APPROVED REPORT

Third Quarterly Report

for

A Program of Research and Development of Low Input Voltage Conversion and Regulation

(15 December 1965 - 14 March 1966)

Contract No. NAS 5-9212

Prepared by

Honeywell Inc.
Ordnance Division
Hopkins, Minnesota

for

Goddard Space Flight Center
Greenbelt, Maryland

STOCK COPY

A PROGRAM OF RESEARCH AND DEVELOPMENT OF LOW INPUT VOLTAGE CONVERSION AND REGULATION

THIRD QUARTERLY PROGRESS REPORT

(15 December 1965 - 14 March 1966)

Contract Number NAS 5-9212

Goddard Space Flight Center
Greenbelt, Maryland

Prepared by:

J. T. Lingle
J. T. Lingle
Technical Consultant

Kenneth J. Jenson
K. J. Jenson
Project Engineer

Approved by:

H T Mooers
H. T. Mooers
Project Supervisor

WK Maenpaa
W. K. Maenpaa
Section Chief

Honeywell Inc.
ORDNANCE DIVISION
Hopkins, Minnesota

SUMMARY

This report discusses the work completed and problems encountered on Contract NAS 5-9212 during the third quarter and the work planned for the final quarter.

The primary effort during this third quarter was directed towards the synchronization of three redundant LIVCs and the fabrication of the LIVCRs for the tri-redundant configuration. In addition, consideration was given to load sharing in redundant LIVCs and in redundant regulators in conjunction with general power configuration evaluation.

The synchronization circuit developed for redundant LIVCs maintains an 120 degree phase separation between the current feedback power oscillators. The approach utilizes respective power transformer phase voltages summed in a judicious manner and applied to the frequency determining inductors of individual LIVCs to effect the phase separated synchronization. The circuit operates very well even after failures occur in respective redundant LIVC branches. A breadboard of the circuit was tested for normal operating conditions and for operation after failures had been simulated in various LIVC redundant branches. The performance characteristics as discussed in this report and verified by laboratory testing include:

1. Synchronization 120 degrees out-of-phase maintained throughout the load range when output (or input) voltages of the LIVCs were equal.
2. Low power ($<$ 1 watt) dissipation by the synchronization loop with equal output voltages.
3. Synchronous frequency proportional to the LIVC output voltage.

4. Starting and synchronization established by pulsing either transistor in any of the three LIVCs.
5. Synchronization 90 degrees out-of-phase maintained through load range when one of the three LIVCs stops oscillating (simulated). The operating frequency is then approximately 1.5 times that characteristic with three operating at comparable voltages.
6. Operating frequency, when two of three LIVCs stop oscillating, equal to that when one of three stop oscillating.
7. No failure coupling by the synchronization circuit to adversely affect performance of operational LIVCs.
8. Synchronous frequency proportional to average LIVC output voltage when they are unequal.
9. Phase separation dependent on LIVC output voltage differences when they are unequal.
10. Restoration of 3-phase synchronization when simulated failures are removed.

While the circuit is primarily intended for use in configurations where the LIVC output (or input) voltages are equal, it also operates satisfactorily when unequal voltages are characteristic.

The circuit is especially well suited to application for redundant dc to dc conversion but could also be used to generate 3-phase ac from dc.

When operating from separate thermoelectric sources, three LIVCs operating into a common load share power handling in proportion the source characteristics. Equations for this load sharing have been defined and are presented in this report.

Composite cores used in the LIVC power transformer and current feedback transformer were found to provide definite improvement toward the elimination of half cycle magnetic unbalance in LIVCs.

One of the LIVCR models for the redundant configuration was tested and shown to have regulated efficiencies of over 85% at 100 watts output. The stated efficiency was measured when operating from 3. 0 volts input and with an LIVC power oscillator frequency of 2. 5 kc/s. This model used high speed, epitaxial base power transistors.

TABLE OF CONTENTS

ILLUSTRATIONS

SECTION I

ACTIVITIES OF THE THIRD QUARTER

A. INTRODUCTION

This report discusses the progress made during the third quarter on contract NAS 5-9212 for "A Research and Development Program in Low Input Voltage Conversion and Regulation". This program is a continuation and amplification of work completed under Contracts NAS 5-3441 and NAS 5-3899 toward advancing the state-of-the-art of Low Input Voltage Conversion and Regulation (LIVCR) for use with new energy conversion sources in future satellites. The purpose of this program is:

1. Advance low input voltage conversion and regulation technology to reduce weight, increase efficiency, and increase reliability.
2. Study the "trade-offs" of various combinations of redundant sources and redundant LIVCRs with a storage battery to achieve higher reliability and higher power capability (300 watts) for a three year satellite mission.
3. Study and solve the redundant source-redundant (LIVCR) system integration and operational problems.
4. Breadboard the optimum 300 watt redundant source-redundant LIVCR battery system using several simulated thermoelectric generator sources.

The work conducted during this third quarter included:

1. The design and testing of a circuit to synchronize three LIVC current feedback oscillators 120 degrees out-of-phase.
2. An analysis of load sharing in three redundant LIVCs powering a common load.

3. Continued design consideration and fabrication work on the tri-redundant configuration to be delivered to NASA-GSFC.
4. The design testing of one LIVCR model to be included in the tri-redundant configuration.

The synchronization circuit for three LIVCs utilizes the same basic concepts used in the synchronization circuit for two LIVCs presented in Progress Report 2. The basic concept used is the judiciously summing of respective power transformer phase voltages for application to the frequency determining inductor of individual LIVCs. The approach as presented in this report appears to be very well suited to redundant power system application. In addition, the approach provides advantages to general power conversion and the capability of generating 3-phase ac power from the system.

The LIVC load sharing analysis is an extension of the analysis for two redundant LIVCs previously presented and is specifically oriented to LIVC operation from thermoelectric generators.

The fabrication of the tri-redundant configuration proceeded this quarter and included the completion of one LIVCR model. The performance of high speed, epitaxial base transistors (2N2832) and of the very low saturation transistors (MHT 2313) were compared in the completed model.

B. CONFERENCES

No formal conferences were held this quarter. However, project work was discussed in telephone conversations between Mr. J. T. Lingle and Mr. K. J. Jenson of Honeywell and Mr. E. R. Pasciutti of NASA-GSFC. The synchronization circuits developed during this program were specifically discussed and a rough draft description of 3-phase synchronization circuit was mailed to Mr. E. R. Pasciutti during the quarter. A conference at the Honeywell facility in Hopkins, Minnesota is planned during the final quarter.

C. TECHNICAL DISCUSSION

1. A Synchronization Circuit for Three Redundant LIVCs

Figure 1 shows an operational circuit for the synchronization of three redundant LIVCs. This synchronization circuit is a modification of the approach for synchronizing three LIVCs suggested in the Second Quarterly Report on pp. 18-19. The approach for three redundant LIVCs suggested in that report was found to present problems in starting; therefore, that approach has been abandoned in favor of the approach shown in Figure 1. It is emphasized that the approach for synchronizing two LIVCs presented in the Second Quarterly Report on pp. 3-17 has been found to be very satisfactory and modification is necessary only for the case of three LIVCs.

The circuit of Figure 1 represents two basic modifications of the approach previously suggested. While algebraic summation of individual LIVC phase voltages is still used, two rather than three phase voltages now determined the frequency of operation and the phase separation. The other modification is that the phase separation is now 120 degrees rather than 60 degrees. The separation between successive switching operations is still 60 degrees. The phase separation of 120 degrees lends itself to a possible three phase ac output from the system if desired.

If one of the three LIVCs stops operating, the two operating LIVCs will be synchronized 90 degrees out-of-phase at a frequency approximately 1.5 times that characteristic when three were operational.

If two of the three LIVCs stops operating, the functional LIVC will have an operating frequency equal to that when only two were operational.

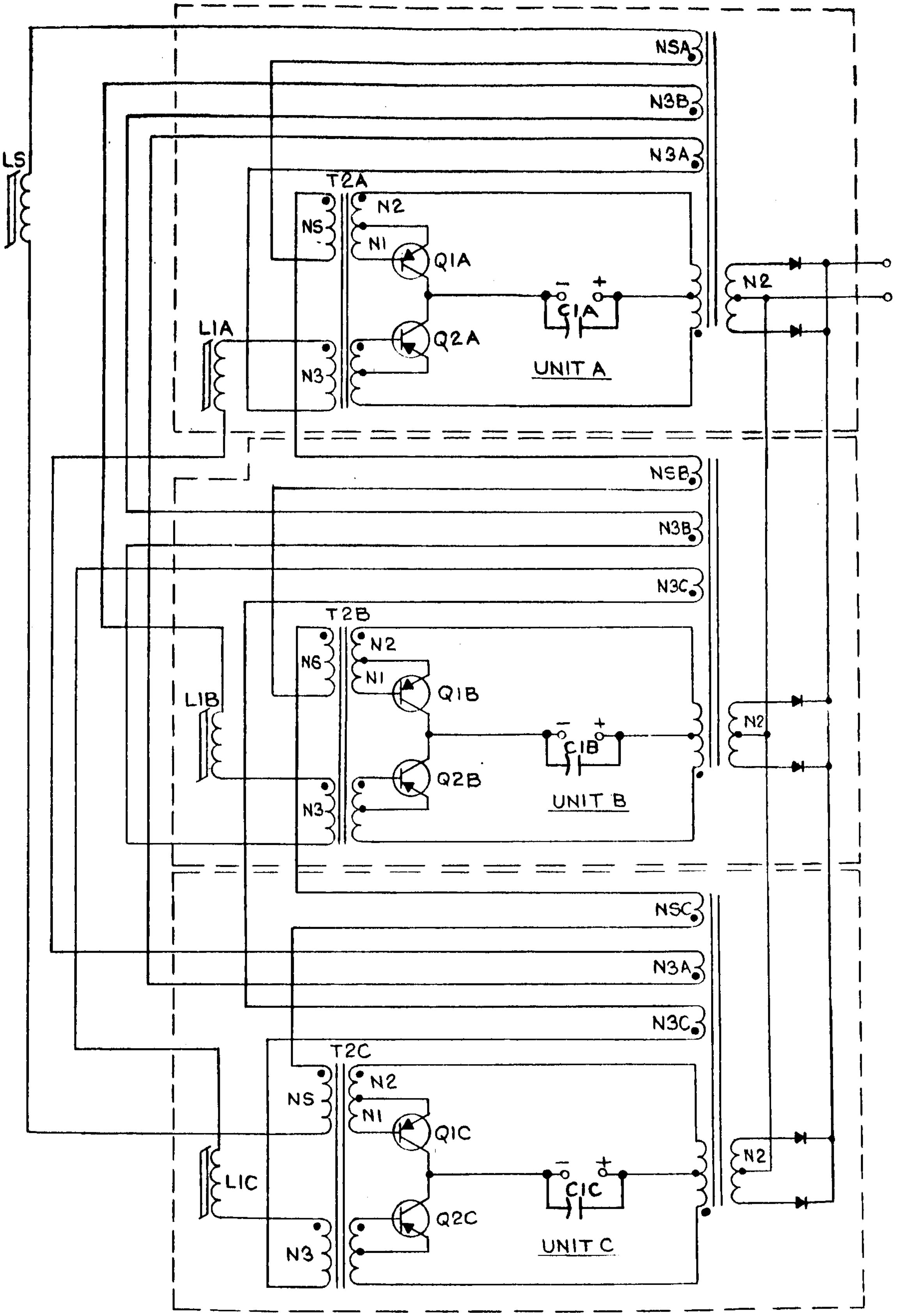


Figure 1 - THREE-PHASE SYNCHRONIZATION CIRCUIT FOR REDUNDANT LIVCs

The laboratory testing of this circuit has provided favorable results. A description of the circuit operation and the laboratory testing is presented in the following paragraphs.

a. Normal Circuit Operation

The synchronization approach shown in Figure 1 is ideally suited to conditions where the LIVC input voltages are equal. Equal input voltages are commonly characteristic in a redundant system. Specific conditions for this characteristic have been discussed in detail in previous reports. When the three LIVC input voltages are equal, synchronization is maintained with a 120 degree phase separation of individual LIVCs. The phase separated synchronization is effected by applying sum and difference phase voltages of respective LIVC power transformers to saturating inductors which effect oscillator switching. The saturating inductors effect switching by allowing a pulse of current to flow upon saturation. This pulse reverses the current feedback transformer voltage similar to the single conventional LIVC circuit. The synchronized frequency is directly dependent on the input voltage.

