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SOME RELIABILITY/EFFICIENCY ASPECTS OF LOW INPUT VOLTAGE INVERSION/CONVERSION FROM RADIOISOTOPIC THERMOELECTRIC GENERATOR POWER SOURCES

BY

EDWARD R. PASCIUTTI

FEBRUARY 1967

GODDARD SPACE FLIGHT CENTER

GREENBELT, MARYLAND

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ABSTRACT

This report presents the solutions obtained to some of the component and circuit problems investigated in the area of low-input-voltage conversion and regulation (LIVCR) from radioisotopic thermoelectric generator (RTG) sources. The overload handling capability of the current feedback (IFB) driven inverter allows implementation of a functionally-integrated RTG source/IFB inverter protection technique for use with the inherently power-limited RTG sources. The method results in a reduction of size and weight and of heat rejection radiator requirements.

High reliability and high power levels can be obtained by the use of multiple-source/multiple-converter module parallel combined configurations. Continued reduced level operation is enabled in the event of degraded source power output or of component failure. Two synchronized parallel combined voltage step-up converters designed for use with SNAP-19 RTG sources demonstrate the functionally-integrated source/conversion protection technique developed. Circuit simplicity is achieved and reliable source/converter protection for all output loading conditions automatically established.

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CONTENTS

		Page
I.	INTRODUCTION	1
II.	COMPONENTS	1
	A. Low Voltage (LV), High Current Transistor Switching Elements	1
	B. Influence of the Power Source Voltage/Current (V/I) Characteristics on Transistor Switching Voltage/Power Stress Conditions	2
	C. Parallel Transistor Operation	8
	D. Switching and Switchover Overlap Losses	8
	E. Abnormal Magnetic Saturations	9
	F. Lead Inductance and Transformer Leakage Reactance	10
III.	DC TO SQUARE WAVE AC INVERSION	11
	A. The Current Feedback Driven Push-Pull Oscillator Inverter	11
	B. The Current Feedback Driven Push-Pull Oscillator Inverter With Voltage Feedback Controlled Switching	14
IV.	POWER SYSTEMS USING THE RTG SOURCE	16
	A. Efficiency and Open-Load Problems of RTG Sources	16
	B. LIV Conversion With the RTG Source	17
	C. A New Approach to RTG-Source/LIV-Converter Protection for Abnormal Loading	19
	D. Output Voltage Regulation and Maximum Utilization of Available Source Power/Energy	20
V.	INCREASED RELIABILITY	22
	A. Multiple-Source/Multiple-Converter Configurations	22
	B. Synchronization	23
VI.	HYBRID-PRIMARY-SOURCE POWER	24
	A. Nimbus B Satellite	24
	B. LIV Converter Development for Use With the SNAP-19 RTG's	25
VII.	CONCLUSIONS	30
VIII.	REFERENCES	30

ILLUSTRATIONS

Figure		Page
1	RTG Output Voltage/Current (V/I) Characteristic Simulation	3
2	Simulated RTG Source Energizing a Push-Pull Inverter Transformer-Coupled Output Stage	3
3	Typical Transitions of RTG Source Output (v_o/i_o) During Inverter Switching Intervals	4
4	Extended Transistor Characteristics	5
5	Transistor Operating Regions	6
6a	MHT 2205, Reverse Voltage Bias Characteristic Room Temperature	7
6b	MHT 2205, Reverse Voltage Bias Characteristic 70°C	7
7a	MHT 2212, Reverse Voltage Bias Characteristic Room Temperature	7
7b	MHT 2212, Reverse Voltage Bias Characteristic 70°C	7
8	Switchover Overlap Condition of Separately Excited Voltage Driven Inverter Push-Pull Output Stage	9
9	Orthonol-Unbalanced Core Flux Operation and Resulting Primary Currents	10
10	Power Transformer Core Saturation One Side of B/H Loop in a Current Feedback Driven Push-Pull Oscillator Inverter .	11
11	Supermalloy-Balanced Core Flux Operation	12
12	Current-Feedback, Push-Pull, Oscillator-Inverter	13
13	Current-Feedback, Drive Push-Pull Oscillator-Inverter With Voltage Controlled Switchover	15

Figure		Page
14	Dissipative Shunt Regulator RTG Light or Open Load Protection	17
15	LIV Conversion With RTG Source	18
16	RTG Over-Voltage Protection Circuit	19
17	Voltage Clamping of RTG Over-Voltage Protection Circuit . . .	21
18	Output Load Voltage Regulation Technique	22
19	Assumed Degradation of RTG Source Output Power	23
20	Multiple-Source/Multiple-Converter Configuration	24
21	Block Diagram GSFC Developed Converter for Use With SNAP-19 RTG Source	26
22	Schematic Diagram of GSFC Developed Converter for Use With SNAP-19 RTG Source	27
23	GSFC Developed Synchronized Dual LIV Converter Breadboard	29

SOME RELIABILITY/EFFICIENCY ASPECTS
OF LOW INPUT VOLTAGE INVERSION/CONVERSION FROM
RADIOISOTOPIC THERMOELECTRIC GENERATOR POWER SOURCES

I. INTRODUCTION

The development of reliable and efficient radioisotopic fueled thermoelectric generators (RTG's) of appropriate power levels has advanced to the state of allowing their use as power sources in satellite and spacecraft power supply systems applications where reliable long-lifetime operation is required. To raise the inherently low DC voltage outputs of these unconventional power sources, it is necessary to develop reliable, efficient and lightweight voltage step-up low-input-voltage conversion and regulation (LIVCR) techniques. To provide solutions in the major problem areas, studies and experimental investigations, are in progress at Goddard Space Flight Center (GSFC). This report presents the major results of this work pertaining to the voltage transformation/regulation and power/energy utilization from RTG sources.

II. COMPONENTS

A. Low Voltage (LV), High Current Transistor Switching Elements

An approximation to the efficiency of a transistor as a switching element is:

$$\text{Efficiency} \approx 1 - \frac{V_{CE}\,(\text{sat})}{V_{\text{Source}}} \tag{1}$$

High speed, low loss, transistor switching elements with switching efficiencies in excess of 90% are required. Silicon transistors have speed and temperature advantages. At high current levels, silicon units do not have low enough V_{CE} (sat) voltages for efficient operation as switching devices at source voltages below three (3) volts. In the source voltage range of 0.5 to 3.0 volts, the most suitable presently available transistor switching element is the highly doped germanium alloy transistor. Several manufacturers have achieved considerable success in developing very low-loss germanium alloy transistors specifically for low-voltage, high-current switching operation.

In a transistor specifically designed for low voltage operation, to achieve high efficiency, it is necessary that it have low internal resistance during the conduction interval. It would be subjected to low inverse voltages during the off-interval, and could tolerate moderate amounts of leakage current. The use of special alloying techniques, and materials with very high doping densities, have produced emitter-collector junctions with very high injection efficiencies. Also, base resistances and base drive power requirements have been lowered. Generally, these efforts have produced power switching transistors for low input voltage operation with low V_{BE} (sat) and V_{CE} (sat) voltages, enabling switching efficiencies in excess of 90% (Reference 1) at source voltages of 1 volt and power levels of 25 watts per transistor. However, the switching speeds of these very low V_{CE} (sat) and V_{BE} (sat) germanium power transistors restrict the efficient upper operating frequencies of push-pull inverters using such units to the 2000-3000 cps range. High frequency of operation enables reduction in the size and weight of inverter/converter components.

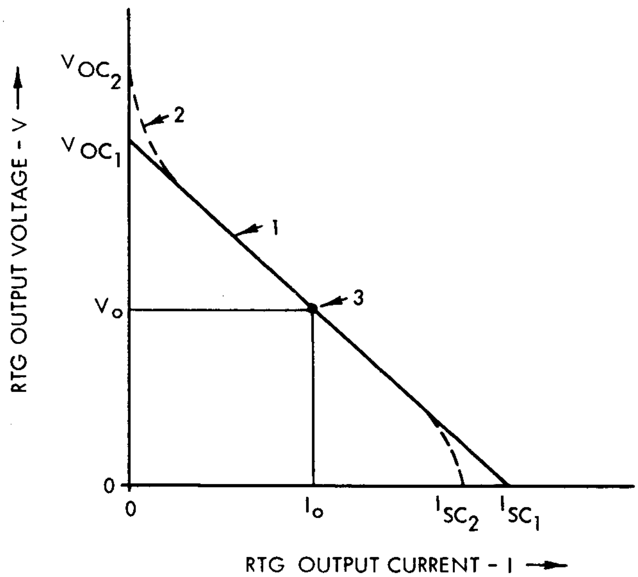
B. Influence of the Power Source Voltage/Current (V/I) Characteristic on Transistor Switching Voltage/Power Stress Conditions

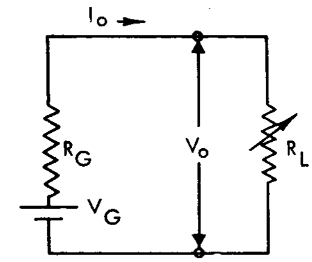
The design emphasis to produce efficient LV transistors has primarily been to minimize the conduction voltage drop V_{CE} (sat). When restricted to rated source voltages and suitable base driving conditions, these transistors can be efficiently and reliably used. Transistor use with poorly regulated sources energizing push-pull transformer coupled power output stages necessitates evaluation to establish efficient and reliable component and circuit operation. It is particularly necessary to study the switching-off and off conditions of transistors, since these become important and seriously affect the reliability and efficiency of the inverter switching operation.

In conversion from RTG sources where the loading range extremes of open to short circuit output loading are considered, the transistor V_{CE} (max) rating must be high enough, under worst case conditions, to assure reliable operation over the range of RTG V/I output characteristics. RTG V/I characteristics are typically illustrated in Figure 1. V_o/I_o is a matched load maximum power output operating condition. R_L is an assumed transformer reflected output load resistance of a push-pull inverter stage, such as shown in Figure 2. Switches SW_1 and SW_2 simulate the base drive controlled emitter-to-collector switching action of the power transistors. These switches open and close alternately. The off-transistor of the push-pull inverter (SW_1 of Figure 2) is subjected to collector-to-emitter voltages of

$$V_{CE}\,(\text{off transistor}) \approx 2V_o \qquad (2)$$

where V_o is the function of loading given by the V/I characteristics of Figure 1. The response time of the thermoelectric generator output voltage is rapid for these considerations and any momentary unloading or loading of the source, for





$V_o = V_G - I_oR_G$

V_{OC} = OPEN-LOAD OUTPUT VOLTAGE

I_{SC} = SHORT CIRCUIT LOAD OUTPUT CURRENT

1 - ASSUMED LINEAR RESISTANCE RTG IMPEDENCE (R_G) SIMULATION

2 - TYPICAL RTG V/I CHARACTERISTIC

3 - MATCHED-LOAD, MAXIMUM-POWER-OUTPUT CONDITION ($R_L = R_G$)

Figure 1. RTG Output Voltage/Current (V/I) Characteristic Simulation.

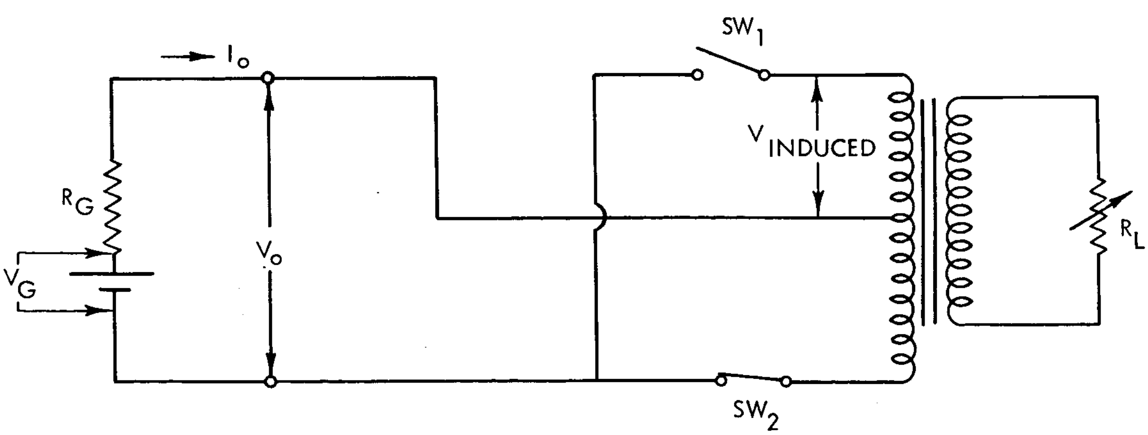


Figure 2. Simulated RTG Source Energizing a Push-Pull Inverter Transformer-Coupled Output Stage.

example, during the switchover interval of the inverter, results in rapid deviations of the instantaneous output voltage (v_o) from the output load related average output voltage value (V_o). Figure 3 illustrates a typical range of voltage/current deviations at the input terminals of the inverter or converter. The illustrated conditions of Figure 3 can result from numerous causes, such as: transistor rise, fall and storage time characteristics; normal functioning of the transistor base drive circuit design; or possible abnormal magnetic saturation effects. These additional transient loading related effects causing deviations of the RTG source output voltage can extend the inverter off-transistor V_{CE} (max) voltage stress condition to

$$V_{CE}\,(\max) \;\approx\; 2\,v_o\,(\max) \tag{3}$$

There is, in addition, stored energy spiking resulting from inductive connections or of transformer leakage reactance which must be eliminated through improved component design or otherwise included into the maximum voltage/power stress requirements of the transistor.

