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APPLICATIONS OF STATIC CONVERTERS IN POWER CONDITIONING

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APPLICATIONS OF STATIC CONVERTERS IN POWER CONDITIONING

Introduction

The purpose of this report is to acquaint the thermoelectric generator design groups with some of the types of static converters and how they work. In addition, information is presented showing how to figure out the approximate efficiency, weight, and volume of a unit required for a given input voltage and power handling capability. Examples are included to show how one figures the approximate efficiency, weight, and volume of a unit for specified input voltage and power handling capability using the curves of Figures 7 through 12.

Particularly pertinent are the curves on Figures 11 and 12 which show the predicted efficiency of units at various input voltages. Significantly, the curves indicate that above approximately 10 volts input voltage the efficiency of the static converters is almost constant. Below 10 volts the curves indicate the penalty in efficiency one must pay to use this type device. The curves are shown down to one volt; however, the germanium curve, Figure 12, can be extended down to approximately 50% efficiency at 0.5 volts, if particular care is taken in the converter design.

The descriptions and data presented are for conventional D.C. to A.C. converters with square wave outputs. Specific output characteristic requirements such as sinusoidal output waveshapes, restrictions on rise and fall times on the square wave outputs, synchronizing circuitry, and the like, will affect all of the approximations.

Where special characteristics are encountered the methods described should not be used. The Electronics and Instrumentation Department should be consulted to provide the

detailed circuitry design requirement and size, weight, and efficiency penalties involved due to these special requirements.

One major area of interest not treated in the report is reliability. Historically the reliability of this type unit has been good, however, how good is not accurately known. A reliability study evaluating the reliability of these devices versus the reliability of thermoelectric generators at various voltages would permit a better evaluation of the area where the use of static converters penalize the overall system reliability and the area where the system reliability is increased by their use.

The characteristics of the various circuits discussed are determined by the particular static switching elements, the transformer, and the rectifiers if used. The selections of which combination of components should be used is determined by the input voltage and power levels and the output requirements.

General Operational Description of Static Converters

Static converters are devices which change or transform a D.C. voltage level to a different A.C. or D.C. level just as transformers change one A.C. voltage level to a different one. In fact, the static converter accomplishes the voltage transformation by first converting the input D.C. to an A.C. voltage, transforming the A.C. to the new level in a transformer, and if desired, rectifying the A.C. back to D.C. at the desired level. Figure 1(a) is a block diagram showing the three essential operational blocks: the D.C. to A.C. converter, the transformer, and the rectifiers. Figure 1(b) shows a practical implementation of these three blocks. The switch is shown as a mechanical switch rather than a static switch for clarity. The switch is operated manually at a constant rate, connecting the input D.C. alternately to the two ends of the center-tapped transformer. The transformer is thus excited with an alternating voltage which in magnitude is equal to twice the input D.C. voltage. The output of the transformer is equal to the turns ratio, $\frac{N_2}{N_1}$, times the input voltage. This transformed voltage is then converted to the desired

output D.C. voltage level in the rectifier section.

It should be noted that the inclusion of a static inverter, between the thermoelectric generator and user output, permits the generator to be designed for optimum performance, essentially independent of the user load requirements except for the magnitude of the power required by the load.

Specific D.C. to D.C. Converter Circuits

The transformation and rectification functions as shown in Figure 1(b) are common to all of the static converter circuits. The physical construction of the transformer can be on a laminated core or on a toroidal tape wound core, however, the differences are relatively small in terms of operation. These differences will be discussed later. The rectifiers also affect the circuit operation only to a minor degree as will be discussed. The main differences in static converter designs is in the elements which are used for chopping the input D.C.

Figure 2 shows a basic transistorized D.C. to D.C. converter circuit. The transistors Q_1 and Q_2 are utilized as switches, being either saturated or open circuited, with their state depending on the polarity of the signal to their base terminals (b). The transformer can be either laminated or toroidal, but must have essentially a square hysteresis loop as shown on Figure 3. Some materials which display this type hysteresis loop characteristic are Hy MU80, 4-79 Permalloy, Orthonol, and 48 Alloy to name just a few. Different materials which display this general loop characteristic will have greatly different magnitudes for B_{max} and H_c . For example:

Orthonol	}	B_{max}	$\approx$	15×10^3	Gauss
Orthonik		H_c	$\approx$	0.2 oersteds	at 60 cps
Deltamax					
Hy MU80	}	B_{max}	$\approx$	7×10^3	Gauss
79 Square MU		H_c	$\approx$	0.04 oersteds	at 60 cps
Square Permalloy

Figure 1
 Functional Block Diagram
 DC to DC Converter

Figure 2
 Basic Transistorized DC
 to DC Converter Circuit

Figure 3
Typical Square Hysteresis
Loop B vs H Curve

Figure 4
 Ideal Waveshapes
 DC to DC Converter of Figure 2

The choice of the core material and construction depends upon the detailed circuit performance requirements. The effects of transformer materials and construction will be discussed further in the section on converter detailed design procedures.