Complete cycle operation may be best discussed by referring to the circuit diagram of Figure 1 and the waveforms shown on Figure 2. The induced voltage per turn is power transformers T1A, T1B, and T1C is shown by Figure 2 waveforms A, B and C respectively. Waveform A + C is applied to inductor L1A; B + A is applied to inductor L1B; and C + B is applied to inductor L1C. Assuming that the LIVCs are operating and that Q1A has just turned on, the circuit operation through one complete cycle proceeds as follows:

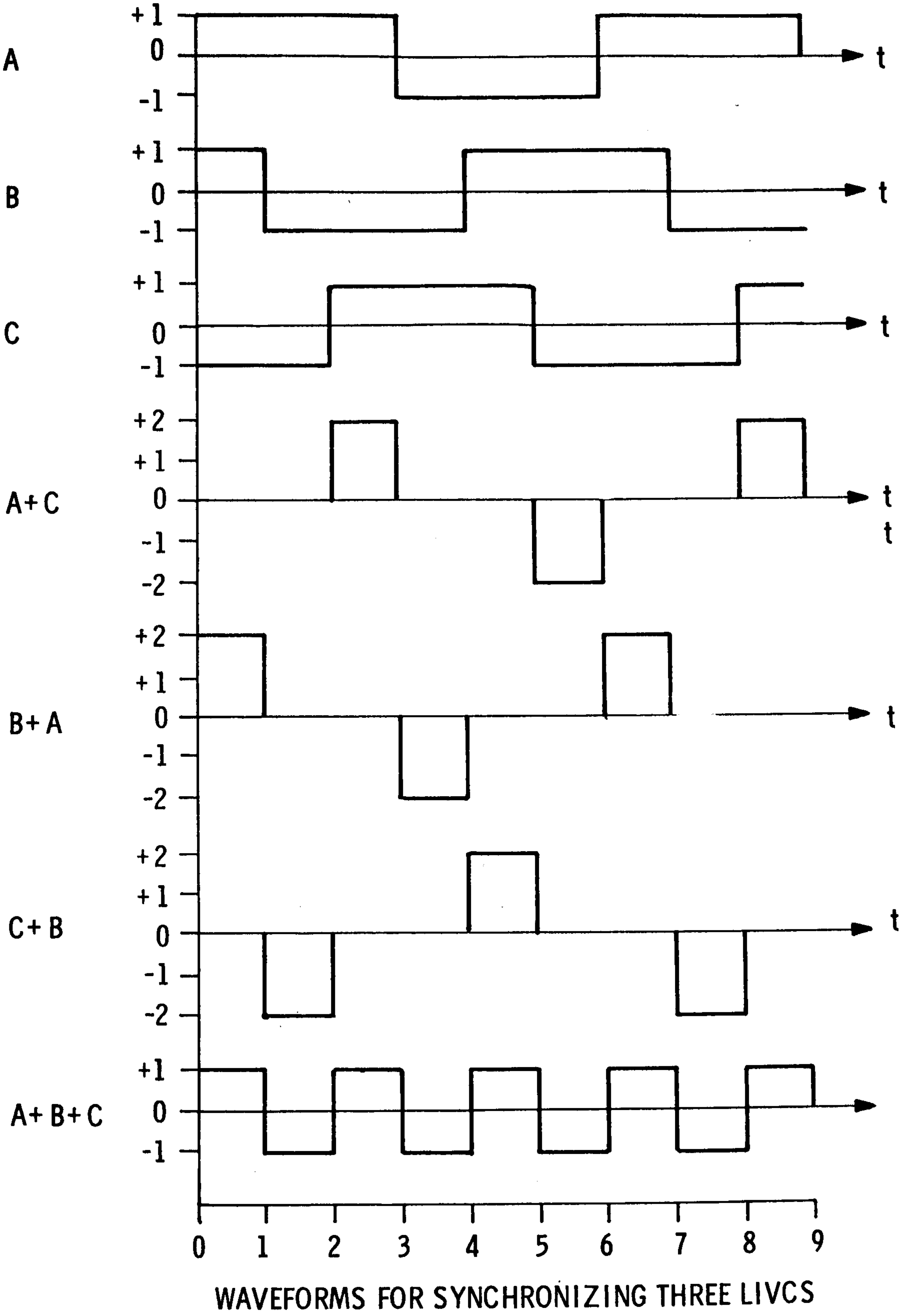


Figure 2 - WAVEFORMS FOR SYNCHRONIZING THREE LIVCs

Q1A has just switched "on" or t=0 on Figure 2.

- Q1B is conducting.
- Q2C is conducting.
- Dotted ends of transformers are positive on unit A, positive on unit B, and negative on unit C.
- Approximately zero voltage is being applied to L1A and L1C respectively.
- A voltage approximately equal to the algebraic sum of voltages on N3B on T1B and N3B on T1A (B + A) is applied to L1B.

Inductor L1B saturates; switching Q1B "off" and Q2B "on" marking one-sixth cycle or t = 1 on Figure 2.

- Q2C is conducting.
- Q1A is conducting.
- Dotted ends of transformers are positive on unit A, negative on unit B, and negative on unit C.
- Approximately zero voltage is being applied to L1A and L1B respectively.
- A voltage approximately equal to the algebraic sum of voltages on N3C on T1C and N3C on T1B (C + B) is applied to L1C.

Inductor L1C saturates; switching Q2C "off" and Q1C "on" marking one-third cycle on t = 2 on Figure 2.

- Q1A is conducting.
- Q2B is conducting.
- Dotted ends of transformers are positive on unit A, negative on unit B, and positive on unit C.

- Approximately zero voltage is being applied to L1B and L1C respectively.
- A voltage approximately equal to the algebraic sum of voltages on N3A on T1A and N3A on T1C (A + C) is applied to L1A.

Inductor L1A saturates; switching Q1A "off" and Q2A "on" marking one-half cycle or t = 3 on Figure 2.

- Q2B is conducting.
- Q1C is conducting.
- Dotted ends of transformers are negative on unit A, negative on unit B, and positive on unit C.
- Approximately zero voltage is being applied to L1A and L1C respectively.
- A voltage approximately equal to the algebraic sum of voltages on N3B of T1B and N3B on T1A (B + A) is applied to L1B.

Inductor L1B saturates (in direction opposite to previous saturation); switching Q2B "off" and Q1B "on" marking two-thirds cycle on t = 4 on Figure 2.

- Q1C is conducting.
- Q2A is conducting.
- Dotted ends of transformers are negative on unit A, positive on unit B, and positive on unit C.
- Approximately zero voltage is being applied to L1A and L1B.
- A voltage approximately equal to the algebraic sum the voltages on N3C of T1C and N3C of T1B (C + B) is applied to L1C.

Inductor L1C saturates (in direction opposite to previous saturation); switching Q1C "off" and Q2C "on" marking five-sixths cycle or t = 5 on Figure 2.

- Q2A is conducting.
- Q1B is conducting.
- Dotted ends of transformers are negative on unit A, positive on unit B, and negative on unit C.
- Approximately zero voltage is being applied to L1B and L1C.
- A voltage approximately equal to the algebraic sum of voltages N3A of T1A and N3A of T1C (A + C) is applied to L1A.

Inductor L1A saturates (in direction opposite to previous saturation); switching Q2A "off" and Q1A "on" marking the end of a complete cycle or t = 6 on Figure 2.

In following the operation through the cycle, it was assumed that the voltage on the N3 windings of the current feedback transformers (T2A, T2B, and T2C) was negligible. Actually, the voltage on the N3 winding of each current feedback transformer is applied to the respective saturating inductor which effects switching of that transformer. Therefore, the assumption made is not strictly the case, but the N3 current feedback transformer voltage is applied in a direction which does not cause a high circulating current. This voltage applied to the inductor changes sign (with the power transformer) after that inductor saturation effects oscillator switching. This sign change means that the voltage sees the high impedance of the inductor progressing toward saturation in the opposite direction at all times except when the narrow pulse of current flows to effect switching. Note that this is very similar to the situation in the circuit for two redundant LIVCs presented in the Second Quarterly Report.

Synchronization frequency is varied proportionally to the input voltage, because the saturating inductors have fixed volt-second integrals. Increasing input voltages are applied to the inductors through the power transformer windings to cause inductor saturation in decreasing time durations. As in the single LIVC circuit, therefore, the maximum flux density in the power transformer core can be kept at a fixed value even as the LIVC input voltage varies.

Phase separation is maintained because of (1) the dependence of the phase voltage summation on the LIVCs' phase separation and (2) the coupling loops between individual LIVCs. The phase voltage summation is shown in Figure 2. The coupling loops are apparent in the circuit diagram of Figure 1 and are discussed in more detail in a following paragraph.

Starting of the three redundant LIVCs can be effected by pulsing either power oscillator transistor in any one of the three LIVCs. Synchronized operation with 120 degree phase separation is established immediately as monitored on an oscilloscope. It was originally though that saturating inductor LS and its associated windings might be necessary to avoid in-phase synchronization following concurrent starting pulses applied to all three LIVCs. Although this will be more thoroughly considered, initial laboratory testing has indicated its inclusion is not necessary.

Applying a starting pulse to transistor Q1A (Figure 1) initiates oscillation of unit A. The inter-oscillator coupling loops also initiate successive starting of unit B and unit C.

b. Description of Operation After A Failure

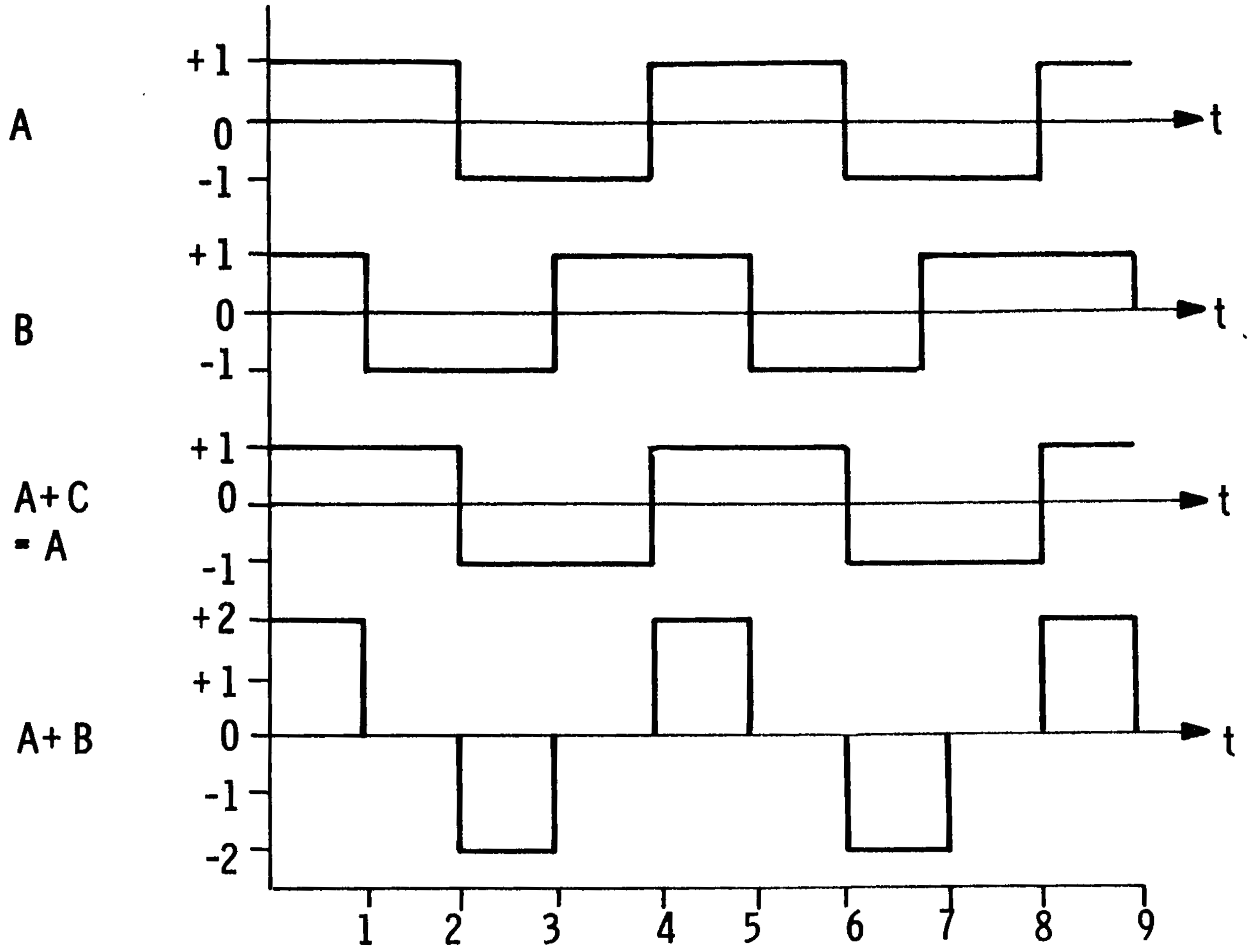
The synchronization circuit shown in Figure 1 should allow the functional LIVCs to operate with no significant decrease in performance even after failures in redundant LIVCs occur.