Figure 4 illustrates some extended transistor characteristics showing for the switching-off transistor possible operating conditions of high transient

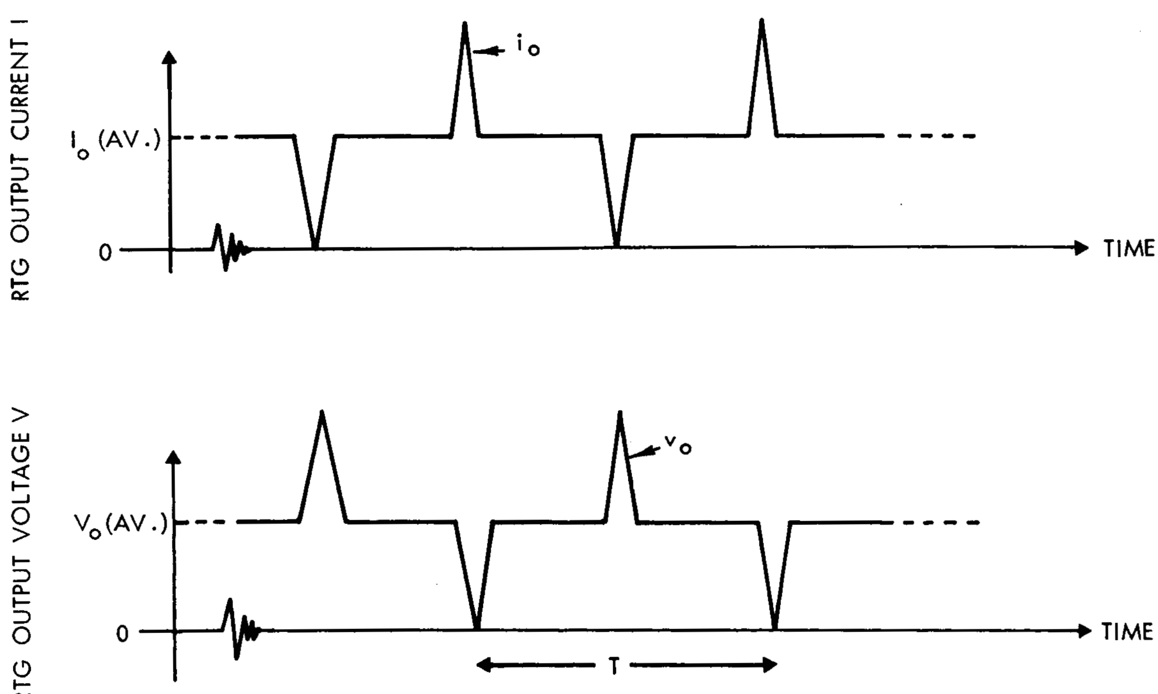
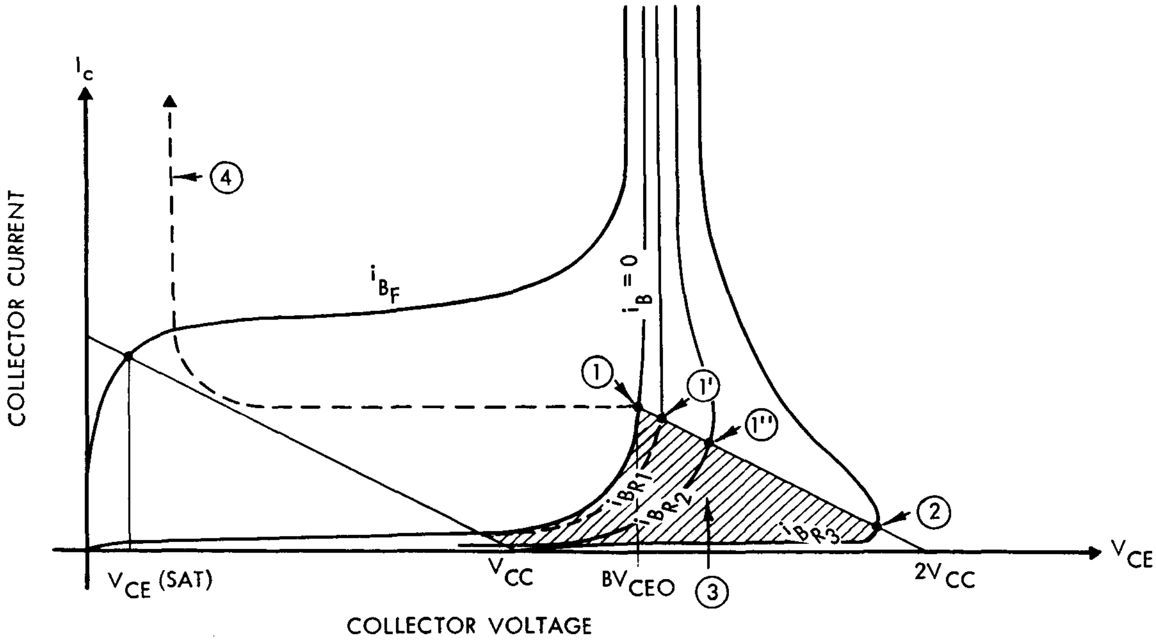


Figure 3. Typical Transitions of RTG Source Output (v_o/i_o) During Inverter Switching Intervals.



i_{B_F} - FORWARD BIAS CONDITION (ON-TRANSISTOR)

i_{B_R} - REVERSE BIAS CONDITION (OFF-TRANSISTOR)

1 1' 1'' - OFF-GOING TRANSISTOR LATCH-UP CONDITION WITH INSUFFICIENT REVERSE BIAS

2 - SAFE OFF-TRANSISTOR OPERATING POINT (i_{BR_3})

3 - HIGH SWITCHING DISSIPATION AREA (OFF-GOING TRANSISTOR)

4 - TRANSISTOR DESTRUCTIVE PATH, EXCESS POWER STRESS (WITH LATCH-UP)

Figure 4. Extended Transistor Characteristics.

switching dissipation and latch-up. These conditions can lead to transistor destruction where maximum power/voltage stress conditions are exceeded. It has been shown (Reference 2) that at collector voltages greater than BV_{CEO} the reverse base bias severely attenuates the effective thermal capacity of the transistor and the peak power during the switching interval can raise local temperatures excessively in microseconds. It is interesting to note that for a resistive load line situation, the instantaneous RTG output power at the extremes of load mismatch such as occur during the switching and switchover transient is not high and this acts as a protective feature. To enhance reliability and efficiency, it is necessary to restrict the permissible voltage/power stress limits and to employ additional protective measures such as adequate heat sinking, using proper on or off transistor base bias-values and selecting low leakage units. For reliable transistor performance, the total range of operation must be restricted to the safe operating region of its characteristics, well below BV_{CEO}, as typically illustrated by Figure 5.

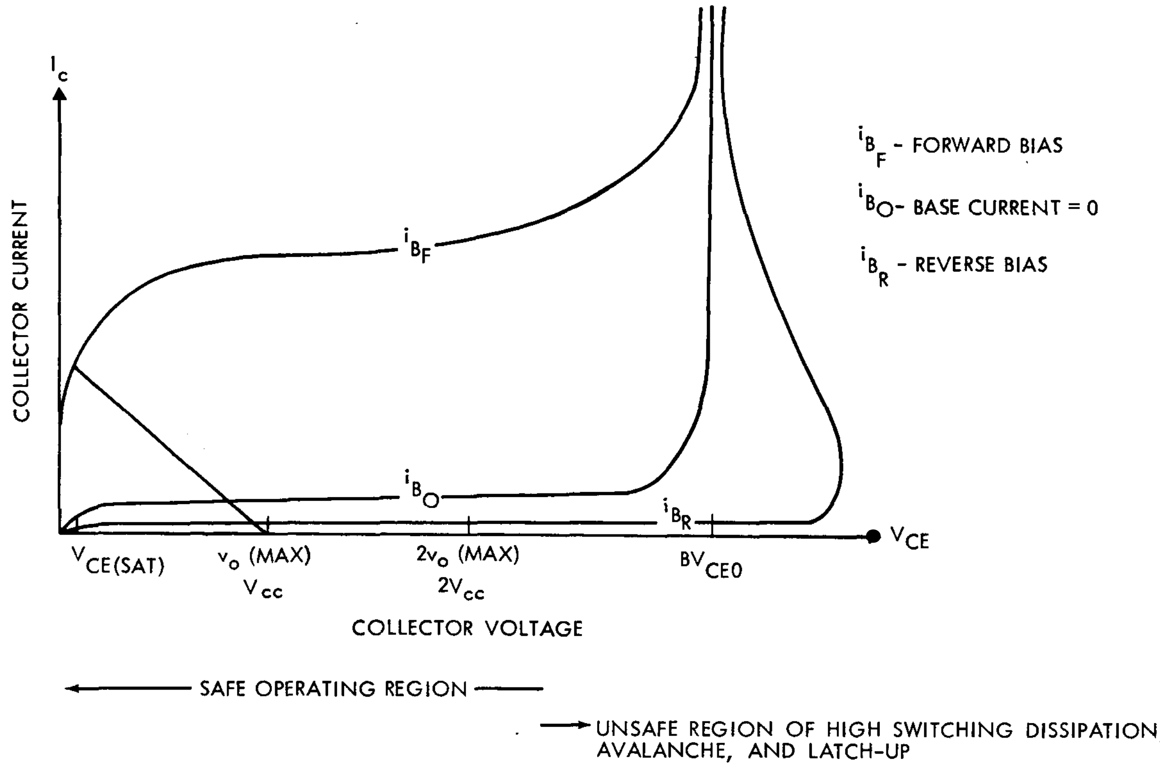


Figure 5. Transistor Operating Regions.

Parameter modification to the existing efficient state of the art designs of low voltage power switching transistors is required. The changes consist primarily of increasing the V_{CE} (max) voltage stress capability and assuring that the common emitter gain is less than unity for the worst case conditions (Reference 3). Figure 6a is a room temperature display of V_{CE} versus I_C characteristics for reverse voltage base bias condition of a very low V_{CE} (sat) transistor, the Solitron Corporation's MHT 2205, a germanium alloy 50-ampere unit. Figure 6b displays the same transistor at an elevated temperature condition. It is important to note the reduction of voltage stress capability at elevated temperatures. Figures 7a and 7b are similar displays for a Solitron MHT 2212. The MHT 2212 is a design modification of the MHT 2205 to achieve a higher V_{CE} (max) rating and which enables its use in somewhat higher source voltage applications. Compared with the MHT 2205, the MHT 2212 has higher V_{CE} (sat) voltages during the conduction interval; longer switching times; and greater base driving requirements. However, with the somewhat higher normal load output voltages available from developed RTG's, this transistor design compromise enables the increased voltage stress reliability consideration to be accomplished

FIRST STEP $V_{BE} = 0$, 0.2 VOLTS/STEP

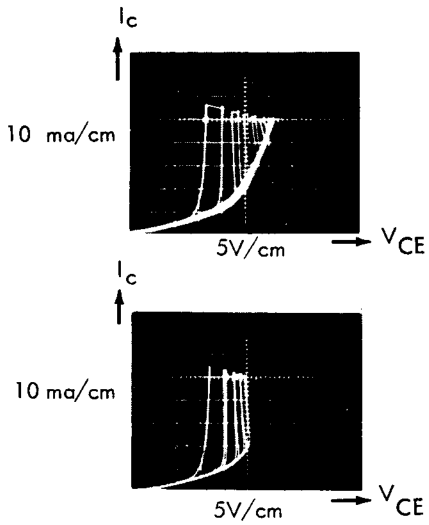


Figure 6a. MHT 2205, Reverse Voltage Bias Characteristic Room Temperature.