The operation of the circuit of Figure 2 is as follows. Assume transistor Q_1 is "on", or short circuit, and the core flux starts at $-\phi_{max}$ (see Figure 3). Winding N_1 is connected across the power supply due to the assumed short circuit condition of Transistor Q_1 . The polarization of the transformer is such that the induced voltages are instantaneously the same at all the dots. The core flux changes in the positive direction until it reaches approximately ϕ_R (see Figure 3). During this time a voltage is induced in winding N_3 which is equal to the turns ratio $\left(\frac{N_3}{N_1}\right)$ times the applied voltage to the primary winding, V_c . This voltage through resistor R_1 provides the base current to maintain transistor Q_1 in its saturated condition. In like manner the voltage induced in winding N_4 which is equal to $\frac{N_4}{N_1}$ is applied to Transistor Q_2 through Resistor R_2 . In this case, however, the polarity is such that the transistor is held "off" or open circuited. During this interval the voltage induced in the load windings N_2 is equal to $\frac{N_2}{N_1} V_c$. Once the core flux reaches ϕ_R , an increase in core flux is accompanied by an increase in coercive current (the current required to drive the core material). This decreases the rate of change of flux and therefore, the induced voltages. As a result, Transistor Q_1 comes out of saturation, removing the applied voltage from winding N_1 . When this occurs the core flux drops to the residual level ϕ_R . This flux change, $\Delta\phi$ on Figure 3, is opposite in polarity to the flux change previously discussed. The induced voltage in windings N_3 and N_4 are opposite to their previous polarities. Transistor Q_2 has a forward bias and assumes its saturated mode while Transistor Q_1 is reverse biased and is "off" or open circuit. The input D.C. is now applied to winding N_1 and the core flux changes in the direction of $-\phi_R$. Once the flux reaches $-\phi_R$ the same action occurs as previously discussed when the flux approached $+\phi_R$. The waveshapes for the parameters discussed are shown on Figure 4. It should be pointed out that these waveforms are for ideal components (transistors, diodes, and transformer). When practical components are used the parameters depart from those of Figure 4. The amount of

Figure 5(a)

Figure 5(b)

Figure 5
 Tunnel Diode DC to DC
 Converter (Parallel)

departure is a measure of the losses in the system. These losses will be discussed in detail later since they determine the efficiency in the converter.

Other switching elements can be utilized as the switches in the circuit of Figure 2; specifically, Tunnel Diodes, silicon controlled switches, or as previously mentioned, mechanical vibrators or choppers.

Figure 5 is a schematic of a Tunnel Diode D.C. to D.C. converter. The circuit is simpler than the transistorized converter of Figure 2 in that no feedback from the transformer is required. The Tunnel Diodes operate as switches as in the transistor designs, however, the negative resistance inherent in the Tunnel Diode produces the two state switching function. The circuit operates as follows: The transformer in this circuit must have a hysteresis loop characteristic similar to that of Figure 4 as in the previous circuit. Assume that Diode D_1 has just switched to its high current state. This switching induces a voltage across the primary in such a direction as to force Diode D_2 to switch from its high state to its low state. The induced voltage across the primary windings then has a polarity that maintains the first Diode D_1 in its high state and the second Diode D_2 in its low state. This induced voltage remains until the flux in the core reaches Φ_{sat} (the transformer saturates) where the current would increase rapidly. When the flux change stops, the induced voltages collapse, causing the diodes to switch to their opposite states. They remain in this state while the core flux drops to $-\Phi_{sat}$ (the transformer saturates in the opposite direction). Unlike the transistorized circuit D.C. to D.C. converters there is no sudden large increase in current through the diodes when the core saturates because the decrease in flux rate of change switches the diodes. While the Tunnel Diode circuit is extremely simple, it suffers the disadvantage that its efficiency is quite low as compared to the transistorized circuit, this occurs as a result of the low operating (input) voltage required for the tunnel diodes, and further because the "on" to "off" voltage and current ratios are quite low. The operating voltage for germanium tunnel diodes is approximately 0.15VDC and for silicon approximately 0.4V. The diode efficiency, N_o , can be expressed by these ratios:

Figure 6

Silicon Controlled Rectifier
 Static Converter Circuit

$$N_o = \frac{(I_p - I_v)(V_v - V_p)}{(I_p + I_v)(V_r + V_p)} \quad 100$$

Voltage and current ratios for presently available Tunnel Diodes run as high as $I_p/I_v = 15$ and $V_v/V_p = 9$.

Overall circuit efficiencies run as high as 50% presently with 60 to 70% possible by use of more advanced diodes.

Another semiconductor which is used in static converters is the silicon controlled rectifier. Figure 6 is a schematic of a typical converter circuit using these devices. The output of this circuit as in the transistor and Tunnel Diode converters discussed is essentially a square wave which is rectified to obtain an output D.C. The operation is as follows: The oscillator circuit provides positive trigger pulses alternately to the gates of SCR1 and SCR2. Assume that SCR1 is conducting and SCR2 is blocking. The current from the supply, V_{in} , flows through the left hand side of the transformer T_1 ; namely, through winding N_1 . The transformer action produces a voltage of approximately $2V_{in}$ at the anode of SCR2 and across the capacitor C. When the next trigger pulse is applied to the gate of SCR2, it will turn on and the voltage at the anode of SCR2 will fall to a value equal to the forward conducting drop, 0.5 to 1.0 volt. The voltage at the anode of SCR1 will fall to approximately $-2V_{in}$ because of the action of the commutating capacitor C_1 . This capacitor will maintain a reverse bias across SCR1 long enough for SCR1 to recover to its blocking state. The next trigger pulse will occur at the gate of SCR1 and cause the circuit to revert to the original state. The inductor L_1 serves as a ballast to prevent excessive current flow during switching since during the switching interval current can flow in both halves of the transformer primary to the commutating capacitors and to the anode of the SCR which has been turned on. If the current is not limited the charging time for the commutating capacitor will be very short and the SCR which is to be turned off will not be reverse biased long enough for it to recover. Large values of L_1 on the other hand will

prevent the supply from adjusting to rapid changes in the load.