If a failure occurred in a redundant branch which caused its LIVC to stop oscillating, the voltage on the power transformer of that LIVC would be zero. An immediate result of this zero voltage is that the phase voltage summation applied to respective saturating inductors is changed. The resulting summation after the failure of one and two LIVCs is discussed below. Another consideration after a failure of this type is the impedance afforded by the coupling windings (N3) in the power transformer of the failed LIVC. A failure which placed a short circuit on a power transformer winding should not present a problem. A failure which introduces an open circuit on a winding should be carefully considered. If this open introduces a high impedance, transistor switching could be slowed and/or delayed. Initial testing has shown that this impedance does not appear to be significant if properly considered and that it can be compensated for if it is significant. More thorough testing of possible failure modes will more firmly establish these considerations necessary.

The design of the saturating inductors and their respective impedance relationship to their associated transformer windings impedance is an important system consideration. It is desirable to have a high, unsaturated inductor loop impedance ratio under all conditions. It is also necessary to insure that a pulse current of sufficient magnitude to effect fast switching is allowed to flow in the loop even after failures may occur in respective redundant branches. These considerations are similar to those necessary in the circuit for synchronizing two redundant LIVCs.

(1) Failure of One LIVC - If a failure occurred in the redundant branch containing unit C to the extent that its power oscillator stopped, the waveforms characteristic would be as shown in Case I of Figure 3. These waveforms show that unit A and unit B are operating 90 degrees out-of-phase at a frequency 1.5 times that shown in Figure 2 (equal input voltages are assumed).

CASE I - FAILURE OF UNIT C



CASE II - FAILURE OF UNIT C AND UNIT A

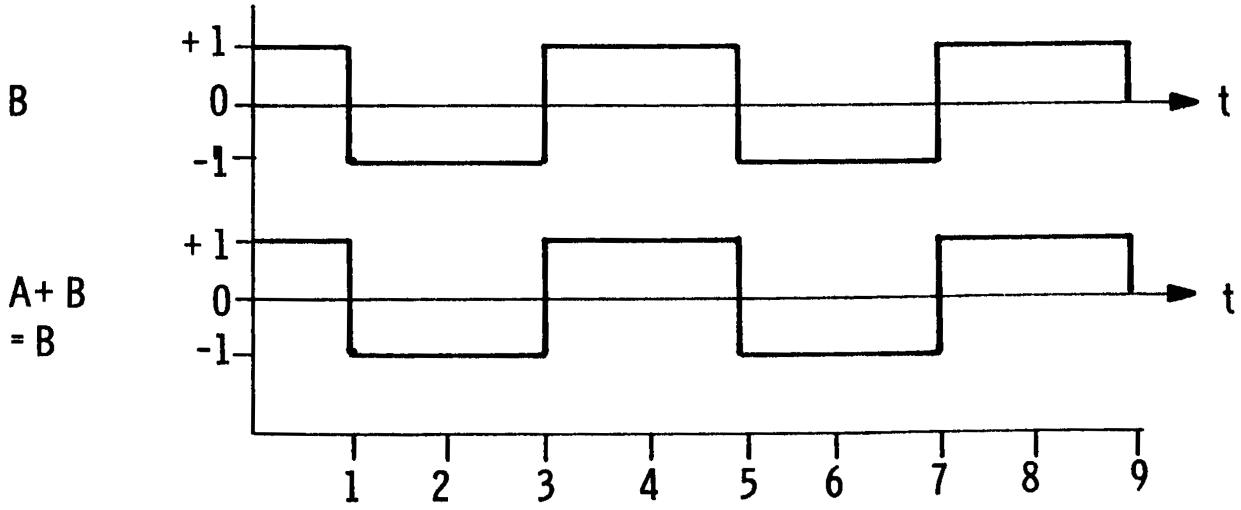


Figure 3 - REDUNDANT FAILURE OF UNIT C AND UNIT A

The A + C waveform is still being applied to L1A, but now A + C equals A. The frequency has been increased because voltage of one-half magnitude is being applied to the saturating inductor for the full half cycle rather than one-third of the half cycle when compared to Figure 2.

The A + B waveform applied to L1B is dependent on the phase relationship of unit A and unit B. This dependence results in unit B being synchronized with unit A at a phase separation of 90 degrees. Note that the area under A + C from t = 0 to t = 2 is equal to the area under A + B from t = 0 to t = 1.

If the failure in unit C is corrected and voltage is supplied to its input, unit C will be immediately started through the coupling windings from the previously operating units A and B. Phase separation at 120 degrees will also be immediately established.

If unit B had failed instead of unit C, unit A would be similarly synchronized 90 degrees out-of-phase with unit C.

If only unit A had failed, unit C would be similarly synchronized 90 degrees out-of-phase with unit B.

(2) Failure of Two LIVCs - If both unit C and unit A power oscillators stopped (in failure mode), the waveforms shown in Case II of Figure 2 would be characteristic. Note that the operating frequency of unit B is the same as it was in Case I even though the waveform has changed.

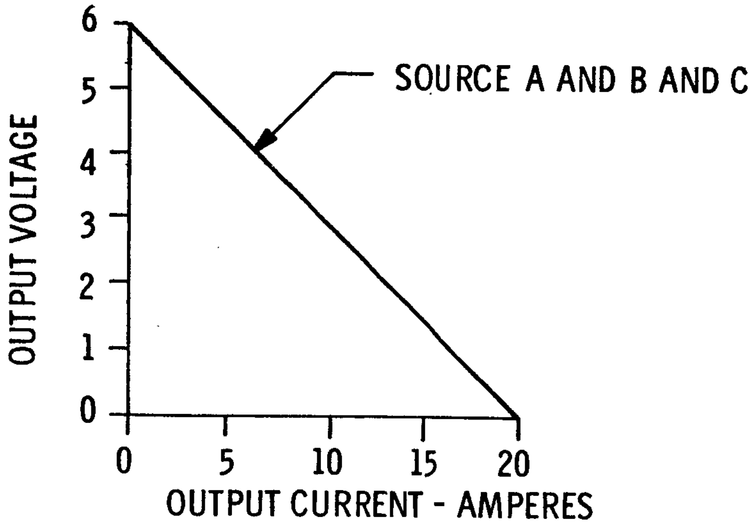
If the failures in both unit C and unit A are corrected and input voltage to both is supplied, unit C and then unit A will be immediately started. Phase separation will be established at 120 degrees. With the failure of only unit C corrected, starting of unit C and 90 degree phase separation will be established. With the failure of only unit A corrected (unit C still failed), operation of unit A will be re-established only by applying a starting pulse to Q1A or Q2A. After applying this pulse, 90 degree phase separation will be established. Unit A would not be started by unit B because there is no direct coupling loop from the power transformer (T1B) of unit B to the feedback transformer (T2A) of unit A. Individual starting oscillators would probably be incorporated in a redundant system anyway so this is no problem.

c. Description of Laboratory Testing

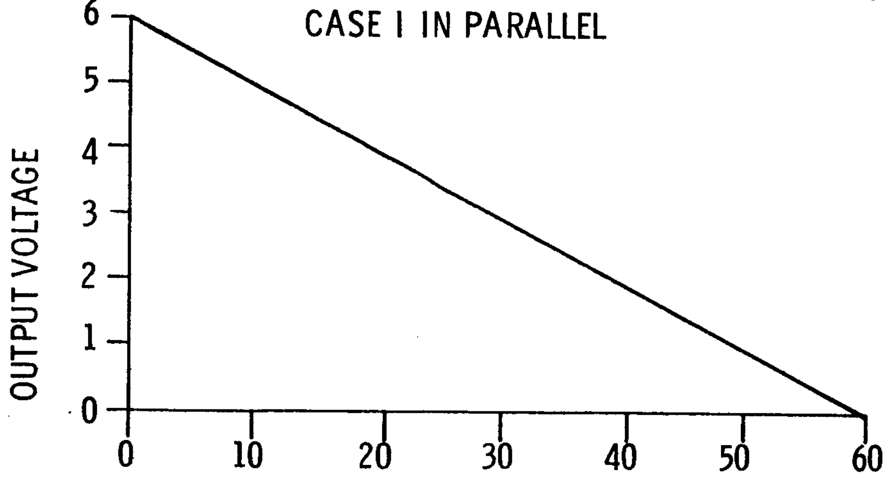
The operational description presented in Section 1. C. 1. a and b. was substantiated by laboratory testing of the breadboarded circuit shown in Figure 1. Synchronized operation of the three LIVCs was maintained for all source-load configurations over the wide input voltage and load ranges tested. The synchronous frequency was proportional to the input voltage, or in cases of unequal input voltages, proportional to the average input voltage. While synchronized, a phase separation of 120 degrees was maintained when operating from a common source and/or into a common load; when operating from separate sources into separate loads, the phase separation was dependent on the difference in input voltages. Simulated failures of one or two LIVCs were not adversely linked into the still operational LIVCs. If one or two LIVCs failed (stopped oscillating), the operating frequency increased to approximately 1.5 times that characteristic for comparable input voltages with all three LIVCs operational.

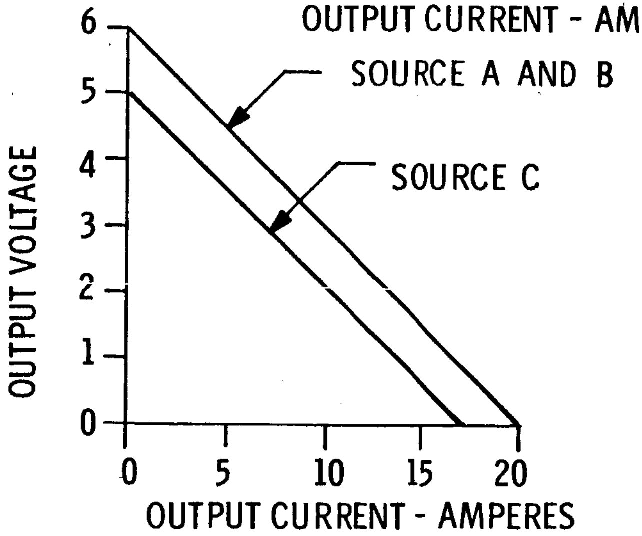
During the laboratory testing, the LIVCs were operated from sources with simulated thermoelectric generator output characteristics. These characteristics were effected by placing a resistor in series with a low impedance voltage supply and are presented in Figure 4. Each individual source simulated had an internal impedance of 0.3 ohms. The characteristic shown in Case I of Figure 4 is typical for each of the three sources (A, B, C)

CASE I - IDENTICAL SOURCE CHARACTERISTICS



CASE II - EFFECTIVE CHARACTERISTICS WITH SOURCES OF CASE I IN PARALLEL





CLASS III - DIFFERENT SOURCE CHARACTERISTICS

Figure 4 - SIMULATED THERMOELECTRIC GENERATOR CHARACTERISTICS

used in testing for normal circuit operation. The 6.0 volt open circuit voltage is representative of thermoelectric generator modules available at NASA-GSFC. Case II of Figure 4 shows the resultant characteristic when three sources, each with the characteristic of Case I, are connected in parallel. The characteristic with the 5.0 volt open circuit voltage shown in Case III was used to simulate possible thermoelectric generator output degradation.