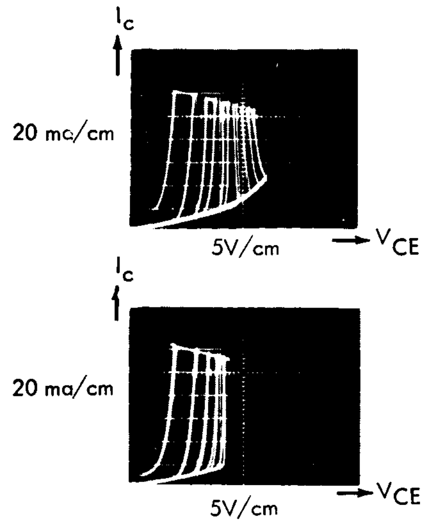


Figure 6b. MHT 2205, Reverse Voltage Bias Characteristic 70°C.

FIRST STEP $V_{BE} = 0$, 0.2 VOLTS/STEP

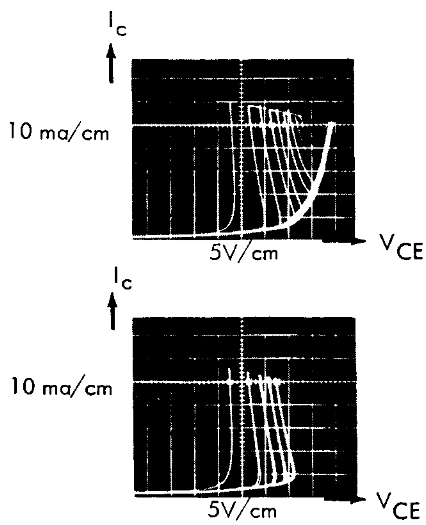


Figure 7a. MHT 2212, Reverse Voltage Bias Characteristic Room Temperature.

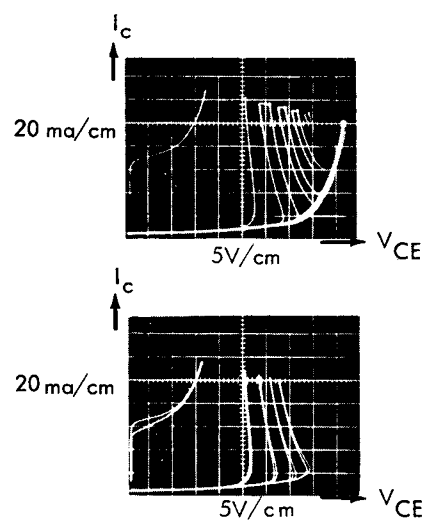


Figure 7b. MHT 2212, Reverse Voltage Bias Characteristic 70°C.

with little or no sacrifice of overall conversion efficiency. Obtaining voltage/power stress reliability on a component level has been emphasized, since dependence upon protection features or controlled loading of the RTG to limit voltage/power stress levels can themselves fail, thereby precipitating complete power supply failures.

C. Parallel Transistor Operation

The transistor should be able to handle the maximum current required without being subjected to excessive collector junction dissipation or necessitating excessive drive requirements. It has been determined in Reference 1 and elsewhere that it may be advantageous, with regard to efficiency, to operate transistors in parallel to achieve higher operating power levels from a given source voltage level. There are some available paralleled transistor units in a single package, notably the 150-ampere rated MHT 2101, which contains six paralleled MHT 2205 type junctions. When it is necessary to parallel transistors to obtain required current ratings, additional reliability/efficiency/performance considerations of load sharing and matching of switching and storage times are introduced. These problem areas are being investigated at GSFC for the case of single junction packaged transistor units connected in parallel.

D. Switching and Switchover Overlap Losses

Low voltage transistor junctions are large in area. This results in their having long rise, fall, and storage times. These characteristics result in transistor switching and circuit overlap losses which reduce overall efficiency and reliability.

Figure 8 illustrates a push-pull output stage with separately excited base voltage drive. Assuming that a constant load is on the output establishing the average I_{CC} level illustrated. The common leg source current would be a continuous DC value if there were no inverter switching or switchover problems. When the off-transistor is driven on, because of storage time of the off-going transistor, essentially the same collector current continues to flow. A condition occurs during crossover where both collector currents are flowing simultaneously. These collector currents buck in the power transformer primary, and a short circuit loading condition exists for the duration of the off-going transistor storage time interval. For this storage time interval, current flow from the source is limited only by the transistor collector-to-emitter impedance and the impedance of the power source. Generally, the range of each of these impedances can be considerable and importantly affects the circuit efficiency/reliability design considerations. During the crossover overlap interval, the possible large current spike flow, multiplied by the full voltage of the power source, is power

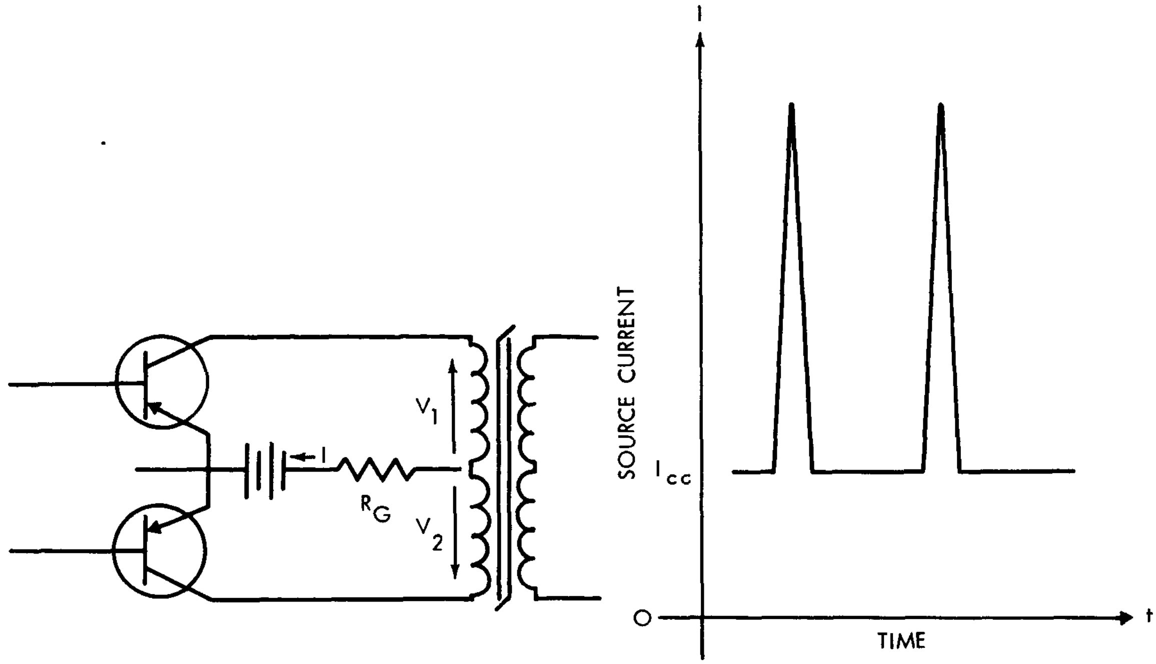


Figure 8. Switchover Overlap Condition of Separately Excited Voltage Driven Inverter Push-Pull Output Stage.

lost. Thus, efficiency is reduced and excessive transistor dissipation can result, compromising reliability. One method of reducing the storage time created overlap problem is through the use of collector current feedback base drive. This method is discussed later in Section III, A.

E. Abnormal Magnetic Saturations

In some magnetic component circuit applications, for example the main power handling transformer or the base drive current feedback transformers, it may be necessary to avoid abnormal deep magnetic saturations. It is also necessary to use magnetic materials compactly and efficiently to reduce size and weight. The simultaneous satisfaction of both these requirements poses difficulty. Unbalanced core flux operation for an orthonol core as illustrated by Figure 9 leads to deep magnetic saturation on cycling of the inverter. Figure 10 illustrates a case of abnormal saturation of the power output transformer of a current feedback drive inverter circuit. Figure 11 illustrates a case of balanced core flux operation using a supermalloy core. In addition to considerations of inherent magnetic material properties, it is necessary that full cycle electrical balance of circuit operation be maintained to prevent magnetic saturation.

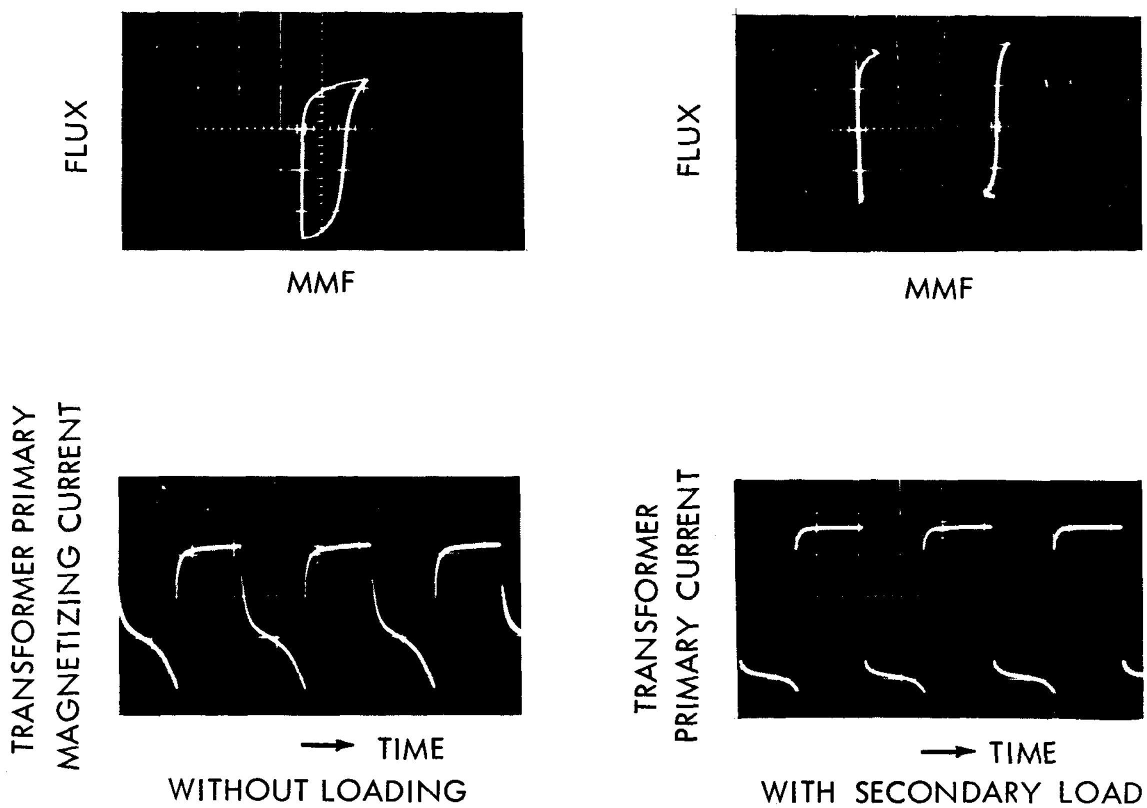


Figure 9. Orthonol-Unbalanced Core Flux Operation and Resulting Primary Currents.

F. Lead Inductance and Transformer Leakage Reactance

The source and the source-to-converter connections have reactive characteristics. In the case of low input voltage conversion, the leakage reactance of the primary winding of the main power handling transformer is especially significant. Saturable reactors exhibit after saturation reactance. The net result of these circuit and component inductive reactances is to slow down switching and switchover times, resulting on increased switching dissipations. The use of very large capacitors to reduce input voltage spiking to the converter is not desirable from a component reliability aspect as well as from a size and weight limitation viewpoint. Large input capacitors, because of excess power dissipation, also inhibit some preferred modes of operation for RTG source protection which are discussed later in Section IV, C.