The parallel SCR inverter discussed above presents a problem with varying load conditions, for the correct amount of commutating capacity can be selected for only one load value. Under light load conditions, the reduced load current makes the waveform depart considerably from a square wave and the peak SCR voltage can rise to several times the supply voltage. This condition is accentuated if the load is reactive. By including commutating diodes across the SCR's (dotted circuitry of Figure 6) the problem can be minimized, in that the voltage across either half of the transformer is prohibited from exceeding the supply voltage. The diodes also compensate for leading or lagging power factor loads by feeding the reactive power back into the supply.

The pulse generator of Figure 6, which provides the pulses to turn "on" the SCR's alternately can be one of the previously discussed inverter circuits where the output power of the circuit is very low. The main advantage of the SCR inverter as discussed is in high power applications where the base drive to operate transistor switches becomes high. The SCR has an internal feedback which causes it to remain in the saturated state once switched there until its anode voltage is reduced below the value which produces sufficient anode current to maintain the SCR in its conducting mode.

Other devices which can be utilized in static converters are field effect transistors and silicon controlled switches. These devices can be utilized in low power inverters directly in the configuration of Figure 2, where the FET units replace the transistors. The silicon controlled switches have the disadvantage that they must be biased "on", requiring more complexity than the basic inverter circuit of Figure 2. This offsets their advantage of requiring only turn "on" and "off" pulse power and their inherent high blocking voltage capability.

Evaluation of Weight, Size, and Power Losses Associated with Power Conditioning By Means of Static Converters

The information presented in this section is based on a study by the Equipment Development Section at Westinghouse Research Laboratories. This information permits one to estimate the size, weight, and power loss associated with integrating a static converter into an electrical power system, in this case a thermoelectric generator system, for the purpose of power conditioning the output. The information is presented in graphical or tabular form for ease of manipulation. By using the procedures described it is possible to estimate the weight, volume, and efficiency of a static converter based on the input voltage level and power transferred within the limits of the assumptions made.

Power Conditioning Considerations

In the determination of this information several assumptions were made. Comments concerning the validity of these assumptions are included below. Specific assumptions made for a particular system are listed under the individual system descriptions.

1) Assumption: For semiconductor junctions the reverse leakage current is considered to be negligible with respect to the forward current capability.

Comment: This assumption will hold for relatively low voltage systems. However, when the scheme under consideration is both high voltage and low power, the reverse leakage may be an appreciable portion of the forward current. This reservation should be considered when working with systems above 500 volts at power levels below 50 watts. It should also be noted that the leakage current roughly doubles for every 10°C increase in temperature. This can also make the leakage current appreciable at elevated temperatures and should not be ignored in systems required to function in high temperature environments.

FIGURE 7 -Two diode weight vs rectified output power at several input voltages

2) Assumption: The semiconductor recovery time is negligible.

Comment: This assumption will hold for low and intermediate frequency systems.

However, when dealing with systems above 100KHZ the recovery interval may become an appreciable portion of the half-cycle period. This is especially true when considering currents above 5 amperes where the increased bulk of semiconductor (required to handle the current) requires a longer period to "sweep out" the carriers from the junction and regain a blocking mode.

3) Assumption: The forward voltage drop of a silicon junction is 0.7 volts while that of a germanium junction is 0.3 volts.

Comment: This assumption is reasonable under most conditions. However, both these figures are somewhat temperature dependent. This could lead to appreciable changes with low voltage systems at extreme temperature. A commonly accepted value for this temperature coefficient is $-2.5 \text{ mv}/^{\circ}\text{C}$.

4) Assumption: The power rating of a system is the power delivered to the load.

Comment: This standard assumption is made simply to clearly define the method of determining the power capability of a particular system.

5) Assumption: A semiconductor device can be constructed in any desired rating within the range of this analysis.

Comment: This assumption has been made to permit a smooth information transition from one device current and voltage level to another. The information, therefore, represents the parameters of devices that would be utilized if they were made exactly at the desired rating. A particular device availability at either extreme of voltage and current is unlikely. For instance, silicon transistor ratings seldom exceed 200 volts and 100 amperes. Any further increase in demands made on the device would have to be met by penalties or a change in the type of device utilized. Hence, a high voltage or high

FIGURE 8 —Two diode volume vs rectified output power at several input voltages

current transistor system might be made more attractive if the transistors are functionally replaced with thyristors. This type of substitution is generally dependent upon the specific application and design goals. Reservations which should be observed as a result of this assumption are listed below.

- a) Germanium devices are seldom rated above the following limits:

Diodes - 500 volts; 100 amps

Transistors - 100 volts; 70 amps

- b) Silicon devices are seldom rated above the following limits:

Diodes - 1200 volts; 400 amps

Transistors - 200 volts; 100 amps

Thyristors - 1200 volts; 400 amps

As a result of these limitations, it is reasonable to expect that the high voltage and/or high current areas which require an active device would be dominated by thyristors circuitry.

- 6) Assumption: The efficiency of all transformers is 94%.

Comment: This assumption is valid for most cases and is based on previous standard information and designs.

- 7) Assumption: Each semiconductor is provided with a heat sink held at constant temperature of 100°F (about 40°C).

Comment: This is a basic assumption agreed upon as one of the ground rules of the analysis. It eliminates the need for calculating the necessary heat sink. If, for a particular application, the assumption were not true, separate investigations should be conducted concerning the required cooling process.