The measured synchronous frequency characteristic of three LIVCs operating into a common output load are shown in Figure 5. As indicated in Figure 5, the synchronous frequency is directly dependent on the LIVC output voltage (which in turn is directly dependent on LIVC input or source output voltage). The common output load results in equal input voltages when each LIVC is delivering power to the unregulated load. Note that the same frequency characteristic was measured when the LIVCs operated (1) from separate and identical sources - Case I, Figure 4, (2) from separate and different sources - Case III, Figure 4, and (3) from a common source - Case II, Figure 4. A phase separation of approximately 120 degrees between LIVCs was maintained throughout the load range tested for all source configurations. The three LIVCs powering a common load were also found to exhibit an identical frequency characteristic when operating from a common, low impedance voltage source.

The synchronous LIVC frequency characteristic after one, and then two, LIVCs fail (stop oscillating) is shown in Figure 6. As discussed in Section I.C.1.b, the synchronous frequency after a failure of this type is approximately 1.5 times that characteristic when all three LIVCs are delivering power. For example, the frequency is approximately 3.3 kc/s at 30 volts out with all three operating (Figure 5); the frequency is approximately 4.8 kc/s at 30 volts out with only two or one operating (Figure 6). (The frequency is not increased exactly 1.5 times because the voltage on the current feedback transformer windings N3, Figure 1, is nearly constant and does contribute to

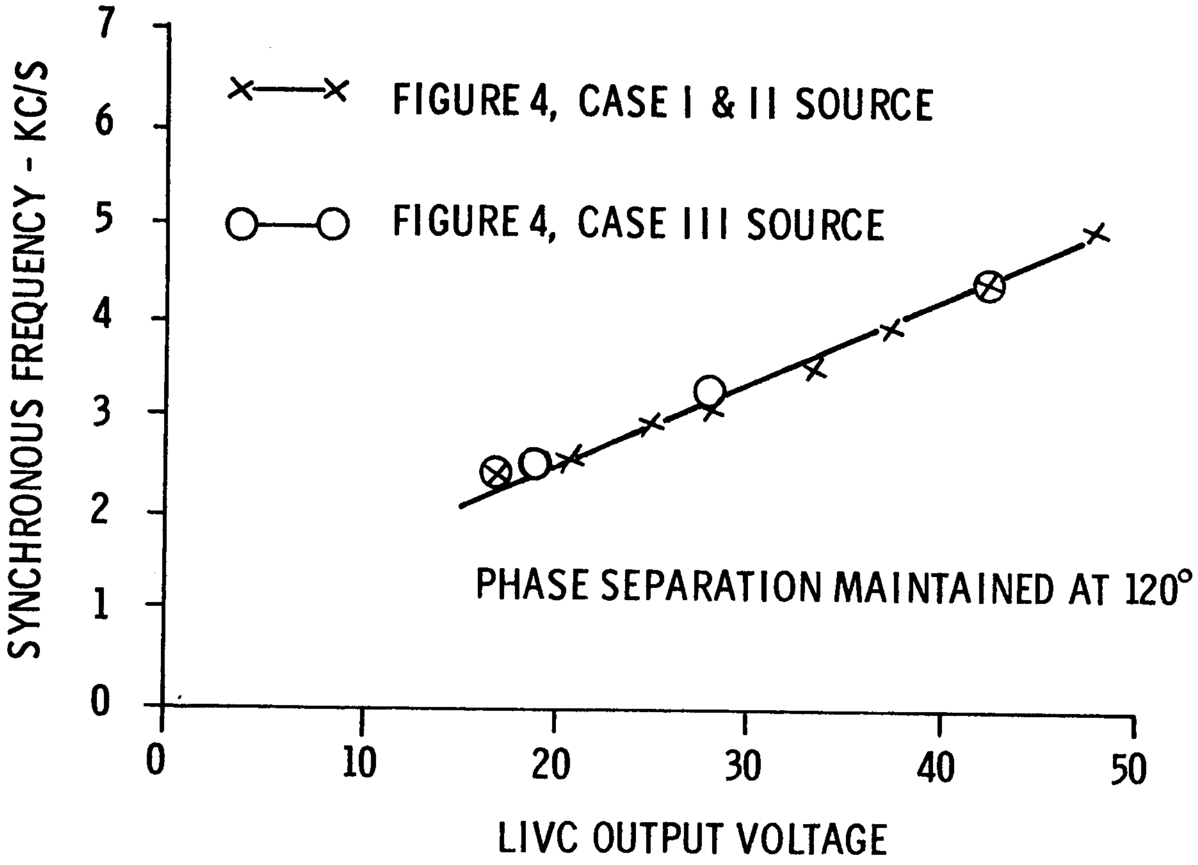


Figure 5 - MEASURED SYNCHRONOUS FREQUENCY CHARACTERISTICS WITH THREE LIVCs OPERATING INTO COMMON LOAD

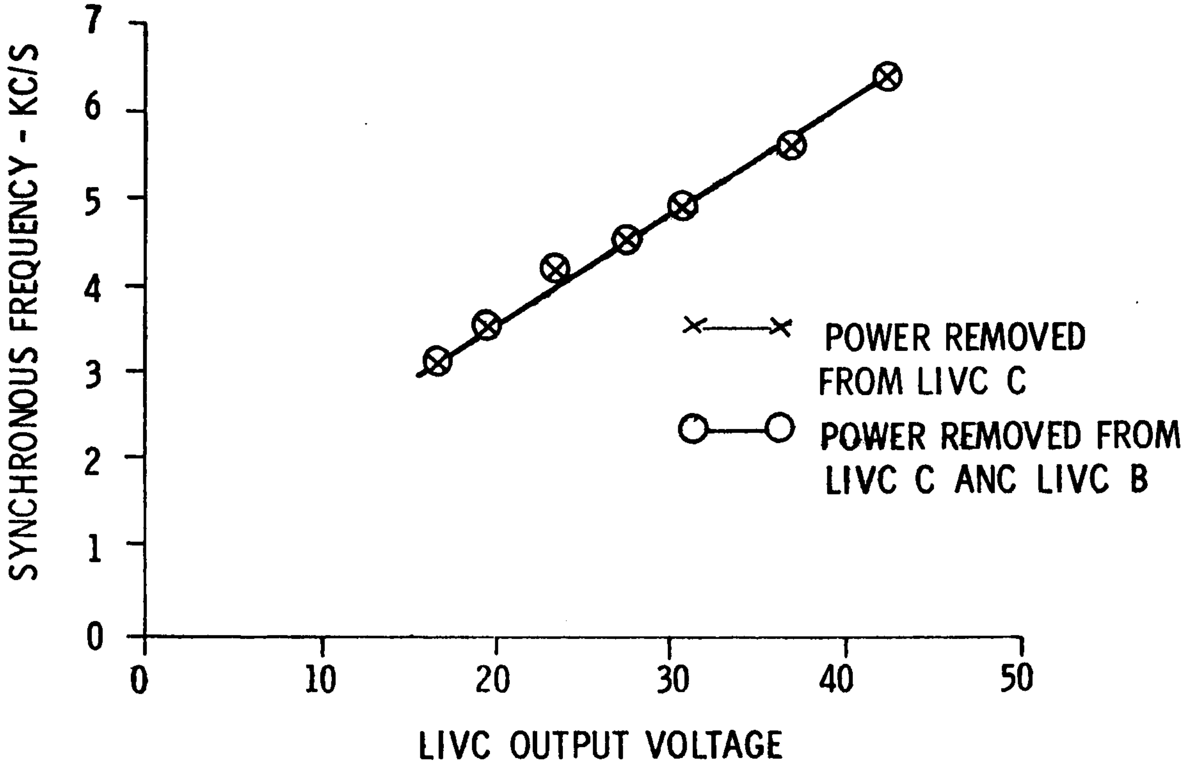


Figure 6 - MEASURED SYNCHRONOUS FREQUENCY AFTER FAILURE WITH LIVC COMMON LOAD

the voltage applied to the frequency inductors (L1A, L1B, L1C).) Note that the operating frequency is the same when either one or two LIVCs are operational. The phase separation when only two LIVCs were operational was approximately 90 degrees over the entire load range.

The modes of failure which cause individual LIVCs to stop oscillating or may be typical of that mode were thoroughly investigated with respect to their effect on the still operational LIVC(s). The types of failures considered included (1) open and short circuits on a power transformer winding, (2) open and short circuits on a current feedback transformer winding, and (3) open and short circuits on the LIVC input. The results and considerations of these various failures are summarized below:

> Open power transformer winding - This failure mode must be given the most consideration of all the modes because it could result in a high impedance presented by the N3 windings on the power transformer.
>
> A high impedance by the N3 winding would decrease the operating frequency and cause significant deviation from the 90 degree phase shift normally characteristic when two of three LIVCs are operational. The high impedance can be avoided by assuring that a low impedance to a pulse (switching current pulse for the operational LIVCs) is provided to at least one winding on the power transformer. This could be a single resistive low impedance but would typically be a capacitor. Capacitive loading can be provided by inserting a capacitor across N3 or some auxiliary winding, but is generally sufficiently provided by the LIVC input capacitor. Transistor (Q_1 or Q_2, Figure 1) junction capacity and leakage usually provide a path to the input capacitor such that it is effectively across the power transformer primary.
>
> Such capacitive loading was found to negate the effects of open circuits on other power transformer windings. In some instances, a slight frequency change on slight phase shift from the normal existed but no adverse affects were noted.
>
> Shorted power transformer winding - No adverse affects were noted. Slight phase shift from 90 degrees with two operational only apparent result.

Open current feedback transformer winding - No adverse affects noted.

Shorted current feedback transformer winding - This failure can effect an open power transformer winding if the power transistor collector-to-emitter junction is not shorted. If capacitive loading is provided on some power transformer winding, however, this is no problem. The shorted current feedback winding clamps the emitter-base junctions of the power transistors. The clamping reduces the leakage path through the transistors to the input capacitor providing capacitive loading. The shorted current feedback winding therefore is a special case of an open power transformer winding and can be compensated for in the same manner.

Shorted input - No adverse affects were noted.

Open input - No adverse affects noted. The measurements for the curves of Figure 6 were for this failure mode; however, approximately the same results were obtained in each of the other failure modes also.

In summary, no adverse affects of LIVC failure were coupled to the operational LIVCs; however, the requirement of capacitive loading on at least one winding of each power transformer to assure such operation was shown during the testing.

Each of the three operational LIVCs were operated from separate sources and into separate loads. While this mode of operation is not planned, it simulates the operation of individual LIVCs from separate sources and into separate regulators. Synchronization was maintained throughout the load range and voltage difference combinations tested. The frequency as shown in Figure 7 was found to be directly proportional to the average of the LIVC output voltages. The frequency characteristic obtained compares directly to that of Figure 5 where a common and equal output voltage was established. It is significant, however, that currents of magnitudes and for time durations proportional to the voltage differences flowed in the negative feedback loops. This current flow resulted in some power dissipation but was held to a low value by resistance in the loop. The most important result was that synchronization was maintained.

