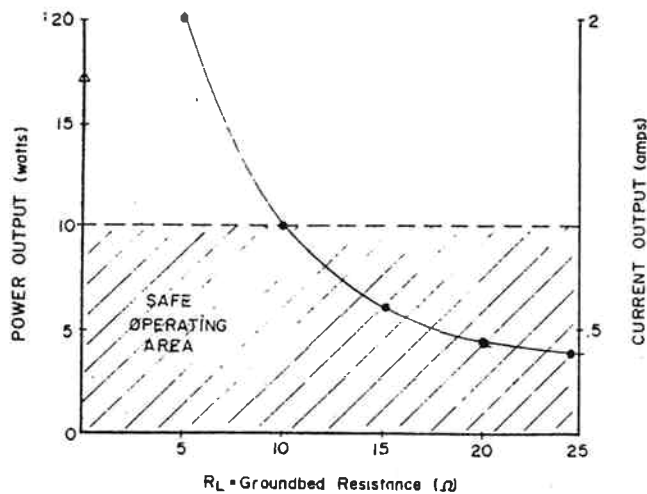
FIGURE 3 - Power output and current output vs groundbed resistance for a power source with V_0 = 10 volts and P_0 max = 10 volts.
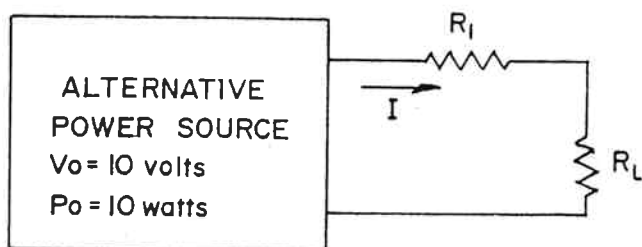
FIGURE 4 - Typical addition of resistance to limit power output.
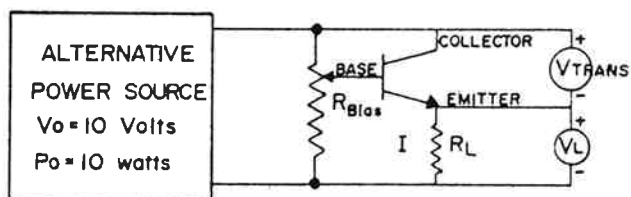
FIGURE 5 - Typical transistor control.
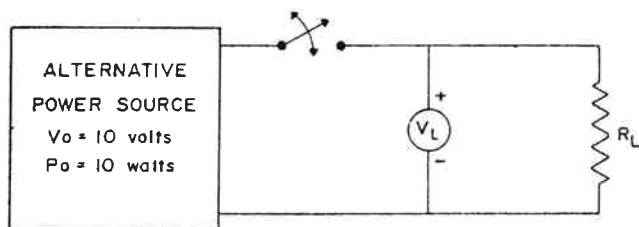
FIGURE 6 - Basic concept of switching DC power supply (DC-to-DC converter).
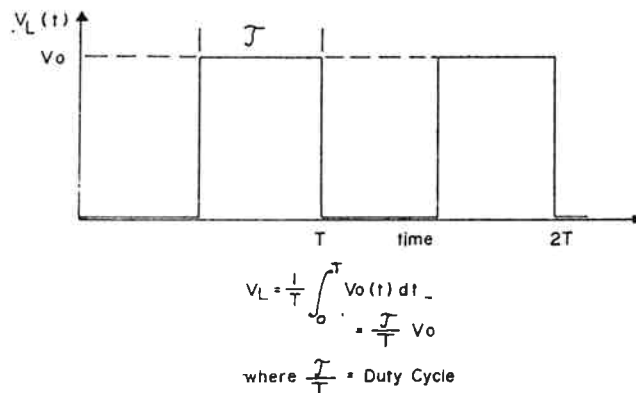

$$V_L = \frac{1}{T} \int_0^T V_0(t)\, dt = \frac{\mathcal{T}}{T} V_0$$

where $\frac{\mathcal{T}}{T}$ = Duty Cycle

FIGURE 7 - Output voltage wave form of circuit in Figure 6.

