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**A GOVERNING ELECTRONIC MECHANISM
OF THE ION PROPULSION ENGINE**

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A GOVERNING ELECTRONIC MECHANISM OF THE ION PROPULSION ENGINE

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Abstract

The ruggedness of an electronic mechanism that transforms, controls and coordinates the electric power for the individual functions of an electric ion propulsion engine is related to the stresses imposed on its semiconductor switching components. Causes and nature of these stresses in transistors and thyristors operating within conventional and unorthodox systems are discussed. A system is described which allows the use of highly stress tolerant switching components and yet minimizes these stresses under static and dynamic conditions of operation. Experimental results of integration of a 95% efficient, single module, 2 kW electronic converter with a 20 cm ion propulsion engine are presented.

I. Introduction

The reaction caused by the focused acceleration of a large number of electrically charged small particles, such as ionized gas molecules, manifests itself in the form of thrust and finds application to space vehicle propulsion. Electric energy is used for vaporization of liquid metals, followed by the ionization, acceleration and eventual deionization of these vapors. The advantage sought over chemical propulsion is that of higher energy density of the combined electric and ion engine equipment when compared to that of chemical propellants and the associated structures. This expected advantage increases with duration of the thrust application if one derives the required electric energy from the sun or from nuclear-thermal sources. Physical size and weight of the electric equipment are determined by the peak power level, rather than the duration of the mission within reasonable limits, such as several years. The mass of needed propellant remains proportional to the duration and magnitude of thrust; however, the mass of propellant for electric propulsion is moderate compared to that of chemical propellants which incorporate both mass and the fuel for propulsion.

A. The Electromechanical System

Availability of an adequate amount of electric energy for a given mission and of a working ion engine appear requisite to the implementation of such a propulsion system. The flow of power from the source of electric energy to the engine is governed by an electronic control system. This system implements current or predetermined command functions and channels electric power to the individual internal functions of the ion engine. These include its metal vaporizer,

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the cathode heater, the magnet coil, and the electric beam, to name some (1, 2). The electronic control system interacts with every one of the significant components of the ion engine, providing energy at time varying rates to these components, and in so doing, governing the functions of the individual engine components and of the engine as a whole. The electronic power supply and control system is in this sense an integral part of the engine and performs its governing and coordinating functions through its extraneous tools, which are mechanical parts of the engine. A partition of the system into mechanical and electrical portions appears rather as an artificial cut along the disciplines of concerned personnel, than to reflect the character of engine technology.

System Requirements - The misconception that these engines need a "power supply" rather than a complex electronic system which is an integral part of the engine to supply, coordinate, and control the power flow to its various functions has contributed to a retardation of the development in this area of technology. This electronic system performs the functions to:

1. Supply power to the individual engine components.
2. Coordinate the power flow to any of the components with the instantaneous state of all other components for purposes of implementing a given command of the control system.
3. Protect the engine structure and the prime source of electrical energy from violent transient electric stresses that may be caused by engine operation characteristics.
4. Reconcile the static and the dynamic characteristics of engine operation with that of the source of electrical energy.

Concepts of Operation - The functional philosophy and the implementary mechanisms of the ion propulsion engine are described in the literature (1, 2). The electronic power and control system supplies continuous electric power to every one of the engine's functions when operating in the steady state mode. There are approximately ten such functions as indicated in Figure 1. All of these could be supplied with dc power. The operating voltages are, in some instances, chosen at levels of five or ten volts, such as for the beam focusing magnet, coil, and for various heater functions. In some cases, one has resorted to the application of ac power for reasons of economy of energy, to avoid the power loss of rectifier filter systems which become significant for low-voltage applications. Some of these power supply channels float at potentials of several kilovolts and are the cause of substantial concern to prevent voltage breakdown near appreciable quantities of ionized gases within a very low gas pressure environment.

During the starting phase of the engine, it is required that its individual functions are initiated in proper sequence and according to predetermined modes. Neither sequence nor mode are, however, necessarily invariant and require modifications according to incident conditions of operation. This is implemented by a self-aligning feedback system that controls all channels of power transfer at any time.

Normal operation of the engine is frequently interrupted at times when the steady-state field in the plasma is disturbed by arcing, mostly due to sputtering of the propellant. Engine operation is then usually discontinued by removing the electric power that sustains the beam and is subsequently resumed by reapplication of power to the various engine elements in an appropriate sequence of events. This procedure may or may not clear the previously existing fault conditions and could require continued recycling of engine operation in this fashion until steady-state conditions can be reestablished.