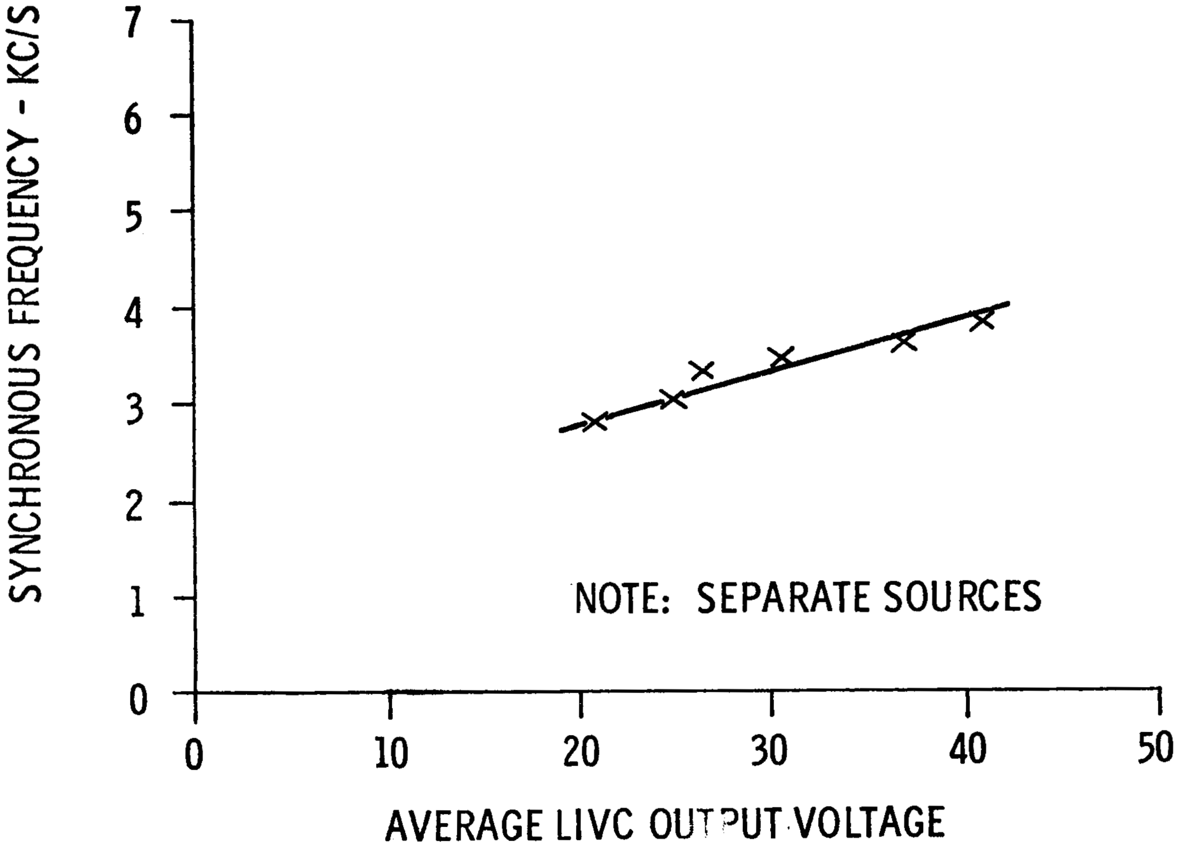


Figure 7 - MEASURED SYNCHRONOUS FREQUENCY WITH THREE LIVCs OPERATING INTO SEPARATE LOADS

Figure 8 presents the phase separation variation as the output voltages become unequal. The slope of the characteristic presented varies with the operating voltage of the units used for comparison.

While operating from separate sources and into a common load, the power transformer secondary winding N2 was opened from one LIVC. Power was then delivered to the load by only two LIVCs, but all three were oscillating. The operating, synchronous frequency was proportional to the average LIVC input voltage. No adverse affects were noted.

If the failure modes were removed which caused the LIVC(s) to stop oscillating, synchronous operation was immediately restored. As is discussed in Section I. C. 1. b. (1) and (2), synchronization is re-established without starting pulses unless only one of two failed LIVCs are corrected. In this case, it depends on which LIVC has been corrected and which unit has been operational. For example, if LIVC B is operational and LIVC A but not LIVC C has had a failure mode corrected, LIVC A will require a starting pulse to establish operation and synchronization. If LIVC C had been corrected, but not LIVC A, LIVC C would start and be synchronized with LIVC B without a starting pulse. The referenced Section treats this in more detail.

The redundant LIVCs could be started by pulsing either power transistor in any one of the three LIVCs. Synchronization was established immediately as monitored on an oscilloscope.

d. Capability for 3-Phase AC Output

While the synchronization approach shown in Figures 2 and 3 was specifically developed to synchronously, phase separate oscillator switching in a redundant LIVC configuration, 3-phase ac outputs may also be provided by it. The accuracy of the phase separation is determined by the equality of the saturating inductor volt-second integrals and the equality of the transformer voltages.

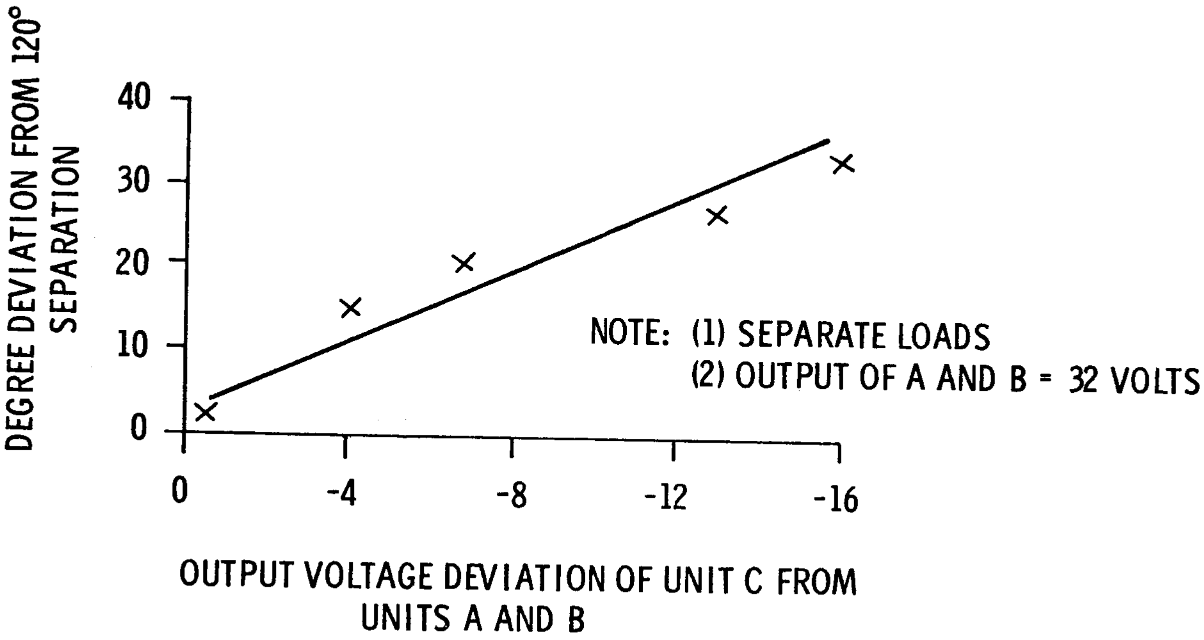


Figure 8 - PHASE SEPARATION OF LIVC C WITH OUTPUT OF LIVCs A AND B CONSTANT

A suggested voltage addition for 3-phase ac output is shown in Figure 9. The addition would be realized by the proper phase connection of respective power output windings on the respective power transformers. This particular addition was previously developed in conjunction with voltage drive 3-phase circuits by Honeywell. The output addition could be identical here in the current drive application. This addition reduces the third harmonic content and simplifies necessary filtering as there is no void in the waveform. The facet of 3-phase outputs could be considered in more detail if indicated to be desirable by NASA-GSFC.

The frequency of the ac output would vary directly with input voltage in this particular application.

2. Load Sharing in Three Redundant LIVCs Powering a Common Load

The operation of redundant unregulated LIVCs into a common load causes the input voltages (source voltages) as well as the output load voltage to be equal if all redundant LIVCs are contributing power to the load. The operating source voltage is equal to that voltage at which the load requirements and the sources' capabilities are equal. The equal source voltages and the source characteristics determine the individual source - LIVC load sharing when each LIVC is operating from a separate source. This load sharing was discussed in some detail in Progress Report I (pp. 35 - 40) for two redundant LIVCs operating from separate thermoelectric generators. The discussion is extended to include three redundant LIVCs below.

The source characteristics shown in Figure 10 are assumed for this discussion. It is assumed that each source impedance is resistive and equal to the other two. These characteristics may be typical of three identical thermoelectric generators operating at different temperatures. The load resistance (R_L) on the source is that provided by the LIVC - LIVC output load resistor combination. The LIVCs are identical to each other.