$$I_{Lx} = \frac{1}{T} \int_0^T I\,max.(t)\, dt = \frac{\mathcal{T}}{T} I\,max.$$
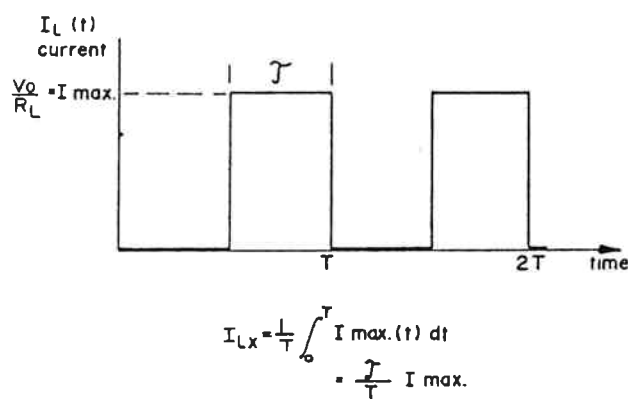
FIGURE 8 - Output current wave form of circuit in Figure 6.
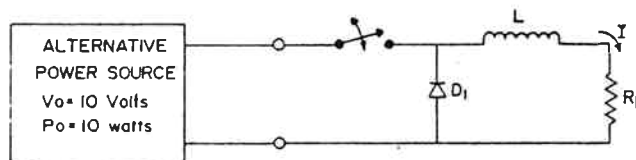
FIGURE 9 - DC-to-DC converter with filtering.
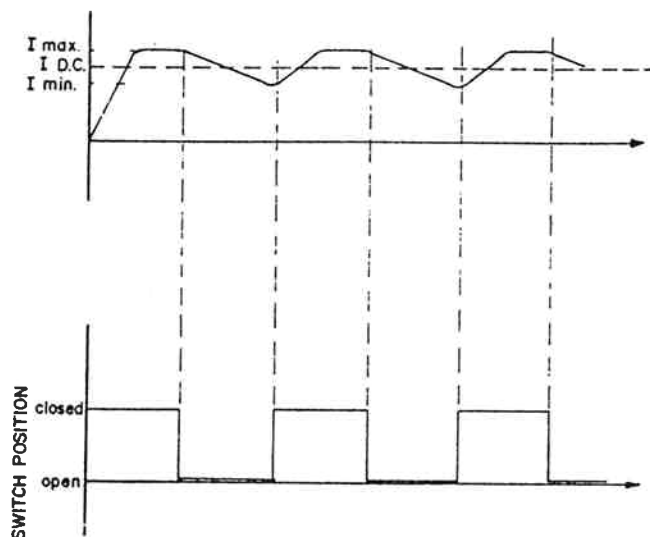
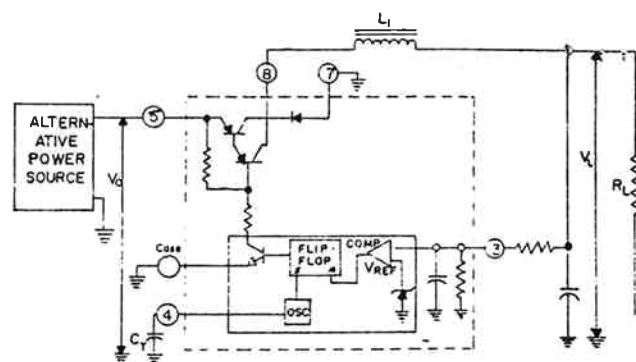FIGURE 10 - Output wave forms of circuit in Figure 9 showing effects of filtering.

FIGURE 11 - Typical DC-to-DC converter.
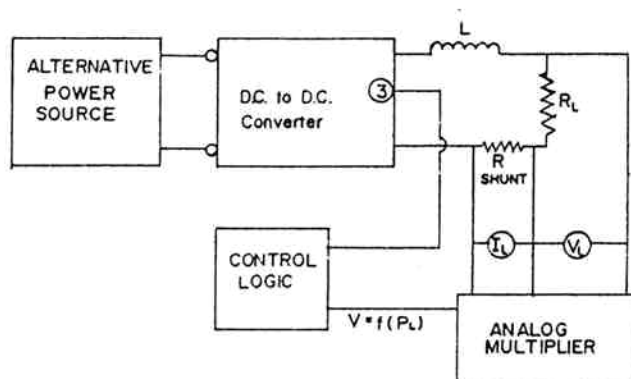
FIGURE 12 - Automatic constant power output system.

FIGURE 13 - Typical use of an alternative power source for cathodic protection c/w equivalent circuit.

$$I = \frac{V_0 - V_{ANODE} + V_{STRUCTURE}}{R_L}$$
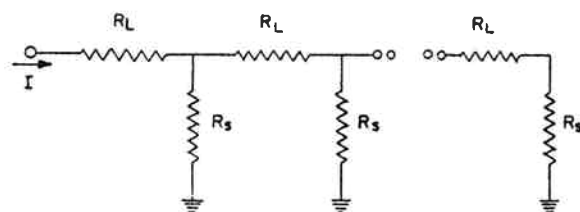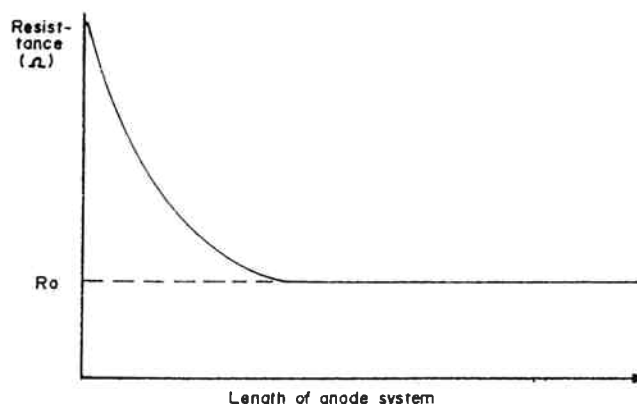

$$R_0 = \sqrt{R_s R_L}$$

FIGURE 14 - Resistance of anode array vs length.