When considering the necessary heat sink, it would be reasonable to first determine the system losses, then choose a method of cooling (forced or natural convection)

- 10A -

FIGURE 9 -Transformer specific weight vs frequency

FIGURE 10 -Transformer specific volume vs frequency

and add to the calculated system size and weight the following quantities:

Forced Convection Cooling

Weight = (Losses) (0.5 oz/watt)

Volume = (Losses) (0.1 in³/watt)

Natural Convection Cooling

Weight = (Losses) (0.5 oz/watt)

Volume = (Losses) (2 in³/watt)

If forced convection cooling is used on higher power systems, it might be possible to direct the coolants through existing spaces in the system. In this case, the additional weight and volume would be negligible.

AC to DC Conversion Considerations

Several specific assumptions were made in the analysis of AC to DC power conversion (rectification). These assumptions, with appropriate comments, are listed below.

1) Assumption: The output current is carried through one of the devices at all times.

Comment: This assumption is valid for a basic rectifying scheme using a center-tapped AC source and two rectifiers. If, for a particular application, the full wave, four rectifier approach is more attractive, then any numbers derived from the graphs depicting losses, weight, and volume of AC to DC rectification should be modified.

The choice of a two device or a four device system depends mainly upon the system configuration. In AC/DC application, if a center tapped source is available, a two device rectifier scheme would offer the most advantage. In a DC/AC application the optimum system would be where a center tapped load would permit the use of a two device inverter. In either case, if the tap is not available, a four device scheme would have to be used to perform the function. The two device or four device choice also depends, to a lesser degree, upon the voltage of the system. With a two device scheme each device must

FIGURE 11 - Silicon device power conversion percentage efficiency vs input voltage

FIGURE 12 -Germanium device power conversion percentage efficiency vs input voltage

have a rating at least twice the input voltage (from one side to center tap). Using the four device configuration, each device can be rated at the input voltage. Hence, at high voltage applications, it is sometimes advantageous to use the four device scheme because of the ratings of available components.

2) Assumption: The rectification occurs from a square wave source.

Comment: This assumption was made to permit rapid and accurate calculation of the device parameters. If sine wave inputs are assumed, the device ratings depend, to a great extent, on the type of filter used to smooth the DC voltage and/or current. The resulting device current is difficult to analyze in a direct manner without a specific circuit as a design goal. The assumption will lead to a slight deviation from the theoretical data in the information, but this deviation will remain insignificant for the majority of systems that would normally be considered.

3) Assumption: The smallest available two diode package weighs no less than 10^{-2} ounces or has a volume no less than 3.1×10^{-3} cubic inches.

Comment: This assumption is reasonable because, even if the actual semiconductor material becomes smaller than the assumed values, the fabrication and mounting procedures would probably increase the total weight and volume of the final package to these figures. In most cases, these numbers would represent such a minor fraction of the weight and volume in a complete system that further reductions would be difficult to justify. Indeed, penalties in quality, assembly, and cost might be the result of attempts to reach lower values than assumed as minimum weights.

The results of investigations concerning the weight and volume of AC to DC power conditioning apparatus are graphically displayed in Figures 7 and 8, respectively. In both cases the results are plotted as a function of system input voltage and output power.

Hence, to arrive at the weight or volume of a particular rectifier scheme

- a) Determine the required power rating.
- b) Determine the system working voltage.
- c) Use a) and b) to determine the system weight or volume from Figure 7 or 8.
- d) Multiply by any factor associated with the number of devices.

factor = 2 for 4 device single phase.

factor = 3 for 6 device three phase.

Example: Determine the weight and volume of a four device AC to DC silicon rectifier whose power capability is 100 watts and whose input voltage is 10 volts.

- a) Power = 100 watts
- b) Voltage = 10 volts
- c) Two device weight = 0.25 ounces (Figure 7)
Two device volume = 0.084 in.³ (Figure 8)
- d) Devices = 4 hence, multiply both weight and volume by 2
System Weight = (0.25) (2) = 0.5 ounces
System Volume = (0.084) (2) = 0.168 cubic inches

DC to AC Conversion Considerations

Several specific assumptions were made in the analysis of DC to AC power conversion (inversion). These assumptions with appropriate comments are listed below.

1) Assumption: The output current is carried through one of the devices at all times.

Comment: This assumption is valid for a basic inversion scheme using a center-tapped load and two devices. If, for a particular application, a single phase bridge (4 devices) or a three phase bridge (6 devices) is used, any numbers derived from the graphs depicting losses, weight, and volume of DC to AC inversion should be modified.

2) Assumption: The inversion results in a square wave output.

Comment: Since efficiency is one of the major goals of the investigations, and device switching is the most efficient process of power control, square wave outputs will result from the most efficient DC to AC conversion process.

3) Assumption: The switching device weight and volume is approximately one and one-half times the weight and volume of a diode of comparable rating.

Comment: This assumption is valid for the majority of controlled semiconductors used in power conversion apparatus. This would include transistors, thyristors, unijunction transistors, field effect transistors, etc. The assumption is based on comparison of existing devices and on the practical considerations that a switching device generally has half again as much semiconductor bulk, and at least one more junction, than a diode.

Hence, to arrive at the weight or volume of a particular inversion scheme

- a) Determine the required power rating.
- b) Determine the system working voltage.
- c) Use a) and b) to determine the two diode weight and volume from Figures 7 and 8.
- d) Multiply the result of 3 by 1.5 to get the weight and volume of a two device inversion scheme.
- e) Multiply by the factor associated with the number of devices.

factor = 2 for 4 device single phase bridge.

factor = 3 for 6 device three phase bridge.

Example: Determine the weight and volume of a four device DC to AC silicon inverter whose power capability is 100 watts and whose input voltage is 10 volts.