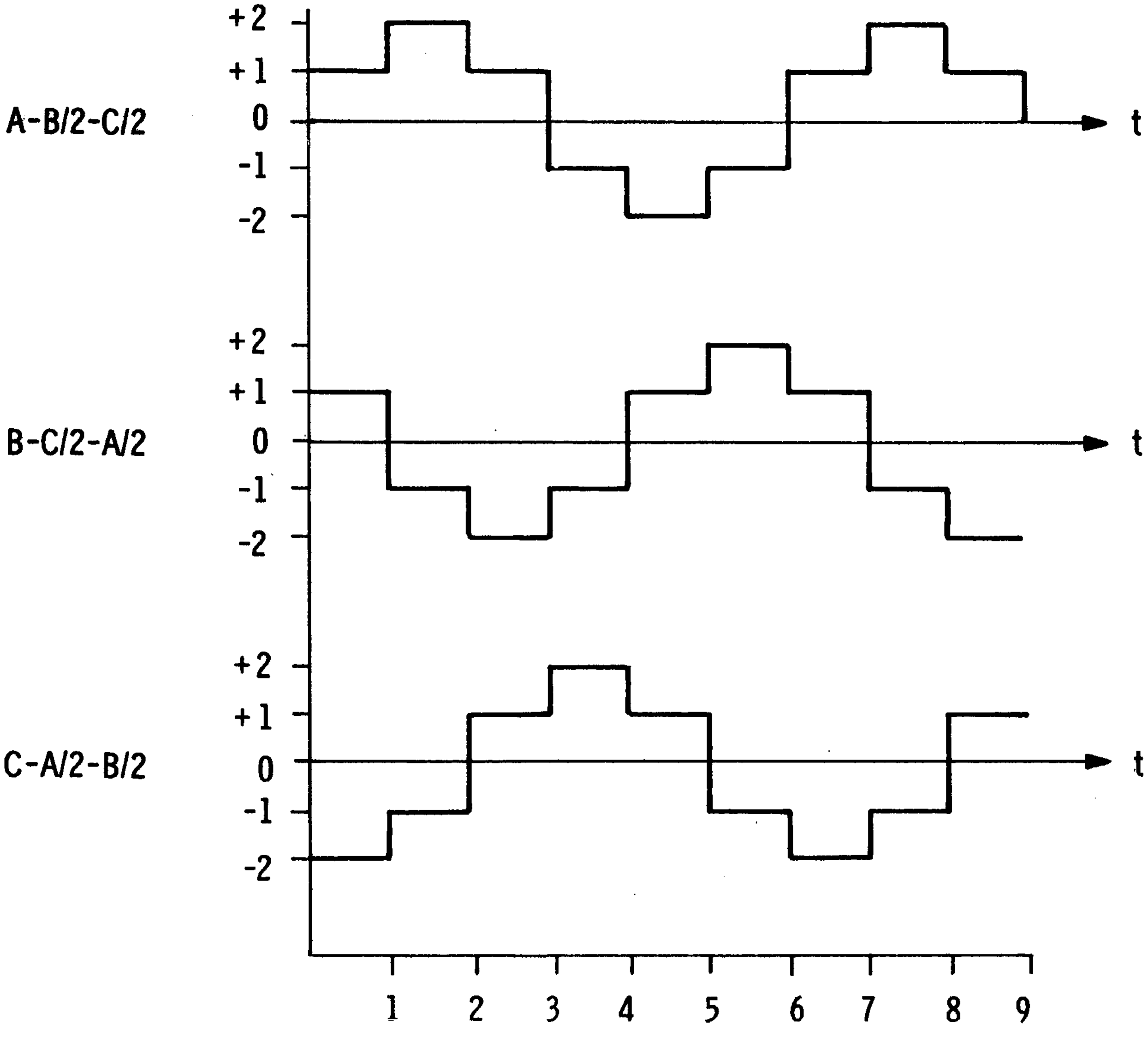


Figure 9 - SUGGESTED VOLTAGE ADDITION FOR 3-PHASE AC OUTPUT

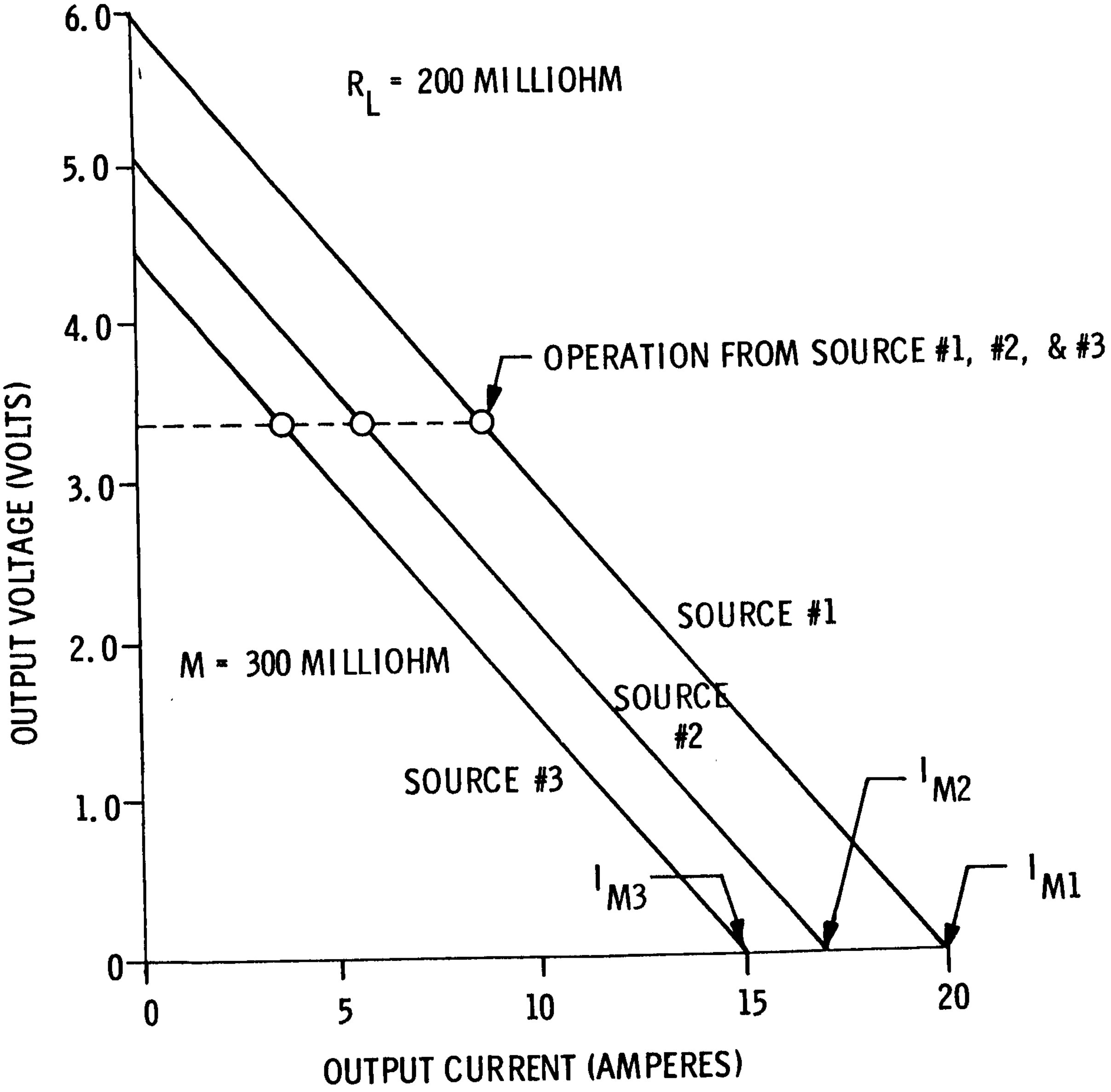


Figure 10 - THERMOELECTRIC GENERATOR SOURCE CHARACTERISTICS AND COMMON OUTPUT LOAD SHARING

The source voltages are caused to be equal by the reflection of the common LIVC output through the power transformers. Therefore:

$$V_1 = V_2 = V_3 \tag{1}$$

where

V_1 = terminal voltage of source 1

V_2 = terminal voltage of source 2

V_3 = terminal voltage of source 3.

These voltages are defined by the individual characteristics of Figure 10 to be

$$V_1 = m\,(I_{m1} - I_1), \quad V_2 = m\,(I_{m_2} - I_2), \quad V_3 = m\,(I_{m_3} - I_3) \tag{2}$$

where

m = source impedance

I_1 = output current of source 1

I_2 = output current of source 2

I_3 = output current of source 3

I_{m1} = maximum current of source 1 characteristics

I_{m2} = maximum current of source 2 characteristics

I_{m3} = maximum current of source 3 characteristics.

From equation (1) and (2)

$$I_{m1} - I_1 = I_{m2} - I_2 = I_{m3} - I_3 = B \qquad (3)$$

where B is defined only by equation (3).

The resulting power out vs. power in equation is

$$\frac{V_1^{\,2}}{R_L} = V_1 I_1 + V_2 I_2 + V_3 I_3$$

or

$$\frac{V_1}{R_L} = I_1 + I_2 + I_3 \qquad (4)$$

where R_L = resistive load.

Solving for I_1 at a specific R_L we get

$$\frac{m\,B}{R_L} = I_1 + I_{m2} + I_{m3} - 2B \qquad (5)$$

rearranging

$$I_1 = \frac{mB}{R_L} + 2B - I_{m2} - I_{m3}$$

or

$$I_1 = \frac{I_{m1}\left(\frac{m}{R_L} + 2\right) - I_{m2} - I_{m3}}{3 + \frac{m}{R_L}} \qquad (6)$$

Similarly,

$$I_2 = \frac{I_{m2}\left(\frac{m}{R_L} + 2\right) - I_{m2} - I_{m3}}{3 + \frac{m}{R_L}} \qquad (7)$$

and

$$I_3 = \frac{I_{m3}\left(\frac{m}{R_L} + 2\right) - I_{m1} - I_{m2}}{3 + \frac{m}{R_L}} \qquad (8)$$

Solving for B in this three redundant case, we get

$$B^{(III)} = \left(\frac{R_L}{3R_L + m}\right) \left(I_{m1} + I_{m2} + I_{m3}\right) \qquad (9)$$

As shown in Progress Report 1 (p. 40), this compares to a value of

$$B^{(II)} = \left(\frac{R_L}{2R_L + m}\right) \left(I_{m1} + I_{m2}\right) \text{ for the two redundant case} \qquad (10)$$

and

$$B^{(I)} = \left(\frac{R_L}{R_L + m}\right) I_{m1} \quad \text{for operation from a single source.} \qquad (11)$$

The equations above define the individual LIVC load sharing when each LIVC is operating from a separate source and into a common load (Figure 11A). Because of the series connection, this is also the load sharing between sources. To obtain the value of the resistive source load (R_L) in the above equations, the following equation is used.

$$R_L = R \left(\frac{N_p}{N_s}\right)^2 \eta$$

where

R = resistive load in the LIVC output

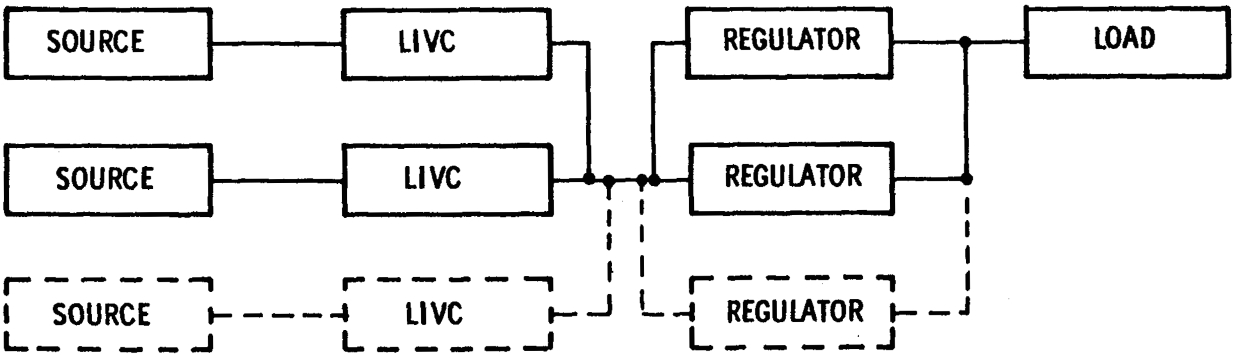
$\left(\frac{N_p}{N_s}\right)$ = primary to secondary turns ratio on power transformer

= LIVC efficiency expressed as fraction of 1.00.

It should be noted that if the LIVCs are operating into a common load consisting of a regulator-resistive load combination, the LIVC load is that presented by the combination. The LIVC load will therefore not be equal (generally) to the load on the regulator.

If a common LIVC input- LIVC output configuration (Figure 11B) is used, the preceding equations apply only to the load sharing in the sources. The LIVC load sharing would be approximately equal if the LIVCs are identical.

A) SEPARATE SOURCES



B) COMMON SOURCES

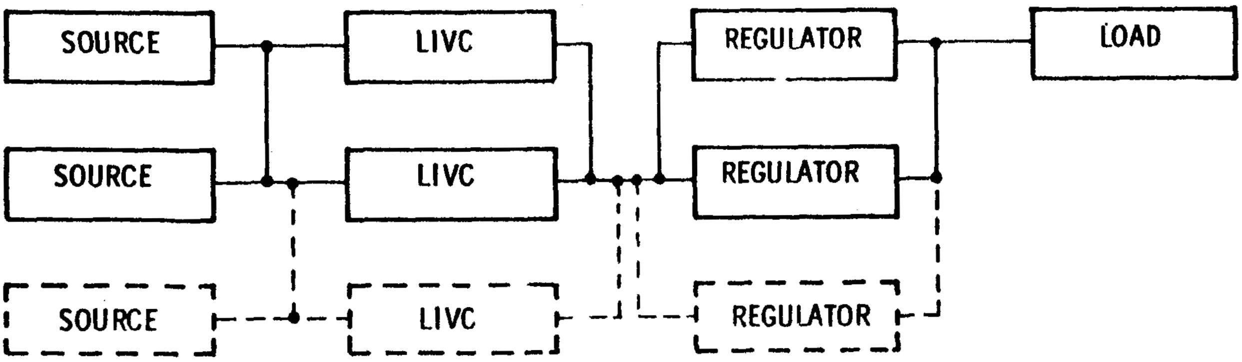


Figure 11 - SOURCE - LIVC - REGULATOR CONFIGURATIONS

3. Redundant Configuration Fabrication

One LIVCR model (Figure 12) for the tri-redundant configuration has been fabricated and its performance is discussed in Section I. C. 4. As shown in Figure 12, the unit is of a breadboard-type construction and does not represent minimum size. The breadboard-type construction faciltiates fabrication, design testing, and any modifications which may be necessary during testing. The second LIVCR model is presently being fabricated and will have the same construction as the first unit. These two units will be used specifically to test and verify load sharing and overload characteristics of parallel regulator sections.