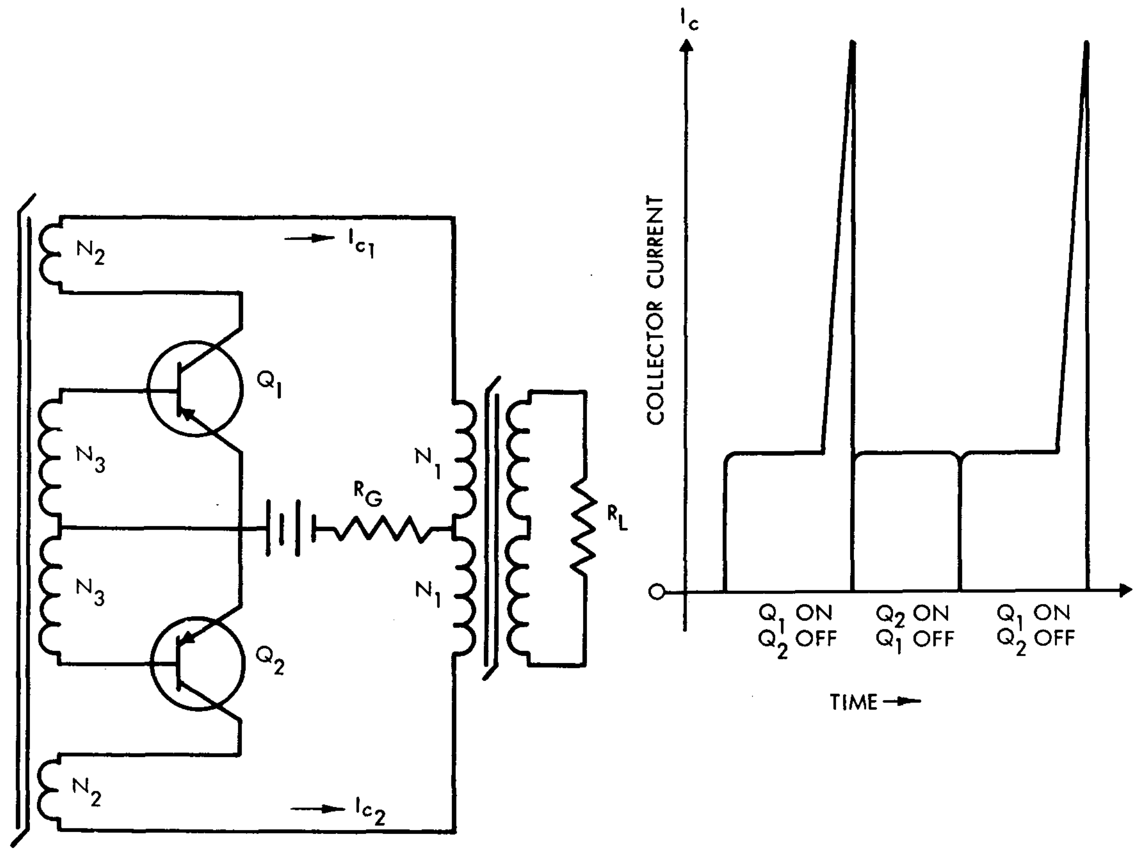


Figure 10. Power Transformer Core Saturation One Side of B/H Loop in a Current Feedback Driven Push-Pull Oscillator Inverter.

III. DC TO SQUARE WAVE AC INVERSION

A. The Current Feedback Driven Push-Pull Oscillator Inverter

The current feedback driven inverter circuits have proved to be especially useful for use with low voltage power sources (Reference 4). Figure 12 illustrates a current feedback driven oscillator inverter. The base current drive is related to the collector load current by

$$I_B = \frac{N_1}{N_2} I_C \tag{4}$$

The current feedback transformer T_1 is designed to saturate and is the frequency determining element in this circuit. The frequency of operation is a function of

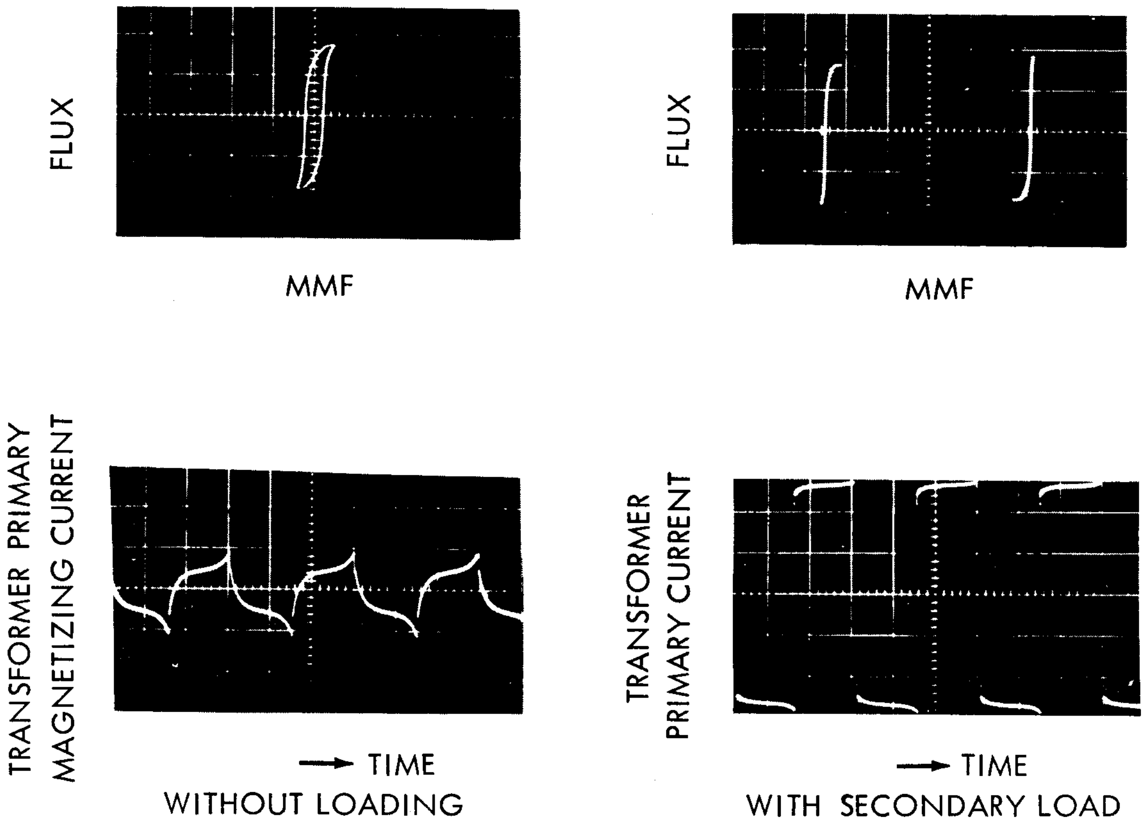


Figure 11. Supermalloy-Balanced Core Flux Operation.

transformer T_1 design and the base-to-emitter voltage (V_{BE}) of Q_1 or Q_2. Since V_{BE} is also a function of loading, a small frequency increase with increased loading results.

With this circuit configuration the efficiency of a transistor as a switching element (Reference 1 and 4) is given by

$$\text{Efficiency} = \frac{V_{CC}\int_0^T i_c\,dt - \int_0^T v_{CE}\,i_c\,dt - \int_0^T v_{BE}\,i_b\,dt}{V_{CC}\int_0^T i_c\,dt} \tag{5}$$

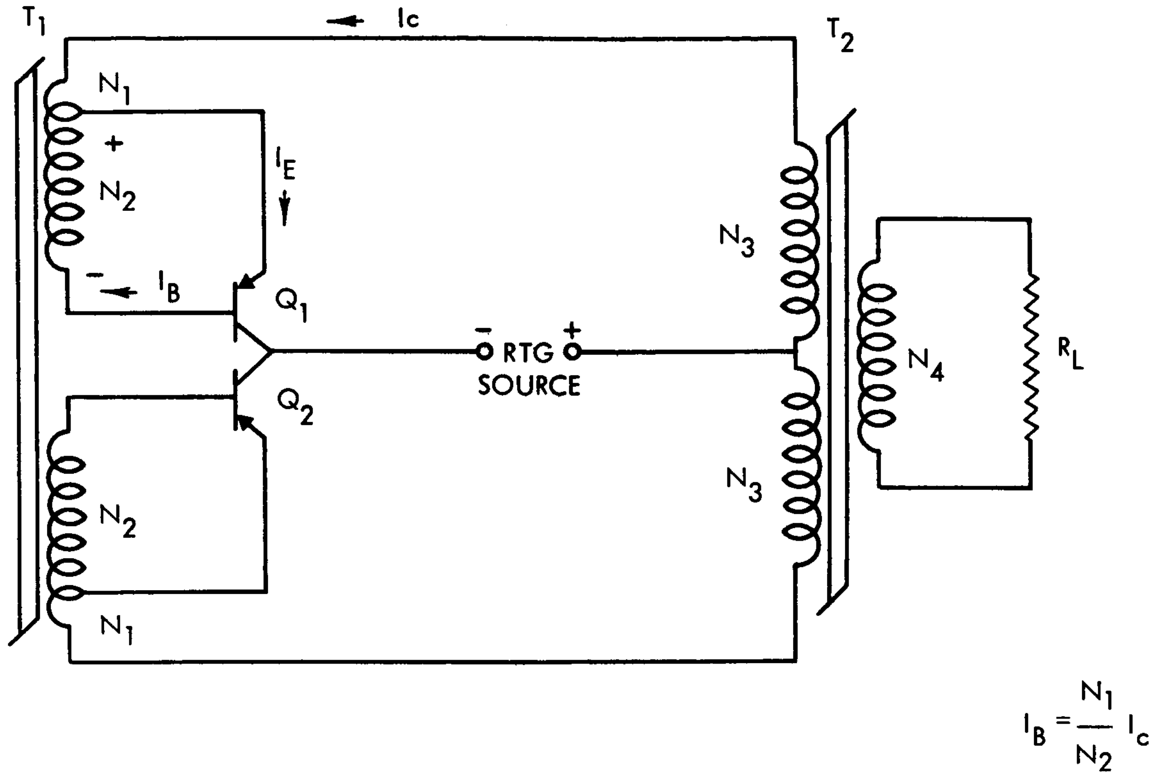


Figure 12. Current-Feedback, Push-Pull, Oscillator-Inverter.

V_{CC} = power source voltage

T = period

i_c = instantaneous value of collector current

v_{CE} = instantaneous value of collector voltage

t = time

v_{BE} = instantaneous value of base-to-emitter voltage

i_b = instantaneous value of base current

Examination of Equation 5 reveals that the current feedback method enables the transistor switching efficiency to be maintained high over large ranges of source voltage or of load demand. The current feedback drive enables the establishment of proper transistor base current drive which is a fixed fraction of the collector current (Equation 4) regardless of load demand or source voltage. Thus with current feedback the inverter transistors can be maintained well into saturation (low V_{CE} sat), enabling reliable low dissipative operation. Since proper rather than excess drive can be maintained, storage times can also be minimized, and efficient operation is possible over a large range of input voltage and output loading.

In the circuit of Figure 12, the overlap crossover losses created by storage time referred to in the voltage drive circuit of Section II, D, is not a problem because circuit switching and on-transistor storage termination occur essentially simultaneously. During the inverter switching interval, the input voltage deviation is above the V_o line as shown in Figure 3, creating the high input voltage condition illustrated. Thus, another situation of input voltage spiking which affects the voltage stress reliability conditions is apparent.

The main disadvantage of the current feedback circuits typically illustrated by Figure 12 for use with variable input source voltages is that the output transformer T_2 cannot be optimized for size and weight. Since the output transformer is the largest component of the inverter, this disadvantage is particularly significant. Where the source voltage is relatively stable, enabling relatively constant frequency operation use, the circuit has the advantages of simplicity and is efficient with regard to the inverter switchover, collector dissipation, and base driving conditions.

B. <u>The Current Feedback Driven Push-Pull Oscillator Inverter With Voltage Feedback Controlled Switching</u>

Figure 13 illustrates the most used low input voltage inverter circuit technique. During essentially all of its on-time, the on-transistor has positive current feedback drive. As previously described by Equation 4, the base current drive is a fixed fraction of the collector current. Though square loop magnetic core materials are indicated for transformers T_1 and T_2, they are designed for nonsaturating operation in this circuit application. Improvement in efficiency is achieved through the use of narrow hysteresis loop core materials.