- a) Power = 100 watts
- b) Voltage = 10 volts
- c) Two Diode Weight = 0.25 ounces
Two Diode Volume = 0.084 cubic inches
- d) Two Device Weight = $(0.25) (1.5) = 0.375$ ounces
Two Device Volume = $(0.084) (1.5) = 0.126$ cubic inches

e) Devices = 4 hence multiply both weight and cubic volume by 2

System Weight = $(0.375) (2) = 0.75$ ounces

System Volume = $(0.126) (2) = 0.252$ cubic inches

Transformer Considerations

Two major assumptions were made in the analysis of transformer parameters. These assumptions, with appropriate comments, are listed below.

1) Assumption: All transformers under consideration have ferro-magnetic cores.

Comment: In the transformer considerations, air core unit parameters were calculated. Since the information indicated that the air core transformers offered no advantage at frequencies below a megahertz (especially in the volume considerations), their use as a circuit component was not further considered.

2) Assumption: At a given frequency there is a specific relationship between the power rating of the transformer and its weight and size.

Comment: This assumption is valid over a small range of power levels. Since the investigations were performed from 5 va to 150 va the assumption will produce very little error.

No assumptions were made concerning the use of transformers; as a consequence, the information may be regarded as having very few additional reservations if the transformers are used in a conventional manner.

The information resulting from the transformer investigation is shown graphically in Figures 9 and 10. These figures represent the per unit weight and volume of a transformer at various frequencies.

Hence, to determine the weight or volume of a transformer

- a) Determine the working frequency.
- b) Determine the desired power level.
- c) Use a) to determine the per unit parameters for the transformer from Figures 9 or 10.

- d) Use b) and c) to determine the parameter of the desired transformer by multiplying the desired power level times the appropriate per unit value.

Example: Determine the weight and volume of a 50 va transformer at a working frequency of 10KHZ.

- a) Frequency = 10KHZ
- b) Power = 50 va
- c) $\text{Weight/va} = 0.0075 \text{ lbs/va}$
 $\text{Volume/va} = 0.062 \text{ in}^3/\text{va}$
- d) xfmr weight = $(50) (0.0075) = 0.375 \text{ lb}$
xfmr volume = $(50) (0.062) = 3.1 \text{ cubic inches}$

Efficiency Considerations

The results of the investigations concerning the efficiency of various power conditioning schemes are graphically displayed in Figures 11 and 12.

Figure 11 indicates first, the conversion efficiency of silicon devices in DC to AC configurations; and, second, the conversion efficiency of silicon devices in AC to DC configurations.

Figure 12 is similar to Figure 11 except the semiconductor material used for the device construction is germanium instead of silicon. It should be noted that above approximately 10 volts the efficiencies of silicon and germanium are very nearly the same. It is for this reason that the weight and volume are based on the use of silicon devices since they are more prominent in the semiconductor field (generally because of their increased temperature and voltage capability). This change does not represent any significant error since the weight and volume of a germanium device would be very nearly the same as a silicon device of the same rating.

Hence, to arrive at the efficiency of a particular system

- a) Determine the system working voltage.
- b) Determine the system working mode (dc/dc or dc/ac).
- c) Use a) and b) to determine the system efficiency from Figures 11 and 12.
- d) Multiply by any factor associated with the number of devices.
- e) Multiply by 0.94 if a transformer is to be included in the system.

System Considerations

1. Dual Conversion

For DC to AC or DC to DC conversion both the rectifying and inversion processes are generally used. In the case of DC to AC conversion the power must only be inverted to AC at the desired frequency and voltage level. In the case of DC to DC conversion the power must first be inverted to an intermediate frequency and voltage level then, rectified to produce the desired output level. Since the power, in either of the dual conversion processes, is handled by two of the methods previously described, the determination of the size and weight will be a combination of all the previous information.

Of major importance in the dual conversion scheme is the operating frequencies of the transformer.

The optimum frequency will be determined by the individual system and can be chosen to minimize the size and weight of the transformer. Semiconductor size and weight can generally be minimized by higher voltages and lower currents while the transformer weight and volume will be reduced (at a given power level) where the working frequency is highest.

Hence, to determine the parameters of a dual conversion scheme

- a) Determine the power level.
- b) Determine the input and output voltage and frequency requirements.

- c) Determine the optimum frequency for the transformer.
- d) Separate and calculate the parameters of the DC to AC operation.
- e) Separate and calculate the parameters of the AC to DC operation.
- f) Determine the parameters of the transformer involved.
- g) Combine the results (by addition) of d), e), and f) to arrive at the parameters of the dual conversion system.
- h) Determine the efficiency of the overall scheme by using the dual conversion curve of Figure 11 or the separate values if the voltages are different. Include 94% efficiency of the transformer.

Example: Determine the weight, volume and efficiency of a DC to DC power conditioning scheme with 50 watt capability. The input voltage will be 10 volts and the output should be 24 volts DC.