The third LIVCR model is being designed with some consideration given to packaging for limited environmental testing. The environmental tests defined in the proposal Scope of Work include:

1. Operate and record performance at -20° C to +70° C.
2. Subject to 1×10^{-4} mm mercury ambient pressure.
3. Humidity: MIL-E-5272A, Procedure 1.
4. Vibration: Sinusoidal vibration of 10 g's from 20 - 2000 cps for 10 minutes in each of three planes, and random Gaussian applied to 0.07G^2 R MS/cps from 20-2000 cps for 5 minutes in each of three planes.
5. Check for reliable starting at -50° C.

It is not necessarily intended that this third model be suited for a specific flight application, but rather that it incorporate general packaging techniques suitable for a flightworthy unit.

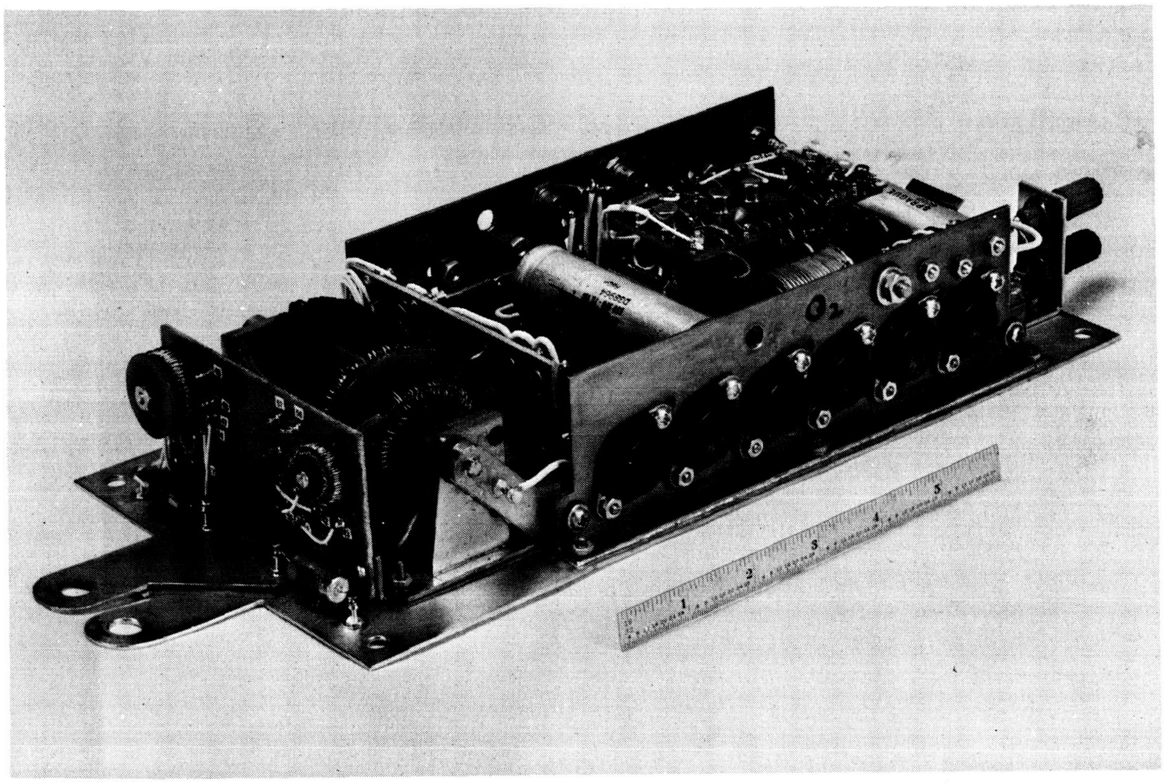


Figure 12 - LIVCR FOR TRI-REDUNDANT CONFIGURATION

The reliability analysis conducted during the second quarter is being reviewed and evaluated specifically with respect to the tri-redundant configuration and the manual switching to be provided. Military rotary switches have been procured to switch the LIVCs output, regulator input and output, and various bias supplies as necessary in the regulator section. It is presently planned that the basic redundant configuration will have (1) separate LIVC inputs, (2) common LIVC outputs, (3) common regulator inputs, and (4) a common load to the regulators. In this configuration, LIVC load sharing would be determined as discussed in Section I. C. 2 assuming thermoelectric generator characteristics; regulator load sharing will require considerations as discussed in Progress Report II. It is planned that voltage droop in each regulator will be used to effect load sharing and that overload protection be a function of the total current delivered by all regulators. This overload protection will allow two regulators to supply full power if one of the three fail. The overload could be made to limit the output of each regulator to a specific value if required, but would require some redesign if the regulators are operated in parallel.

4. Design and Performance of Fabricated LIVCR

A photograph of the first LIVCR fabricated for incorporation into the deliverable redundant configuration is shown in Figure 12. The positive and negative inputs were designed so that they have a parallel plate construction to present a more capacitive, less inductive lead impedance. The power transformer has a two turn primary winding. The transistor mounting plate is constructed to allow the incorporation of either the high speed transistors in the TO-3 can as shown or the very low saturation transistors in a TO-36 can. This unit weighs 4. 7 pounds.

During laboratory testing, the MHT 2313 low saturation transistors tested in the LIVC were found to have inadequate voltage capabilities when the LIVC was operated from 6. 0 volt open circuit, thermoelectric generator output characteristics. Even though these transistors were specially selected from the low saturation transistor family for high V_{ECO} voltage, the transistors were not capable of withstanding the voltages encountered. High speed, epitaxial base transistors (2N2832) were found to be more satisfactory for this particular application. The higher saturation voltage of the 2N2832 is not very significant at the input voltages above 2.5 volts and their faster switching capability allow higher frequency LIVC operation. This model operates from approximately 2.5 kc/s at 3.0 volts input to approximately 5.0 kc/s at 6.0 volts input. The use of the higher speed transistors also made it possible to eliminate some of the switching speed-up circuitry found to be advantageous when the slow, low saturation transistors are used.

A circuit diagram of the model is shown in Figure 13. Note that this is a modification of the circuit diagram presented in Progress Report II (Figure 9, page 27 of that report) involving the elimination of pulse transformers T3 and T4 and the addition of two constant current supplies for zener diodes in the overload circuit. The pulse transformers were eliminated because, with the high speed transistors, the reduction in switching loss caused by their inclusion was less than the added I^2R power loss. Removing the transformers T3 and T4, also simplifies the circuit. The inclusion of the constant current supplies reduces power consumption in the zener series resistor and maintains the respective zener currents closer to their temperature compensated value.

While not apparent on the circuit diagram, composite cores have been incorporated in the power transformer and the current feedback transformers. The current feedback transformer core is comprised of 80% Supermalloy and 20% (outside portion) non-oriented Silicon steel. The power transformer core is comprised of 75% Supermalloy, 12.5% Round Orthonol, and 12.5% non-oriented Silicon steel. The initial evaluation of these cores on a ∅-H Curve

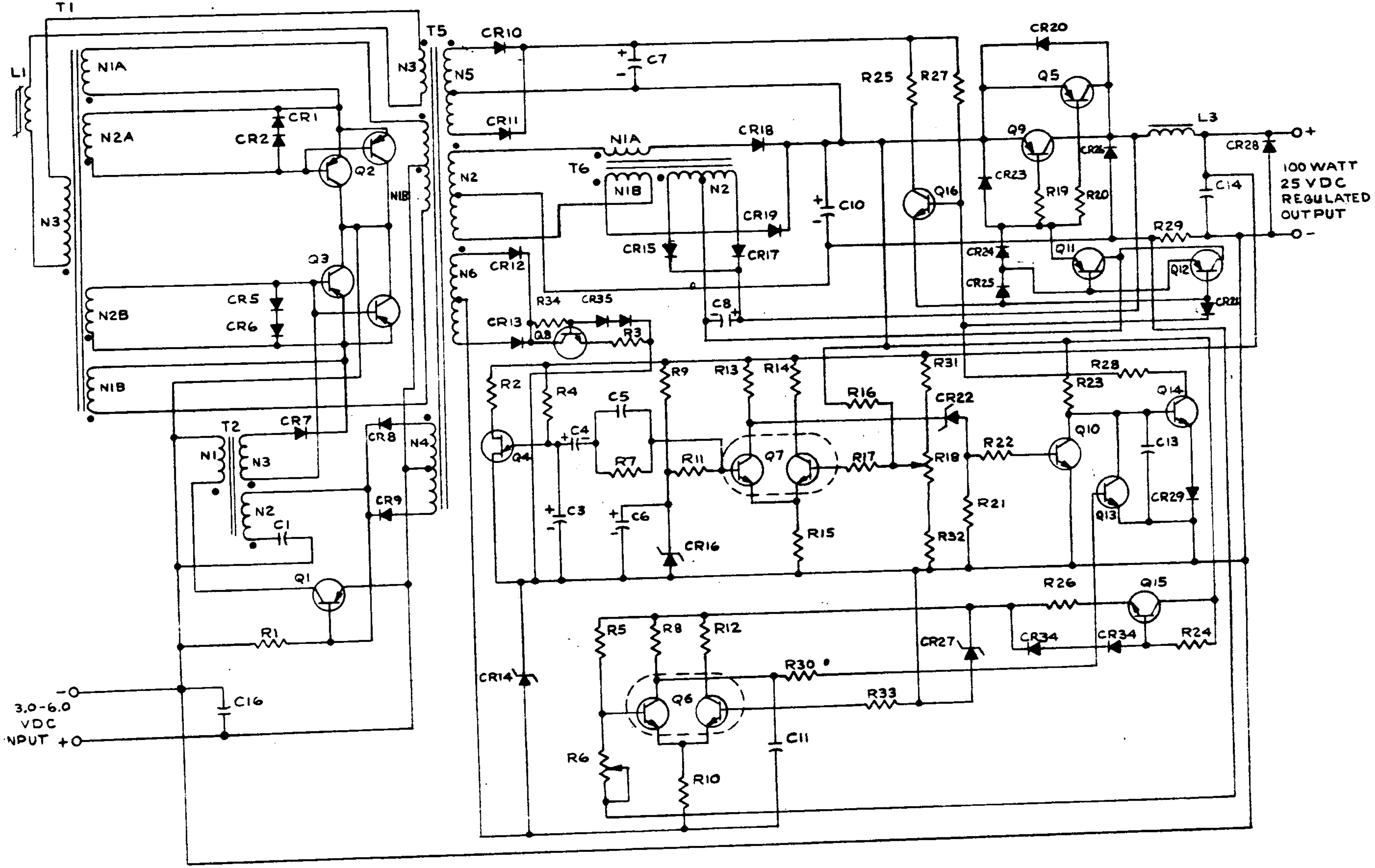


Figure 13 - LIVCR CIRCUIT DIAGRAM

Plotter indicates they will tend to diminish the effects of magnetic half cycle unbalance in the core. No half cycle unbalance has been noted to date in LIVC models using the composite cores.

The efficiency vs. power performance of this LIVCR as measured in the laboratory is presented in Figure 14. The curves are presented for the entire load range at each input voltage (3.0, 4.0, 5.0, 6.0 volts dc). It is recognized however that when operating from a thermoelectric generator the input voltage will vary with load. With a thermoelectric generator providing the power, the efficiency of 85% at 3.0 volts would probably be the most significant operating point for efficiency considerations.

This model was operated from a simulated thermoelectric generator characteristic (6.0 volts open circuit, 75 milliohms impedance). The model operated with no problems. The efficiencies compared directly to those presented in Figure 14 for various loads and resulting input voltages.