Efficient switchover of the inverter (Reference 5) is caused by negative voltage feedback from winding N_5 which is applied to winding N_6 after SR_1 saturates. The negative voltage feedback overrides the positive current feedback drive. SR_1 is the frequency determining element whose time to saturate is determined by SR_1 design and the voltage induced in winding N_5. The voltage induced in N_5 is given by

$$V_{N_5} = V_{source} \left(\frac{N_5}{N_3}\right) \tag{6}$$

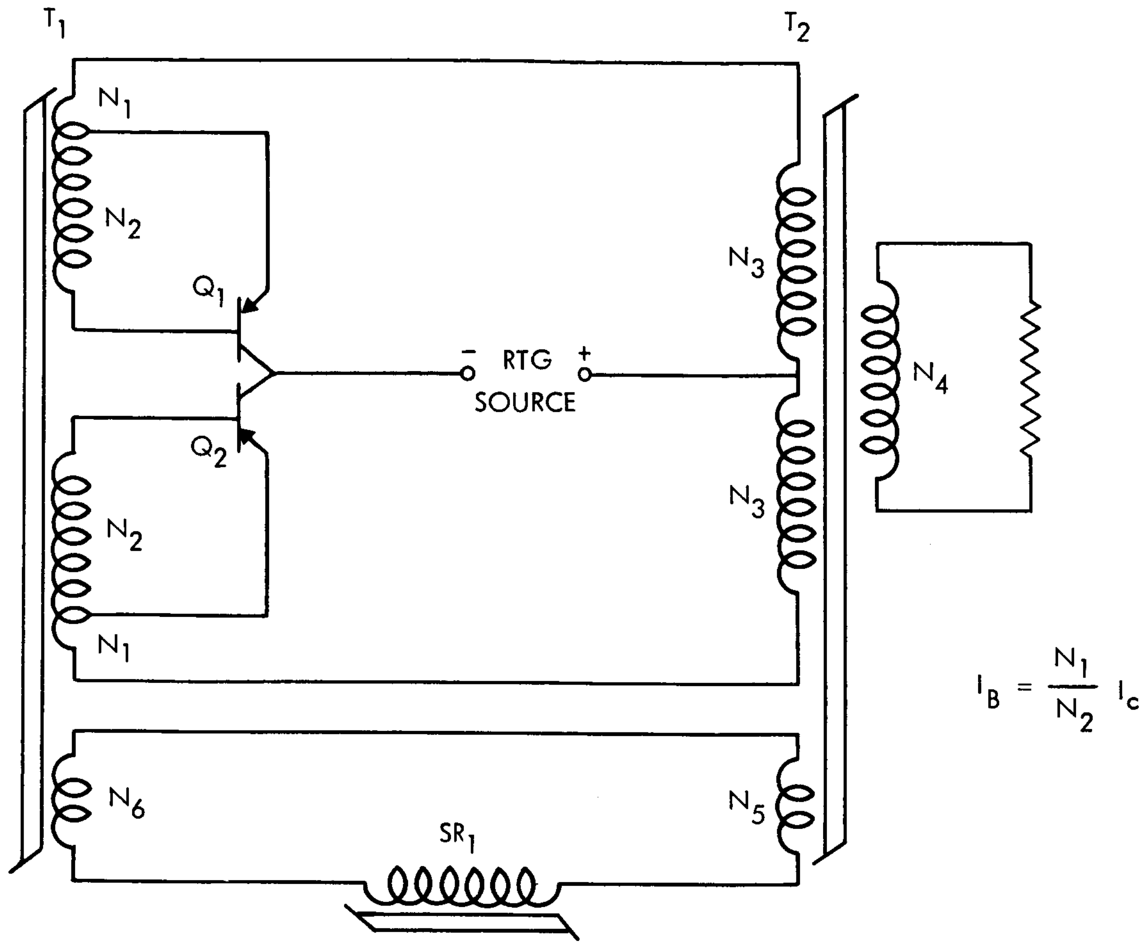


Figure 13. Current-Feedback Drive Push-Pull Oscillator-Inverter With Voltage Controlled Switchover.

V_{N_5} is a direct function of source voltage. The inverter switching frequency is thus a function source voltage. With the inverter switching frequency a function of source voltage, the output transformer can be optimized for size and weight while still avoiding deep magnetic saturation during normal operation.

The switchover interval, inverter input conditions for this circuit may differ significantly from that of the circuit described in Section III, A. The inverter input transient voltage can deviate above, below, or in both directions from the V_o line of Figure 3 during switching. The exact nature of the input voltage/current transient deviation is a function of combined design of the negative voltage feedback and the positive current feedback circuits, as well as the effects of input or output filtering, component characteristics, and source impedance.

With low impedance loading, the RTG source output voltage V_o, which is the source voltage of Equation 6, is low. V_{N_5} also becomes correspondingly small and thus the switching frequency of the inverter becomes very low. This low frequency operation results in further reduction of the inherent internal dissipation of the inverter. This capability of the current feedback driven inverter to operate reliably and with low dissipation under conditions of high output loading when the source V/I characteristics are as typically illustrated by Figure 1, is used to advantage in an RTG-source/LIV-converter protection technique which is described fully later in Section IV, C. Cognizance needs to be taken of the fact that with short circuit loading, a current feedback driven inverter circuit can be designed to operate with low dissipation and thus made to reflect a very low impedance to its input or source connected terminals.

IV. POWER SYSTEMS USING THE RTG SOURCE

A. Efficiency and Open-Load Problems of RTG Sources

To achieve high direct energy conversion (DEC) efficiency of radioisotopic decay heat energy to electrical energy in thermoelectric generator power sources, it is necessary that a large temperature difference exist between the hot and cold side of the thermoelectric junctions (Reference 6). The cold side thermoelectric junction temperature is fixed by the cold sink or radiator conditions. The normal-load hot side temperature may be near the upper temperature limit of the junction material. Any further increase in temperature could permanently degrade the thermoelectric junction electrical output capability. Another temperature problem area of RTG's concerns the radioisotopic fueling elements, and fuel capsule strengths at temperatures above their normal operating temperatures (Reference 7). It is necessary to keep internal operating temperature below the fuel melting points and also below where the strength of the fuel encapsulating container material is inadequate.

The internal temperatures of RTG's are reduced in the normal load operating condition by Peltier cooling which results from the external load current flow which also flows through the thermoelectric junctions. If the load current is interrupted by open circuit operation, the Peltier cooling stops and the fuel capsule and thermoelectric element temperatures may rise excessively. Previous practice has been to impose a suitable dummy or dissipative shunt regulator load across the RTG output, should the output current be decreased or in the extreme case the output load become open circuited. This RTG-protective, voltage-regulating procedure is illustrated in Figure 14. A disadvantage of this external

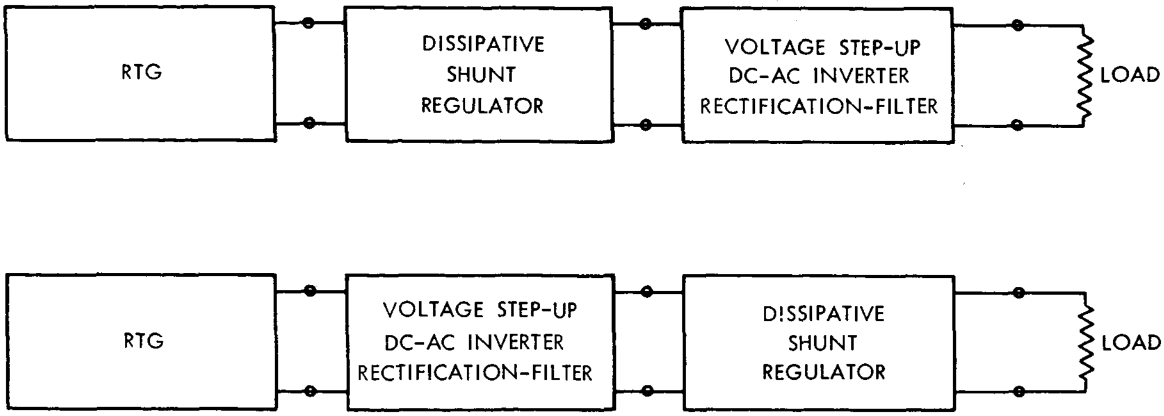


Figure 14. Dissipative Shunt Regulator RTG Light or Open Load Protection.

to the source dissipative technique is that the heat sinking of the shunt regulator is at the low temperature of the satellite or spacecraft structure itself. The dumping of excess heat generated is a difficult disposal problem in the vacuum of outer space, where the heat transfer to space is by radiation. This imposes a serious heat sinking or radiator weight and size penalty (Reference 8). The shunt regulator electronic components also present reliability problems at increased temperatures.

B. LIV Conversion With the RTG Source

Some interrelated effects of combining the RTG source with the converter are illustrated by Figures 15a and 15b. Also, some insight as to the overall efficiency and reliability of the current feedback drive inverter circuits as compared with voltage feedback drive inverter circuits for use with the RTG source can be gained from examining the figures. In Figure 15a, R_G is the RTG internal resistance; R_L is the transformer reflected output load; R_{CE} is the power transistor collector-to-emitter junction resistance; and R is the combined resistance of all the circuit losses including transistor driving losses and magnetic losses. Plotted on the Figure 15b is a typical power transistor V_{CE} versus I_C characteristic. Imposed also are some assumed RTG V/I characteristics for several load line conditions; of specific interest is the inverter on-transistor operating condition. Case I depicts a normal matched load condition for both a voltage feedback driven inverter and for a current feedback driven inverter. I_1 is the normal-load RTG current which also flows through the on-transistor of the inverter. Case II load line is for the current feedback driven inverter when R_L is shorted out. For Case II, it is seen that the RTG and inverter current double. The base drive current also doubles. The inverter collector-to-emitter dissipation (P_{CE}) losses remain within reasonable values, although the fixed losses rise

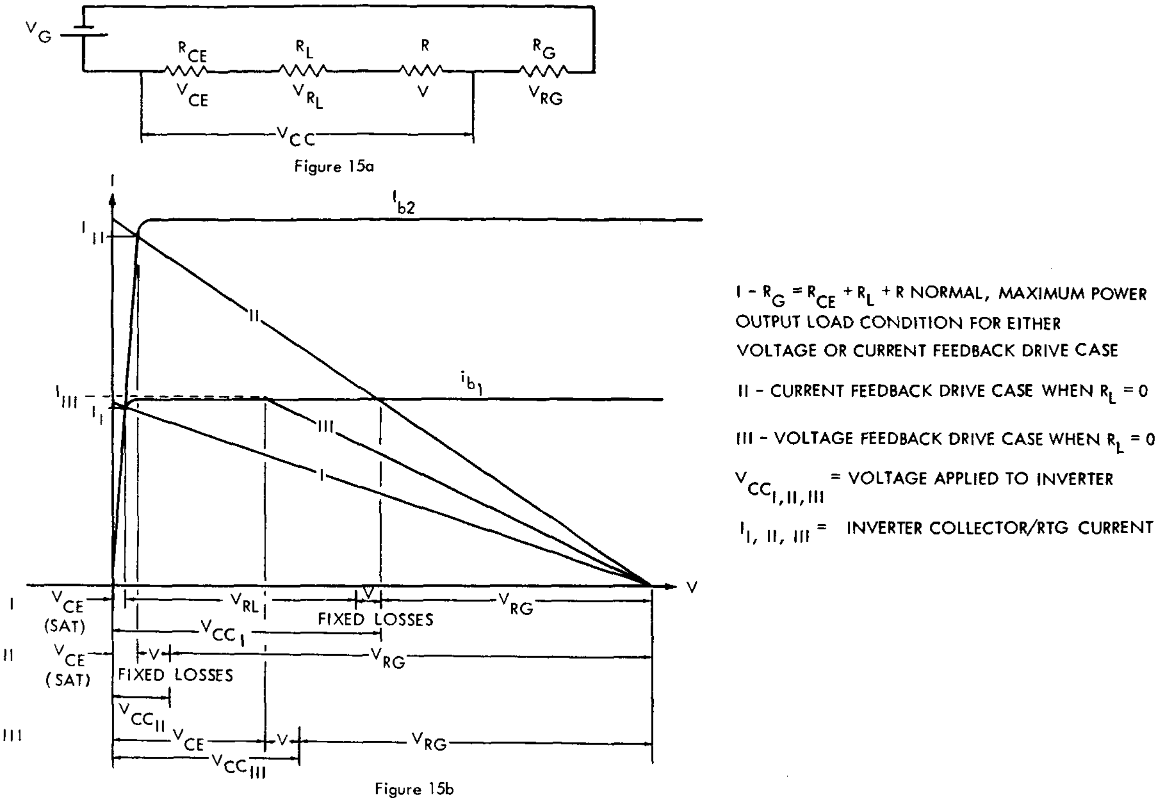


Figure 15. LIV Conversion With RTG Source.

somewhat. The total power dissipated within the current feedback driven inverter remains low even with short circuit loading. Case III load line is for a voltage feedback driven inverter with shorted output loading. In Case III, the collector-to-emitter junction resistance becomes high due to inadequate base drive and the junction dissipation P_{CE} becomes very high. In Case III, extensive heat sinking is required to assure that the junction maximum operating temperatures are not exceeded.