- a) Power = 50 watts
- b) Input = 10 volts DC
Output = 24 volts DC
- c) Transformer frequency should be as high as possible to minimize weight and size, consistent with switching speed of the transistor switches. Use 10KHZ as operating frequency.
- d) DC to AC operation

$$\begin{aligned}\text{Input power} &= \text{output req}/\text{overall efficiency} \\ &= 50/84.25 = 59.5\end{aligned}$$

since DC to AC eff. at 10V = 92, AC to DC at 24 volts eff. = 97%, and transformer eff. = 94%

$$92.5 \times 97 \times 94 = 84.25\%$$

voltage = 10 volts

weight = 0.065 ounces (from Figure 7) $\times$ 1.5 = 0.0975 ounces

volume = 0.0235 cubic inches (from Figure 8) $\times$ 1.5 = 0.3525 cubic inches

e) Transformer

$$\text{frequency} = 10\text{KHZ}$$

$$\text{power} = 52 \times 0.94 = 49.0 \text{ watts}$$

since AC to DC rectifier 98% efficient at 20 volts

$$\text{weight} = (49.0) (0.0075) = 0.368 \text{ pounds}$$

$$\text{volume} = (49.0) (0.062) = 3.04 \text{ cubic inches}$$

f) AC to DC operation

$$\text{power} = 50 \text{ watts}$$

$$\text{voltage} = 24 \text{ volts}$$

$$\text{weight} = 0.06 \text{ ounces}$$

$$\text{volume} = 0.022 \text{ cubic inches}$$

g) System Volume

$$\text{xfmr} = 3.04 \text{ in}^3$$

$$\text{AC/DC} = 0.022$$

$$\text{DC/AC} = 0.03525$$

$$\text{Total} \quad \underline{\quad\quad\quad} 3.09 \text{ in}^3$$

System Weight

$$\text{xfmr} = 5.89 \text{ ounces}$$

$$\text{AC/DC} = 0.06$$

$$\text{DC/AC} = 0.0975$$

$$\text{Total} \quad \underline{\quad\quad\quad} 6.05 \text{ ounces}$$

h) DC to AC efficiency = 92%

$$\text{transformer efficiency} = 94\%$$

$$\text{AC to DC efficiency} = 97\%$$

$$\text{system efficiency} = 92 \times 94 \times 97 = 84.25\%$$

2. Control Functions

In most of the power conversion circuitry where active devices are a functional necessity a certain amount of control circuitry is mandatory. This is especially true if a particular power circuit is to be controlled over a range of voltage, current or frequency. Although the amount of control circuitry depends upon the complexity of control desired,

the size and weight should be approximately an order of magnitude below that of the power circuit. Hence, if a proposed circuit is to contain a reasonable amount of control, it would be acceptable to increase the size and weight of the basic power circuit by 10 to 15% to include this auxiliary control.

3. Waveshaping

In instances where a square wave output is obtained from an inverter, it is sometimes desirable to alter the waveshape such that the result is more representative of a sine wave. The waveshaping components generally are in the form of a reactive element so that a reasonable system efficiency is maintained. In the most commonly used circuit the waveshaping is in the form of a series L-C circuit resonant at the fundamental frequency. The weight and volume of a filter to reduce a square wave to a 5% distortion sine wave would be approximately 2.5 times the size of a transformer that handles an equivalent amount of output power.

4. Reactive Loading

In systems, especially DC/AC systems, where the load can be reactive, it is necessary to construct circuitry that permits reverse current flow through the apparatus. Most commonly this capability takes the form of reverse current diodes. Each power switching device is shunted, in the reverse direction, by one of these diodes. The volt-amp capability of the system remains unchanged but the power rating of the DC/AC circuit is reduced due to this reactive loading.

Design Factors and Considerations of DC to DC Static Converter

In designing a solid state DC to DC or DC to AC converter there are a number of factors to be considered, and depending on the design criteria, the importance of certain factors may influence the design. All static inverters can be resolved into the simple

circuit of Figure 2 where the semiconductor switches may be any of the devices previously discussed. The energy required to operate the semiconductors as switches is supplied by the feedback from the windings N_3 and N_4 to the bases of the transistors (Figure 2) or by the inherent bistable characteristic of the tunnel diodes (Figure 5) or by an external pulse generator with SCR's (Figure 6). Other semiconductors which could be utilized as the switches would use one of these three methods of powering the devices. The iron core of the transformer is utilized fully in that the flux is driven to positive and negative saturation on alternate half cycles and induces in all windings an alternating square wave voltage. This square wave may be delivered directly to the load or rectified to DC at a voltage higher or lower than the source voltage depending on the turns ratio and circuit losses according to the following equation:

$$V_{\text{sec}} = \frac{N_1}{N_2} (V_{\text{in}} - R_{\text{equiv.}} I_p)$$

where $R_{\text{equiv.}}$ is the sum of the primary resistance (transformer wire resistance and transistor saturated impedance), and the resistance in each of the secondary windings reflected to the primary through the turns ratio squared. The voltage spike on the leading edge of each half cycle (see Figure 4) is produced by the inductive kickback of a switch opening an inductive circuit, in this case the transistor turning off. This voltage pulse generated by one switch opening is the means by which the other switch is turned on, hence serves a useful purpose. If the pulse is too high, however, there is danger of damage to the switches. For this reason it is desirable to use magnetic materials in the transformer which have a rectangular hysteresis loop such that at saturation the windings exhibit low inductance and little induced kickback. Studies on semiconductor failures found in DC to DC converters indicate that most, if not all, failures are not attributed to "wear out." Rather, it appears that failures can occur due to design problems in the circuit. Specifically two types of secondary breakdown failures have been found. One is a result of high

collector currents, and the other due to high voltage in the collector base junction.

Semiconductor Switch Selection

The semiconductor switches, when employed in circuits similar to that of Figure 2, must be selected to withstand at least twice the maximum input voltage. When one transistor is on, the transistor which is off must block the input voltage, plus the induced input voltage in the primary winding, plus transient spikes (which can be as high or higher than source voltage). Transient voltage suppression circuits may be employed across the transistors to eliminate excessive voltage transients, but in any event the maximum voltage ratings for the switches must be selected to be higher than twice the maximum input voltage.