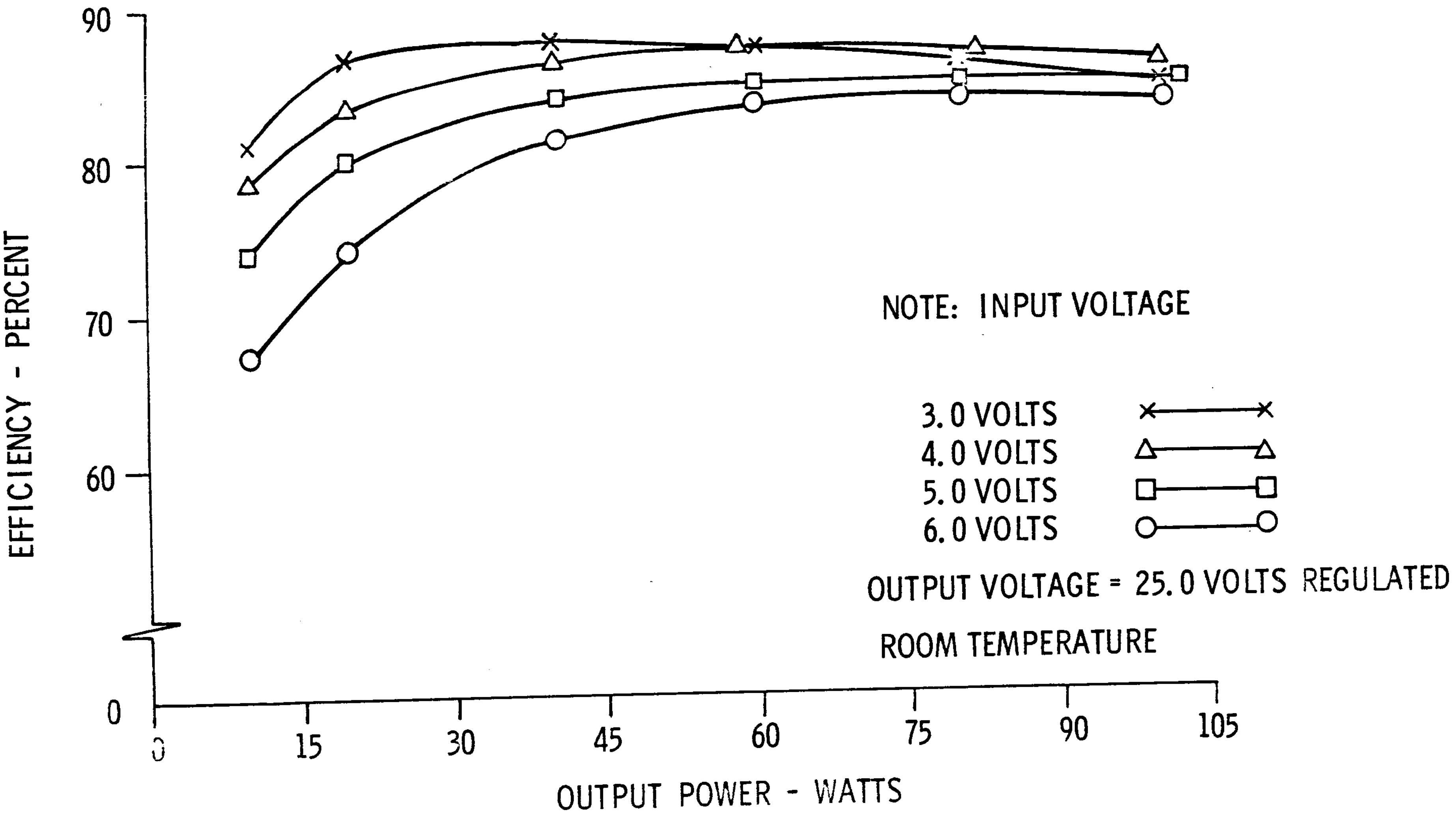


Figure 14 - EFFICIENCY CHARACTERISTICS OF FABRICATED LIVCR MODEL

SECTION II

NEW TECHNOLOGY

A circuit for the 3-phase synchronization of three redundant LIVC current feedback oscillators was developed this quarter. This circuit maintains a 120 degree phase separation between LIVC power oscillators over wide load and input voltage ranges. The synchronous frequency is directly dependent on LIVC input voltage. Besides providing the advantages of synchronous operation, this approach provides the added advantage of separating respective switching operations by 60 degrees. By separating switching operations, input and output transients and therefore filtering requirements are reduced. The approach is especially well suited to the redundant system application in that synchronization of the two operational LIVCs is maintained after the failure of one LIVC. In addition, the two LIVCs are then phase separated. Failures in an individual LIVC are not adversely coupled to the still operational units by the synchronization circuit.

A description of the circuit operation during normal operation and after failures in redundant branches is presented in Section I. C. 1. The laboratory testing of the breadboarded circuit is also discussed in conjunction with a presentation of measured performance.

This circuit approach also lends itself to the generation of 3 phase ac power.

SECTION III

PROGRAM FOR NEXT QUARTER

During the next quarter, fabrication of the tri-redundant LIVCR configuration will be completed. Design testing will be conducted on the system to verify proper load sharing and stable operation. Any design changes which may be necessary to improve the configuration performance will be incorporated. The effects of possible failure modes will also be evaluated further. The reliability analysis conducted will be used in determining the manual switching to be provided in this deliverable model.

One of the three LIVCRs for the redundant configuration will be designed to withstand limited environmental testing. This environmental testing will include (1) operation at temperature extremes (-20° C to +70° C), (2) subjection to low pressures, humidity, and vibration, and (3) a check for reliable starting at -50° C.

The final version of the redundant configuration will be subjected to pre-shipment tests by the Evaluation Department.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

The design analysis and laboratory testing of the developed 3-phase synchronization circuit for three current feedback oscillators indicates that it is very well suited to the redundant LIVC application.

The circuit was developed for LIVC configurations which result in equal input (or output) voltages; therefore, it is best suited to configurations with (1) common LIVC input voltages, (2) common LIVC output voltages and operating from high impedance sources, or (3) equal LIVC loads and operating from identical, high impedance sources (such as a thermoelectric generator). With equal input or output LIVC voltages, synchronization is maintained with 120 degree phase separation at a frequency proportional to the LIVC voltage.

The circuit also maintains synchronization when unequal LIVC voltages are characteristic. These unequal voltages are likely when LIVCs are operated into individual and/or unequal loads or separate regulators unequally supplying a common load. In this case, synchronization is maintained at a phase separation proportional to the LIVC voltage difference at a frequency proportional to the average LIVC voltage.

Assuming equal LIVC voltages, the failure of one of the three LIVCs results in synchronization of the two operational LIVCs 90 degrees out-of-phase at a frequency 1.5 times that characteristic for comparable voltages with three operational. This characteristic is very desirable because the two LIVCs may well be capable of supplying the load after a failure of one, thereby enhancing mission success.

Simulated failures in redundant LIVCs were not adversely coupled by the synchronization circuit into the still operational LIVCs; therefore, the increased reliability afforded by the redundancy is not impaired.

The power transformers of each LIVC must be provided with a capacitive load on at least one winding to insure a low impedance path even after possible LIVC failures for the current pulses effecting switching in the operational LIVCs. This capacitive loading is generally provided by the LIVC input capacitor or may be provided by an auxiliary winding load. If a power transformer is shorted on the failed unit, no capacitive loading is necessary.

The 60 degree separation of individual LIVC switching operations reduces system input and output transients and required filtering. This is a decided advantage not only in a redundant system but also for general power conversion. In other words, strictly from the standpoint of reducing transients it may be desirable to operate three synchronized converters handling one-third the total power each rather than one large converter handling all of the power. Transient reduction is especially desirable in the low voltage conversion application because of the associated high current levels.

Three-phase ac power, free of third harmonics can be obtained from the synchronized configuration by proper winding design and voltage addition.

The LIVC load sharing resulting when the converters are operated from separate, high impedance sources into a common load, can easily be predicted and is shown in this report. The LIVC input voltage will be determined by the voltage at which the load requirements and the sources' capabilities are equal.

The use of composite cores for the LIVC power transformer and current feedback transformer has shown definite reduction in the occurrence and effects of magnetic half cycle unbalance in the LIVC. This has been shown in core evaluation and also in actual LIVC application; in fact, no half cycle has been noted to date in LIVCs using composite cores.

The very low saturation transistors were found to be unsuitable for inclusion in the LIVC when it is operated from a thermoelectric source with a 6.0 volt open circuit voltage because of inadequate V_{ECO} ratings.

High speed, epitaxial base transistors were found to be very adequate at this input voltage and allow higher (up to 5 kc/s) power oscillator frequencies. The use of the high speed transistors also allows the elimination of some switching enhancement circuitry, specifically the base pulse transformers, necessary with the slow speed, low saturation transistors.

The LIVCR using the high speed transistor exhibited efficiencies of over 85% with 100 watts output and 3.0 volts input.

DISTRIBUTION LIST

Contract No. NAS 5-9212

NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
Attention:

Office of the Director - Code 100	(1)
Office of the Assistant Director for Administration and Technical Services - Code 200	(3)
Office of the Assistant Director for Systems Reliability - Code 300	(1)
Office of the Assistant Director for Projects - Code 400	(1)
Office of the Assistant Director for Tracking and Data Systems - Code 500	(1)
Office of the Assistant Director for Space Sciences - Code 600	(1)
Office of the Assistant Director for Technology - Code 700	(1)
GSFC Library - Code 252	(2)
Contracting Officer - Code 246	(1)

NASA-Scientific and Technical Information Facility P. O. Box 5700, Bethesda, Maryland 20014	(3) (1 reproducible)

NASA Headquarters
Washington, D. C. 20546
ATTN:

Preston T. Maxwell (RNW)	(1)
James J. Lynch (RNP)	(1)
A. M. Greg Andrus (ST)	(1)
James R. Miles, Sr. (SL)	(1)
Milan J. Krasnican (MAT)	(1)

NASA Manned Spacecraft Center
Houston, Texas 77001
ATTN: A. B. Eickmeier (1)

NASA Goddard Space Flight Center - Code 716
Greenbelt, Maryland 20771
ATTN: Wm. R. Cherry (1)
Fred C. Yagerhofer (1)
Charles M. MacKenzie (1)
E. R. Pasciutti (6)

NASA Marshall Space Flight Center
Huntsville, Alabama 35812
ATTN: James C. Taylor R-ASTR-R (1)
Richard Boehme R-ASTR-E (1)
Richard G. Smith R-ASTR-E (1)

NASA Lewis Research Center
Cleveland, Ohio 44135
ATTN: Robert L. Cummings (1)
Howard Shumaker (1)
Charles Corcoran (1)

NASA Langley Research Center
Hampton, Virginia 23365
ATTN: John L. Patterson (1)
Wm. O'Sullivan, Jr. (1)

NASA Electronic Research Center
Cambridge, Massachusetts
ATTN: Dr. F. C. Schwarz (1)

NASA Ames Research Center
Moffett Field, California 94035
ATTN: James Swain (1)

Jet Propulsion Laboratory
Pasadena, California 91103
ATTN: Paul Goldsmith (1)
Charles D. Fredrickson (1)
Alden Schloss (1)

Naval Research Center
Department of the Navy
Washington 25, D. C.
ATTN: B. J. Wilson (1)

Bureau of Naval Weapons
Department of the Navy
Washington 25, D. C.
ATTN: Milton Knight (1)

Air Force Aeropropulsion Laboratory
Wright Patterson AFB
Dayton, Ohio
ATTN: APIE-3 (1)

U. S. Army R&D Laboratory
Energy Conversion Branch
Ft. Belvoir, Virginia
ATTN: Ralph E. Hopkins (1)

Power Information Center
Moore School Bldg.
200 S. 33rd St.
Philadelphia 4, Pennsylvania (1)

Duke University
College of Engineering
Department of Electrical Engineering
Durham, North Carolina
ATTN: Professor T. G. Wilson (1)

U. S. Army Electronics Command R&D Lab
Energy Conversion Branch
Fort Monmouth, New Jersey
ATTN: J. J. Byrnes (1)