When the source is a relatively high impedance device such as the RTG, the current feedback driven inverter has an advantage when compared to the voltage feedback driven inverter with regard to power stress reliability in the overload or short circuit load situation. For this reason, as well as greater efficiency, the current feedback driven inverter has been selected for use with power limited RTG sources.

C. A New Approach to RTG-Source/LIV-Converter Protection for Abnormal Loading

It is desirable that the source/converter combination be capable of operation over the total range of open-to-short circuit loading for any time interval without any adverse effects upon either the source or the voltage step-up converter. Normal efficient operation should be resumed upon the return of normal loading. The implementation of these stated requirements provides a power system using RTG sources which is totally protected with regard to output load conditions.

The RTG power source is inherently safe with regard to short circuit output loading. When operating from a power limited source, a current feedback drive converter can be designed to have low internal dissipation with short circuit output loading. A current feedback drive converter properly designed to handle the power limited maximum source current is therefore inherently safe from a short circuit output loading consideration. The implementation of the circuits which functionally integrate the LIV converter and the RTG source protection requirements is illustrated in Figure 16.

The RTG overvoltage protection circuit illustrated in Figure 16 is designed for use with power limited sources with V/I characteristics typically illustrated by Figure 1. Zener diode Z_1 senses an overvoltage limit condition at the transformer secondary whenever open or light load conditions exist. Shorting of the inverter output transformer secondary occurs during each half cycle that the zener voltage limit is exceeded. The transformer secondary voltage is directly related to the source voltage. The alternate low impedance across the power output transformer caused by conduction of SCR_1 and SCR_2 is reflected back to

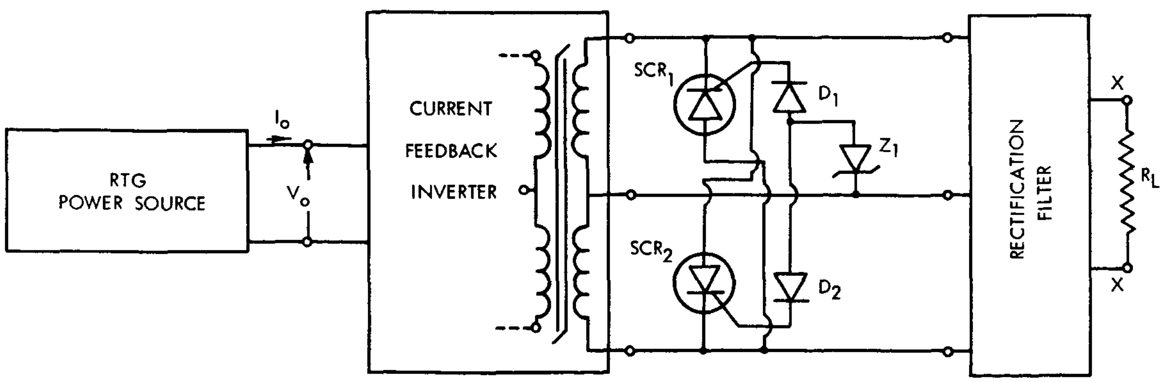


Figure 16. RTG Over-Voltage Protection Circuit.

the primary side as a much lower impedance for the remaining half cycle of inverter operation. This results in essentially short circuit current flow in the thermoelectric generator and maximum Peltier cooling by electrical heat pumping to the thermoelectric generator cold sink or radiator where it is rejected. It is important that the total inverter losses be maintained low to effect the lowest possible impedance at the inverter input terminals. The current feedback drive enables the power transistors of the inverter to maintain proper base drive with the increased collector current flow during the low impedance conduction of the SCR's or for a short circuit output load condition. This results in low collector-to-emitter losses. When the source current is a maximum, the source voltage is very low. Since the frequency of the inverter is proportional to input voltage, the inverter frequency is low under these conditions. The low inverter frequency further reduces transistor and magnetic switching losses enabling very low overall inverter circuit dissipation in this mode of operation.

The RTG overvoltage protective technique presented is particularly applicable in space power systems using RTG sources because it makes possible the minimizing of the amount of heat dumping in the satellite or space probe structure itself. Heat is rejected at the RTG cold sink or radiator where it represents a small fraction of the total heat rejection problem normally associated with RTG's. Because the RTG cold sink is at a high temperature, heat energy radiative transfer to space can be accomplished effectively (Reference 8), imposing a minimum weight size penalty for radiator requirements. The elimination of the shunt regulator, especially its electronic components which must necessarily dissipate large amounts of power in a space environment, enables the new RTG overvoltage protection technique to improve overall power system reliability.

D. Output Voltage Regulation and Maximum Utilization of Available Source Power/Energy

For the open circuit load protection consideration illustrated in Figure 16, the ($D_1 + Z_1$) and ($D_2 + Z_1$) voltage is selected to be above the normal-load or regulated output voltage operating level. This RTG voltage clamping protection operation is illustrated in Figure 17. It is seen that coarse regulation of the average output voltage can be affected at the ($D_1 + Z_1$) and ($D_2 + Z_1$) limit voltage. Approaching the maximum power point, the source impedance alone determines the average output voltage. Beyond the maximum power point, to the right, the average output voltage drops due to the power limited source characteristic.

An alternative output voltage regulation scheme to that of Figure 16 is illustrated by Figure 18. Here ($D_1 + Z_1$) and ($D_2 + Z_1$) voltage limit levels are

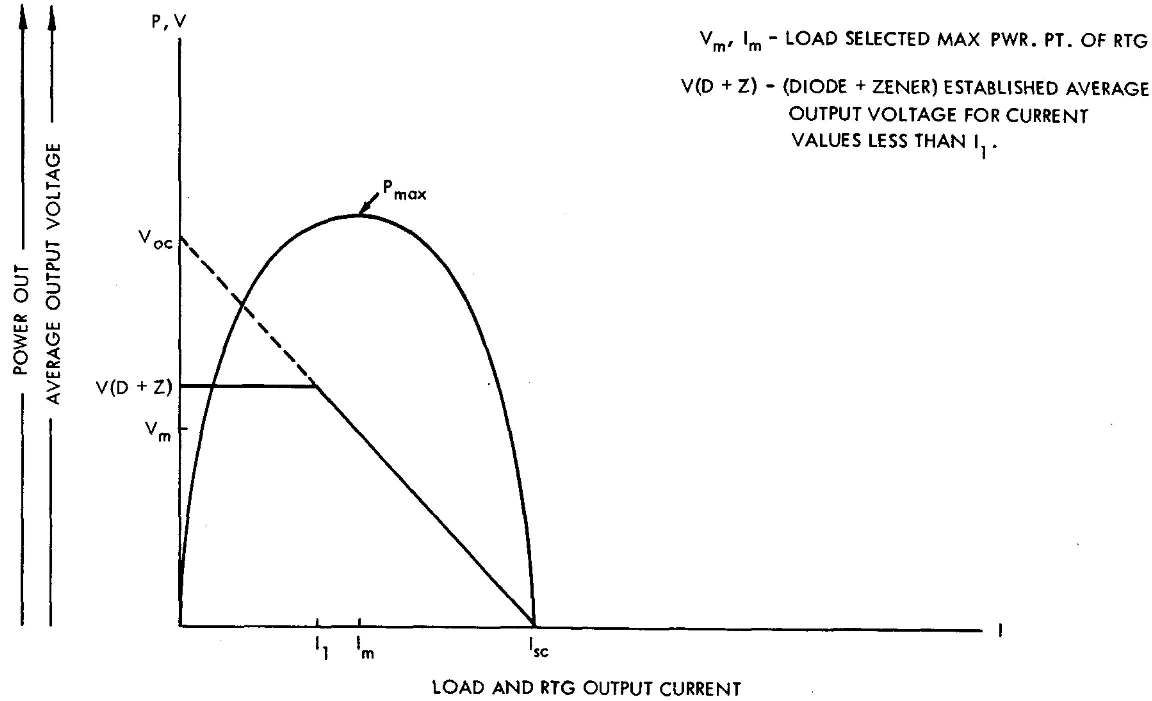


Figure 17. Voltage Clamping of RTG Over-Voltage Protection Circuit.

selected close to the V_m level and used to regulate the output voltage level. The constant frequency (approximate) type inverter used is preferable in this case as it enables lower regulation response time using reasonably sized filter components. This regulation technique maintains the RTG thermal situation constant and thus electrical output conditions are stable for all values of output loading less than P_{max}. Power not required by the output load is dissipated in the RTG radiator, not in the power conditioning circuitry. Also shown in Figure 18 is the addition of a nondissipative switching type regulator for improved output load voltage regulation.

Figure 19 illustrates an assumed degradation of RTG power output with time. In some particular systems application such as in the Nimbus B application, which is discussed later in Section VI, the output terminals (X-X) of Figure 16 are connected to a voltage regulated bus which clamps the converter output voltage level to the bus voltage level. This also clamps the RTG voltage operating point and dictates the source output power condition. Clamped voltage operation does not allow optimization of source power/energy utilization during the source maximum-available-power level change. The design procedure normally chosen enables maximum power utilization at the end life RTG source output power condition when power may be marginal rather than at the beginning of

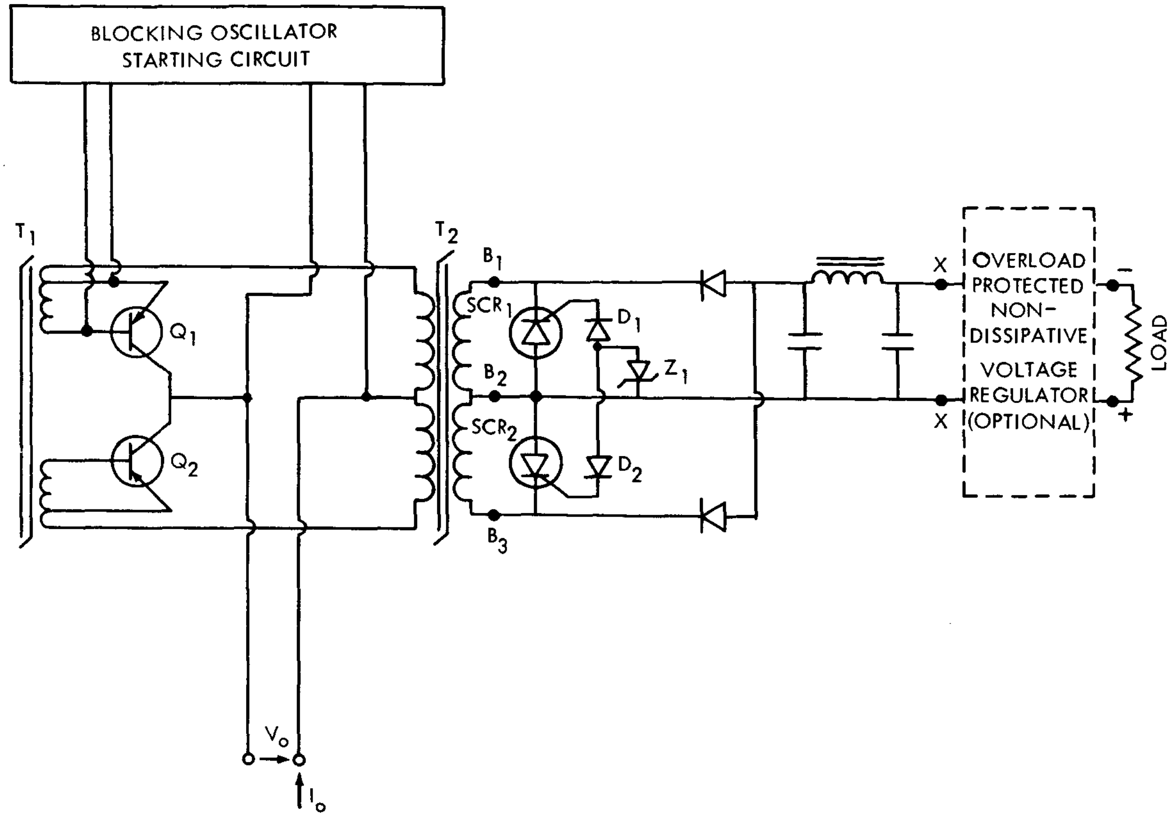


Figure 18. Output Load Voltage Regulation Technique.

life RTG source output power condition when excess power is generally available.