The exact limits of safe operation of semiconductor switches are sometimes not too easily determined, particularly when the transistor is operated outside its class A power rating (Extending Power Transistor Safe Areas for Fast Switching Pulses, R. Greenburg, Motorola Applications Engineering Report No. 87, December, 1962). The appropriateness of the design should be checked once the unit has been constructed by making a V vs. I plot on the switch. This can easily be done by displaying collector emitter voltage vs. collector current on an oscilloscope and observing the transient characteristics.

The transistor switch frequency cut-off characteristic must be selected to be high as compared to the actual switching frequency. If the transistor cannot switch rapidly between the states of saturation and cut-off, excessive junction heating will occur and, as a result, conversion efficiency will be low. A general rule of thumb which is sometimes applied is to use a transistor whose frequency cut-off is ten times the operating frequency. Actual rise time requirements of the output may modify the selection of the transistor in this respect.

The transistor used should have as high gain as possible particularly if the converter efficiency is to be maximized. The power consumed in operating the switches must be

obtained from the source through the transformer. It is necessary to provide current limiting resistors in the base circuits, but the I^2R losses in this resistance should be small to achieve high efficiencies. Hence, the N_1/N_3 and N_1/N_4 ratios should be as high as possible, yet N_3 and N_4 adequate to provide sufficient voltage and current to saturate the transistors at high collector currents.

The basic materials used in the manufacture of transistors are the semiconductor materials which lie between the metals and insulators in their ability to conduct electricity. The two semiconductors now being used are germanium and silicon. The maximum operating junction temperature on germanium is 85°C to 100°C whereas the maximum operating junction temperature on silicon is 175°C to 200°C depending on the type units. In any application it is vital to consider the temperature which the unit will operate in. While static converters utilize the transistors as switches and, therefore, avoid the problem of changes in operating point as a result of temperature variations, still the maximum operating junction temperature must be observed. Forced or natural convection cooling may be utilized by putting the transistors on properly designed heat sinks and the like. The majority of static converter designs will utilize silicon devices as a result of the above-mentioned higher temperature characteristics and in addition the inherent advantage of higher blocking voltage capabilities inherent in silicon. On the other hand at very low voltages the low forward voltage drop of germanium makes them attractive in this class of applications.

Magnetic Core Selections

The choice of core material for a given converter design can be simplified by considering only two different kinds of material. These two materials are:

- a) 50% N_i - Fe, grain oriented such as orthonol
- b) 79% N_i - Fe, such as Permalloy 80

Orthonol has a high maximum flux density with low losses, whereas Permalloy 80 has about 0.5 the maximum flux density of Orthonol, but has much lower losses, in fact, only one-tenth the losses of Orthonol. This means that in most power applications where a given voltage and frequency are required, the best choice is Orthonol. By choosing the higher flux density material, less iron and copper are required, hence maximum miniaturization and high efficiency are obtained. The efficiency is high because the core losses are small compared to the output power which may be many watts. It is interesting to note that high efficiencies can be attained at high audio frequencies because as the frequency is increased, the core size is decreased, hence the increased core loss density is offset by the reduction in core volume as the frequency goes up.

On the other hand, when the converter design calls for a voltage at low power levels such as DC supply for photo tubes and Gieger tubes where high efficiencies are desired under light load conditions, Permalloy 80 should be selected.

Usually such equipment is designed for portable use where it is desired to have high efficiencies at light loads to conserve battery power. For this type of application, core losses may be greater than the power delivered to the load unless cores having extremely low losses are used, hence the choice of a core material should be that material which has the lowest losses.

The effects of windings on circuit characteristics should be appreciated by the converter designer both for the case of too few windings and excessive windings. An appreciation of this can direct the designer to the selection of an appropriate core size for a particular application.

Switching is initiated by core saturation. The change in impedance of the core from the unsaturated state to its saturated state produces a rapid turn off of the transistor. Thus, for proper operation there must be a significant change in the core impedance as it proceeds into saturation. For this reason, there must be sufficient number of turns on the core to produce this change in impedance. The primary windings N_1 should be ten turns or

greater and N_2 should be five turns or greater to insure proper operation of the circuit. An excessive number of turns on the core can result in an apparent increase in magnetizing current due to interwinding capacitance. Winding capacitance is further evidenced by ringing or spurious oscillations produced when the core is excited with a square wave input. Some of this effect can be reduced by progressive sector winding, but it is best to limit windings to a maximum of about 2,500 turns. An optimum design, to give a minimum cost of core and winding, based on keeping output turns below 2,500 can result in an economical and efficient unit.

When a simple DC to DC conversion is the object of the converter designer and there are no specifications for the operating frequency, the designer has a choice as to which size core to choose. Where power conversion is to be made, the load current dictates the size of the wire in the output windings. The supply voltage is usually a fixed value so the turns ratio may be established between primary and secondary.

$$\text{Thus, } N_S/N_P = V_{\text{out}}/V_{\text{supply}}$$

The size of the primary windings may then be found by determining the primary current.

$$\text{Thus, } I_{\text{primary}} = N_S/N_P I_{\text{load}}$$

If either N_P or N_S can be established, then the total cross section of all windings can be found, thus establishing the window area (the required hole size in the toroid) of the cores.

The total flux capacity (Φ_t) of the core may be determined as follows:

Using 1/10 the frequency rating of the transistor as the operating frequency, and knowing the supply voltage, the core flux Φ_t may be determined from $V = 2\Phi_t N_1 f \times 10^{-8}$

$$\text{Thus, } \Phi_t = \frac{V}{2N_1 \times f \times 10^{-8}} \quad \Phi_t = 2 B_m \times A_c$$

where: V = supply voltage in volts
 f = frequency in HZ
 B_m = flux density of core in Gauss
 A_c = effective core cross sectional area in cm^2

For first approximation, use 10 turns for N_1 . If upon calculating Φ_t , a core is not available which has the required flux capacity a new calculation should be made using a lower frequency or a smaller cross section core. Notice that the core flux will vary inversely with frequency and turns.

Usually in power converter design, the frequency of the transistor will dictate the maximum frequency of oscillation since the operating frequency of the converter should be 1/10 the frequency rating of the transistor, as mentioned previously in the section on transistor selection.

Steps used to select core size, turns, and wire size for converter, inverter design:

1) The input voltage, the output power and voltage must be known. The switching frequency or the output frequency of the inverter must also be known or determined from the transistor ratings.

2) Assume a minimum efficiency of 80% and calculate the input power and the input or primary current.

3) Select the wire size for the secondary (N_s) using a 100% duty factor and the wire size for the primary (N_p) using a 50% duty factor.

4) Determine the $W_a \Phi_t$ product required from the formula:

$$W_a \Phi_t = \frac{V A_w}{2Kf \times 10^{-8}}$$

where: W_a = Case window area in circular mils

ϕ_t = Total core flux in maxwells

V = Applied voltage in volts

A_w = Wire area in circular mils

f = Switching frequency

K = Winding factor (In power converters assume 1/2 of the available winding area is used for both primary windings. Since the primary turns (N_p) are the turns on one side of a center-tapped winding, then K equals 1/4 of the nominal winding factor of 0.4. Therefore, $K = 0.1$)

5) Select a core from the Core Data Section with a $W_a \phi_t$ product closest to the value calculated in Step 4). The core $W_a \phi_t$ product can be determined from the formula:

$$W_a \phi_t = W_a \times 2 \times B_m \times A_c$$

Where: B_m = Flux density of core material

A_c = Effective core cross sectional area

W_a = Case window area

In selecting the thickness of core material use .004" or .006" thickness for designs operating below 100HZ. Use .002" thickness below 2,000HZ, .001" thickness below 4,000HZ. Ultra thin materials such as .0005" thickness can be used up to 20KHZ while .00025" thickness can be used to 75KHZ. Above 75KHZ, .000125" thick material is suggested.

6) Solve for N_p from the formula:

$$N_p = \frac{V}{2\phi_t f \times 10^{-8}}$$

7) Determine the secondary turns:

$$N_s = \frac{N_p V_{out}}{V_{in}}$$

8) Feedback turns N_f should apply at least one volt to drive the bases of the transistors.

$$N_f = \frac{N_p \times 1}{V_{in}}$$

If N_f is less than five turns from above formula, use five turns for N_f .

Wire size for N_f is determined from the transistor characteristics. Current flowing in feedback winding $I_f = \frac{I_c}{P}$. Refer to wire table for wire size.

9) Check if core case will accommodate windings from formula.

$$K = \frac{(2N_p A_{w1}) + (N_s A_{w2}) + (N_f A_{w3})}{W_a}$$

K should be between 0.3 and 0.4. It is the stacking or winding factor for the wire vs. window area inside of the core, based on toroidel winding machine winding.

10) If core case is too small select a size larger and repeat the calculations until the windings can be put on the core with a stacking factor of less than 0.4.

Wire Data

Sizes, Areas, Resistance and Current Capacities for Synthetic Film Insulated Wire

<u>Wire Area (Max.) * (Circular mils)</u>					
AWG	Heavy	Triple	Quad	Ohms/1000	Current (MA) Capacity **
8	18,010	18,360	18,960	.6281	16,510
9	14,350	14,670	15,200	.7925	13,090
10	11,470	11,750	12,230	.9987	10,380
11	9,158	9,390	9,821	1.261	8,226
12	7,310	7,517	7,885	1.588	6,529
13	5,852	6,022	6,336	2.001	5,184
14	4,679	4,830	5,112	2.524	4,109
15	3,758	3,894	4,147	3.181	3,260
16	3,003	3,114	3,329	4.020	2,581
17	2,421	2,520	2,704	5.054	2,052
18	1,936	2,025	2,190	6.386	1,624
19	1,560	1,632	1,781	8.046	1,289
20	1,246	1,310	1,436	10.13	1,024
21	1,005	1,063	1,170	12.77	8,123
22	807	853	949	16.20	640.1
23	650	692	778	20.30	510.8
24	524	562	635	25.67	404.0
25	424	458	520	32.37	320.4
26	342	369	424	41.02	252.8
27	272	296	342	51.44	201.6
28	219	240	276	65.31	158.8
29	180	199	231	81.21	127.7
30	144	161	188	103.7	100.0
31	117	132	154	130.9	79.21
32	96.0	110	128	162.0	64.00
33	77.4	90.2	104	205.7	50.41
34	60.8	70.6	82.8	261.3	39.69
35	49.0	57.8	67.2	330.7	31.36
36	39.7	47.6	54.8	414.8	25.00
37	32.5	38.4	44.9	512.1	20.25
38	26.0	31.4	36.0	648.2	16.00
39	20.2	25.0	28.1	846.6	12.25
40	16.0	19.4	22.1	1079.6	9.61
41	13.0	16.0		1323.	7.85
42	10.2	13.0		1659.	6.25
43	8.4	10.2		2143.	4.84
44	7.3	9.0		2593.	4.00

* Areas are for maximum wire area plus maximum insulation build up.
 ** Based on 1000 circular mils/amp current capacity will vary according to the geometry of the unit and may range from 750 to 1200 circular mils/amp.