The maximum utilization of available source energy requires that the source output be free to seek the V_m, I_m operating points. Maximum source-to-load power transfer is effected by matching the variable source and variable output load impedances. In this case, the net load includes a requirement for storage, usually batteries. The output voltage (V_m) from this maximum power/energy transfer scheme is unregulated, therefore output load voltage regulation circuitry is necessary.

V. INCREASED RELIABILITY

A. Multiple-Source/Multiple-Converter Configurations

Analysis (References 9, 10) indicates that the power supply requirements needed for long lifetime time missions can best be accomplished by use of

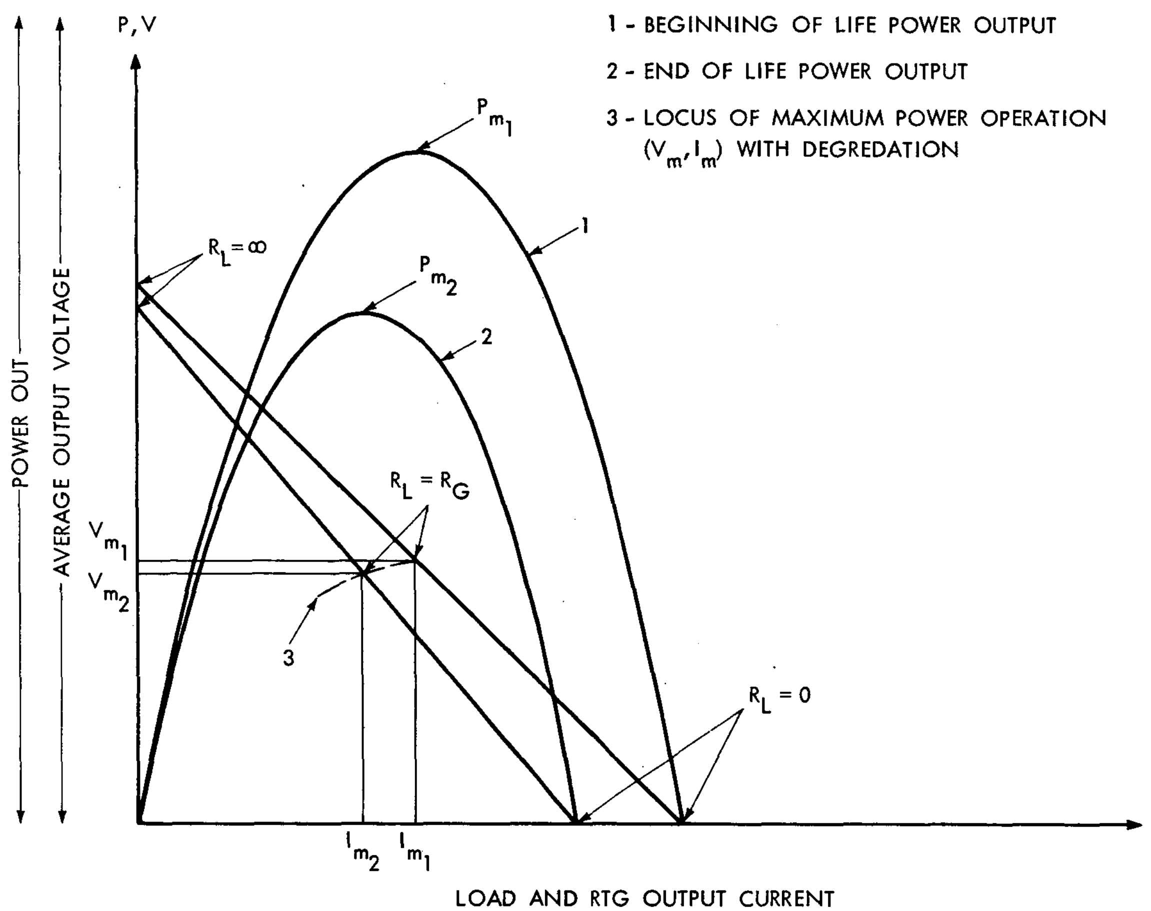


Figure 19. Assumed Degradation of RTG Source Output Power.

paralleled source/paralleled converter configurations. In the event of source/converter module or component failures, ground commandable, or preferably automatic on-board failure sensing and reconfiguration switching capability to utilize maximum available power is needed. High reliabilities are achievable, if the degraded power level resulting still allows performance of essential functions, or allows continued successful operation, although on-board experiments are carried out at a reduced rate or scale. The parallel source/converter approach has the potential for reliably achieving the much higher power level requirements of future long-life long-distance space missions.

B. Synchronization

When the DC outputs of several source/converter power supplies are combined in parallel as shown in Figure 20 into a common output load, very low beat

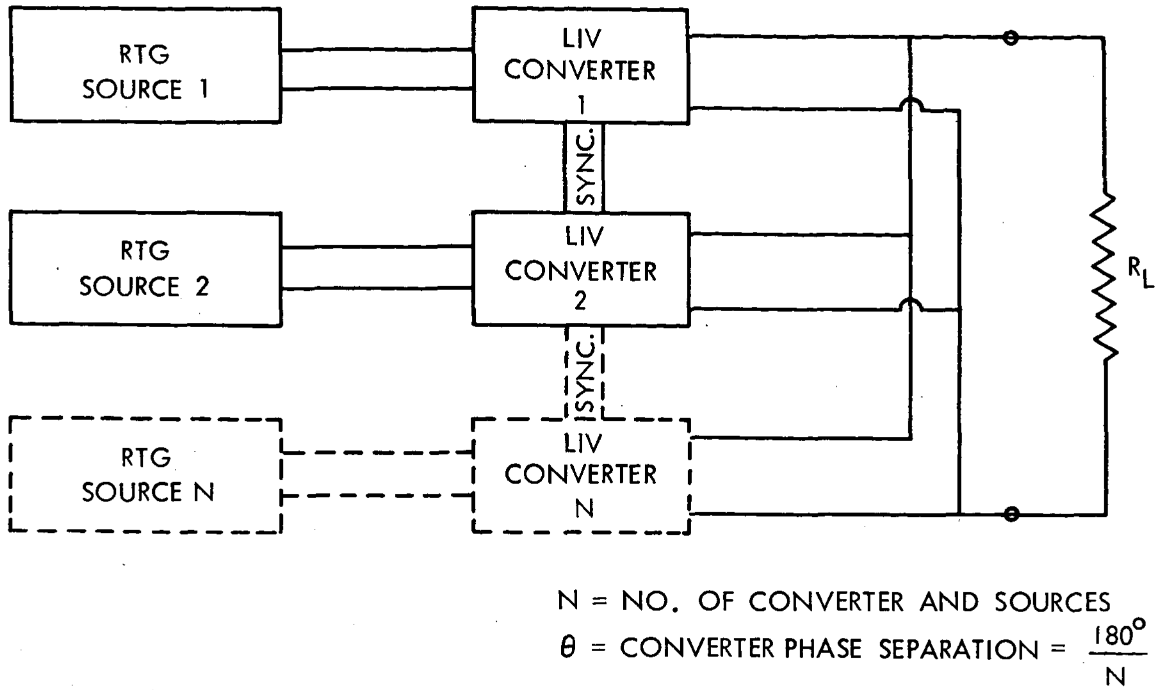


Figure 20. Multiple-Source/Multiple-Converter Configuration.

frequencies are produced which are very difficult to filter out. These beats result from the combining of the ripples of the several converter outputs. The individual inverter sections usually run at slightly different frequencies due to either slight electrical differences in the inverters or differences in the individual source output voltage conditions. The technique developed to eliminate this problem is out-of-phase synchronization of the paralleled inverters. Phase separation employed is $\theta = 180°/N$, where θ = phase angle between the start of the cycle in adjacent inverters, and N = number of inverters/converters connected in parallel. The synchronization is designed not to compromise continued reliable operation of remaining sources or converters if one or more of these units is in a failed mode. The out-of-phase synchronization is also beneficial in reducing RFI and filtering requirements because of the reduced amplitude switch-over transients.

VI. HYBRID-PRIMARY-SOURCE POWER

A. Nimbus-B Satellite

The Nimbus-B meteorological satellite power supply includes solar-photovoltaic and radioisotopic-thermoelectric power sources. The main primary source is the oriented solar cell array which supplies power to the load bus through a voltage regulator. The array also separately supplies battery charging power. In addition primary power is supplied to the load bus by the SNAP-19 RTG power supply. The RTG power source supplements the main oriented solar array power source. This combination or hybriding of the solar-photovoltaic and radioisotopic-thermoelectric power sources is designed to improve reliability and extend the spacecraft electrical power system lifetime.

In the SNAP-19 RTG power supply, the available energy of two radioisotope-fueled thermoelectric generator modules is combined and converted to the -24.5 volts DC required at the Nimbus load bus. The DC to DC conversion is performed by dual converter sections contained in the power conditioning module. The converter outputs are fed to the main bus through bus protecting isolation diodes. Regulation of the load bus to ±1/2 volt DC is accomplished by the main power source voltage regulators.

B. LIV Converter Development for Use With the SNAP-19 RTG's

The GSFC combined in-house R&D and Nimbus-B project support work in the LIV conversion area has developed a state of the art converter for back-up use in the Nimbus-B SNAP-19 RTG power conditioning application. The block and schematic diagrams are Figures 21 and 22, respectively. Some important features of the circuit design are:

a. Primary-transformer-winding current-feedback to assure proper transistor drive under all loading and source conditions.

b. A grounded collector configuration is used to enable better distribution of the heat energy conducted along the input power leads from the RTG source.

c. The individual converter conductors and components are sized to accommodate the short circuit load current available from two paralleled RTG source modules.

d. Capacitor and transistor components are voltage stress rated to enable reliable operation in the open-load condition (highest voltage). This component capability is independent of the nonfunctioning of protective circuitry.

e. A starting circuit which shuts-off automatically after the power oscillator circuit has been started, and whose shut-off bias is established as a function of load current. The starting circuit repetition rate is approximately

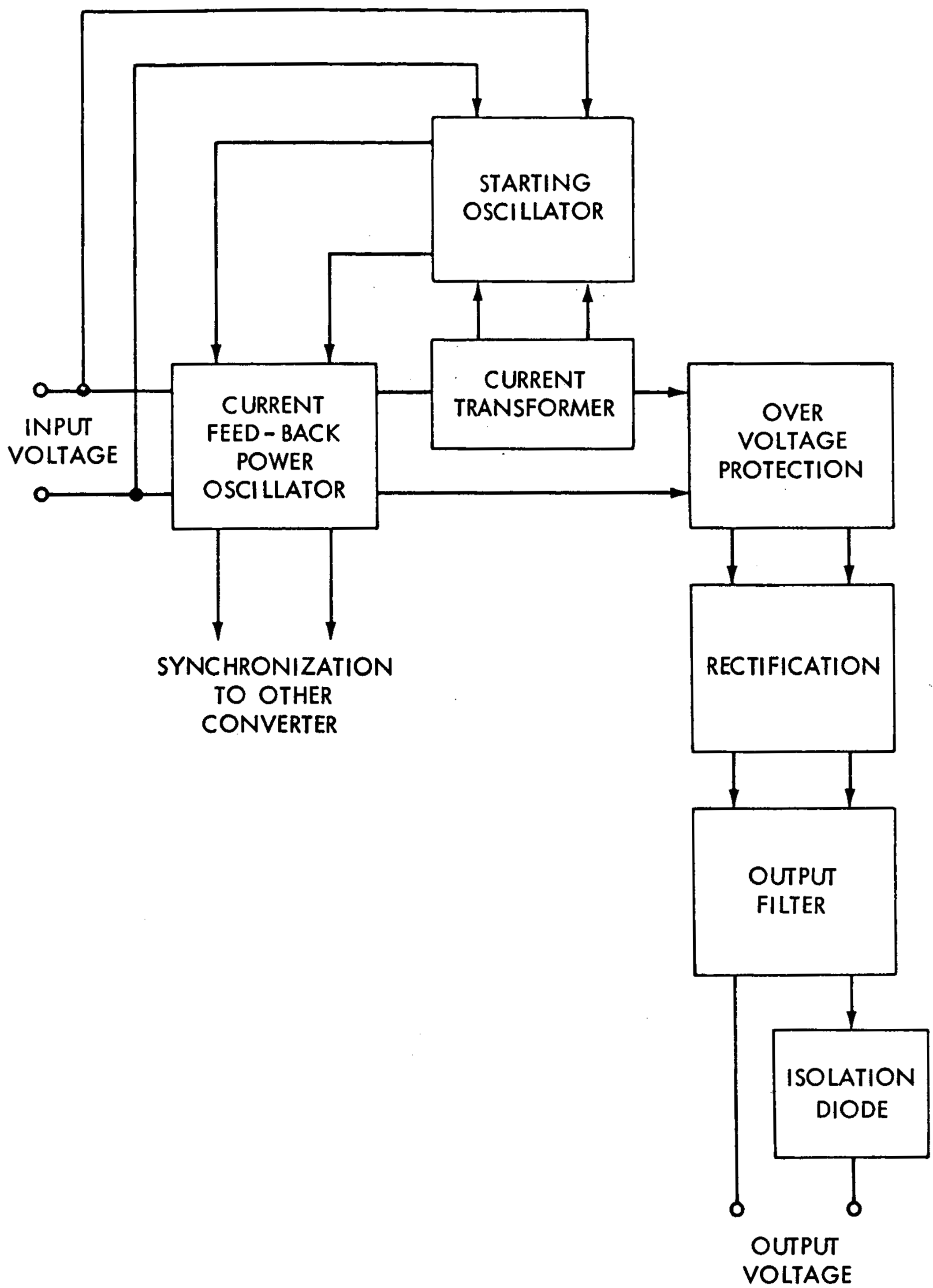


Figure 21. Block Diagram GSFC Developed Converter for Use With SNAP-19 RTG Source.

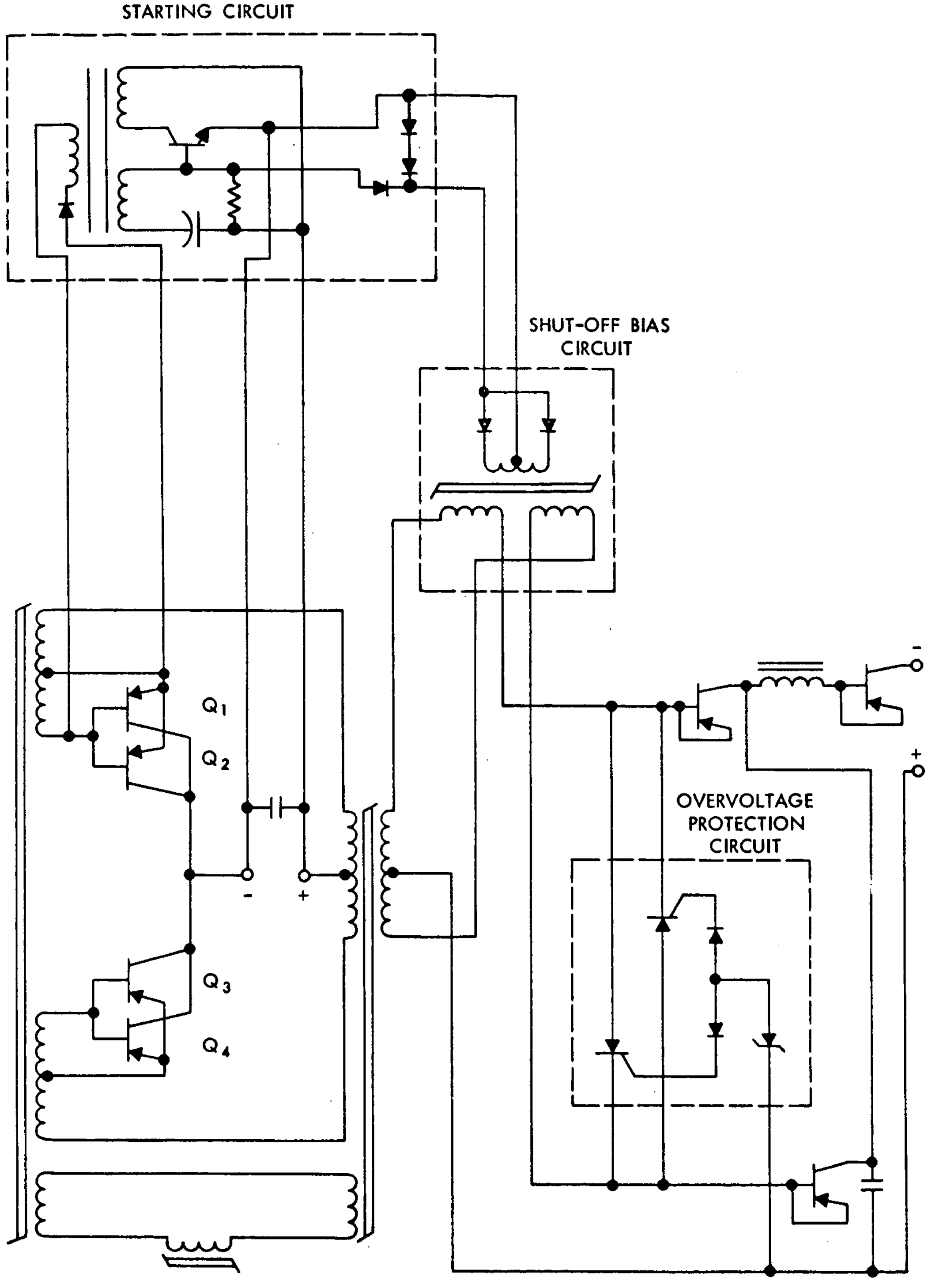


Figure 22. Schematic Diagram of GSFC Developed Converter for Use With SNAP-19 RTG Source.

2 pulses per second, thus the dissipation under conditions of high input voltage (open or light loading) is negligible, allowing when necessary continuous low dissipation operation (shut-off bias held off). The blocking oscillator starting circuit is capable of initiation from a very slowly rising source voltage.

f. Overvoltage protection (light or open load) for the RTG sources is functionally-integrated into each of the LIV DC to DC converters. The NASA GSFC developed circuitry utilizing SCR's (fully described in Section IV, C, of this report) is incorporated at the power transformer secondary. This circuit is designed for use with thermoelectric generator sources having relatively high internal impedance. The function of the overvoltage protection circuit is to sense an overvoltage at the converter transformer secondary and prevent light load operation by shorting the converter output during each half cycle whenever the source and thus secondary voltage exceeds a predetermined voltage limit.

g. The power oscillator transformers and transistors are specified to conduct reliably and efficiently the maximum currents provided by the RTG sources (short circuit condition). The transistors, diodes and capacitors are specified to withstand reliably the maximum source voltage (open load condition—overvoltage circuit not operating).

Figure 23 is a photograph of the GSFC-developed dual LIV converter breadboard. The two converters are synchronized and phase separated by 90 degrees. The following performance data was obtained from the breadboarded dual converters.

a. Converter Efficiency—including isolation diode losses—normal loading.

   1. Input 3 volts at 11 Amperes—33 Watts input power level (one RTG source energizing one converter)—91%.

   2. Input 3 volts at 22 Amperes—66 Watts input power level (two paralleled RTG sources energizing one converter)—88.6%.

b. LIVC Dissipation—abnormal output load (open circuit loading).

   1. One RTG source energizing one converter-overvoltage protection circuit in operation—4.2 watts.

   2. Two paralleled RTG sources energizing one converter-overvoltage protection circuit in operation—10.9 watts.

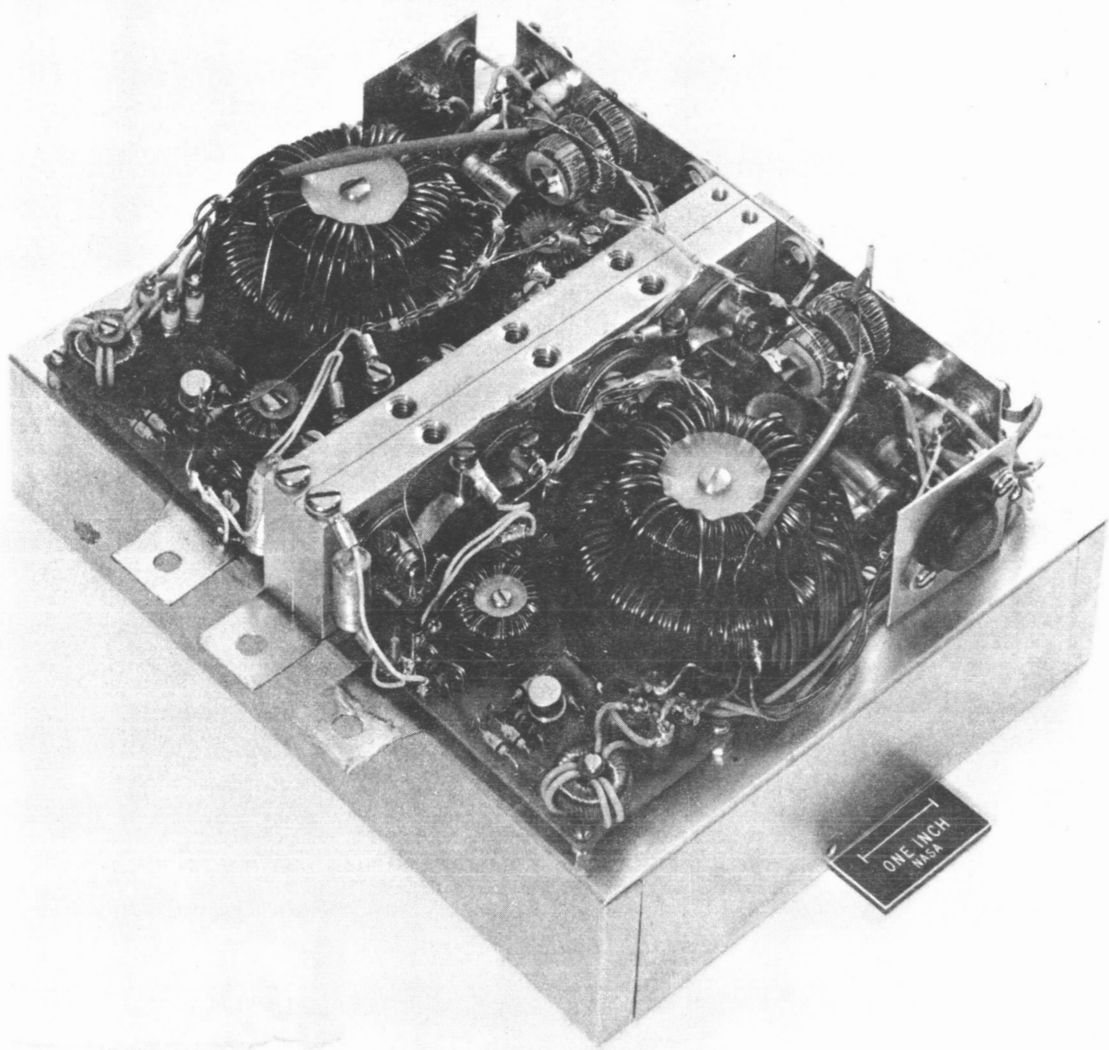


Figure 23. GSFC Developed Synchronized Dual LIV Converter Breadboard.

c. LIVC Dissipation—abnormal output load (short circuit loading)—including isolation diode losses.

1. One RTG source energizing one converter—5.0 watts.
2. Two paralleled RTG sources energizing one converter—13.5 watts.

d. Starting—a slowly rising (approximately 0.25 millivolts per second) source voltage initiates the blocking oscillator of the starting circuit at a voltage level of 0.42 volts, at which voltage, approximately 50 milliamperes peak of pulse base drive is supplied to the oscillator-inverter. It was observed that the starting circuit blocking oscillator reliably started the push-pull oscillator inverter on its first pulse.

The dual synchronized LIV DC to DC converter breadboard of Figure 23 has been under life test without any degradation of output or failures since Oct. 31, 1965.

VII. CONCLUSIONS

1. Some additional understanding of the nature of transistor component failure possibilities in inverter circuits due to voltage/power stress conditions has been obtained. Additional LIV transistor development is required to improve reliability and switching efficiency.

2. A properly designed current feedback driven inverter is inherently safe in the case of overloading when the source is sufficiently power limited. This results from the low internal dissipation of the inverter stage.

3. Functional integrated protection of RTG source and the LIV converter combination against abnormal loading has been successfully developed and applied in the case of the RTG source.

4. The overvoltage protection technique which has low dissipation external to the source output terminals is very useful for space applications of RTG power sources because it enables reduction of size and weight of radiator requirements, and improves overall power system reliability.

5. The approach pursued which requires that reliability be established: at the component, circuit and systems level; for all output loading conditions; for any time interval; for all voltage and for all current capability conditions of the source, has proven to be effective.

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