Some of the power transfer channels will undergo substantial variations of their transfer characteristics during these phases of transition. The output voltage of the so called "arc supply" varies over a ratio of 3:1 or more, and observes simultaneously varying limits that are imposed on the supply of current. The volt-ampere characteristic of this channel of power supply is depicted in Figure 2, which illustrates some of the imposed requirements. The indicated output voltage and current variations are determined by the electronic control systems and are generated in response to its predetermined program, as modified by feedback signals that originate from other engine functions.

The electronic control mechanism is accordingly of substantial complexity, since it interlinks the otherwise uncoordinated functions of a sophisticated engine. This apparent complexity is compounded by several constraints whose purpose it is to secure that:

1. No part of the engine is damaged by untimely or unduly energizing any given functions.
2. The source of energy be protected against violent transient power requirement caused by problems in engine operation.
3. The electronic power and control system protects its own critical components against damage caused by violent transients.
4. The electronic power and control system operate within the constraints of maximum efficiency and reliability, minimum physical weight and size and tolerance of a hostile environment.

The preceding considerations are closely interdependent. Reliability of the electronic system as a whole and minimum physical weight and size are diametrically opposed requirements. System weight and size are inversely proportional to the internal frequency of electronic converter operation, yet the life expectancy of critical components of the system such as semiconductor switching elements decreases with an increase of this frequency. The necessity to accommodate wide variations of the voltage of an exotic source of electric energy and of the power demand of certain engine functions imposes substantial penalties on power electronic apparatus in the form of added power capacities to satisfy temporary requirements.

The speed of dynamic response of the electronic system increases with its frequency, since the energy storage elements in its circuits decrease in size accordingly. This, however, reduces the size of cushions that protect the

vulnerable switching elements of the electronic systems from the impact of sudden electric stresses that arise concurrent with violent transients in engine operation, during and after arcing. The conflict between physical bulk and reliability of power electronics equipment is further compounded by a component problem of long standing which arises with the use of power transistors in circuits that contain inductive storage elements.

B. The Power Transistor as Switching Element

The power transistor has evolved from gradual development of the smaller transistors used in signal level electronic circuits. Its junctions are relatively large to accommodate current flow at power levels and its geometries have been tailored to withstand the voltages encountered in current spacecraft electric systems. The requirements for adequate collector current carrying and voltage hold-off capability reflect the need for high power handling capacity. However, both of these requirements affect the high frequency or switching characteristics of the device unfavorably. This type of device is known to be sluggish during the transition from the conducting to the nonconducting state and vice versa. Appreciable amounts of energy are being dissipated in the devices during these transitions. This dissipation was displayed as a function of time on the screen of an oscilloscope, using a wattmeter with a bandwidth of 10 MHz for that purpose (3). A photograph of the trace is shown in Figure 3. The power dissipated in the device during settled current flow appears as a flat saddle-like shape in the central portion of the curve. The "peaks" located at both ends of that flat portion correspond to the instantaneous volt-ampere product during the closing and opening phases of the switching transistor. A 10 μ H inductance was added to the resistive 10 ohm load to simulate the leakage inductance of a transformer or other distributed effects in order to provide realistic test conditions for this observation.

This photograph indicates that the instantaneous stresses that are imposed on the device are substantially larger than their average. These are, however, the composite stresses imposed on the device as a whole, and do not indicate the localized stresses and their spatial distribution throughout the semiconductor junction and its proximity. The intensity of these localized stresses is not known. The engineer will, therefore, derate the device for some of the following reasons:

1. To allow a safety margin for peak stresses that occur during steady-state operation.
2. To accommodate the increased stresses transient phases of operation such as engine start-up and its shutdown following arcing.

Yet, derating reduces the power handling capability of a switching device often to 10% or less of its maximum volt-ampere product. The overriding reasons for this extent of derating are the needed ratios of the maximum instantaneous to the average steady state values of voltage and current respectively. Because of its structure, can the transistor tolerate only a very modest excursion beyond its maximum rated current for any length of time. One way to increase the power capacity of switching functions is to operate two or more transistors in parallel.

But, unless these devices match perfectly and continue to match over the required range of temperature, and throughout their aging process these attempts may and do lead in unequal load sharing and result, ultimately, in the sequential destruction of the paralleled devices. Finally, one resorts to operation of complete modules of electronic power converters in parallel and in such a way that load sharing is accomplished. The price for this approach is a multiplication of the complexity of the system including the need for a coordinating system for these modules. Furthermore, the actual power handling capability of a pair of power transistors operating in one such module is presently limited to approximately 300 watts. Propulsion systems requiring 10 kW are presently under development and substantially larger systems are envisioned for the future.

It could appear that the reliability of a specific channel of an electronic control and power supply system would be enhanced by a larger number of modules. The fallacy of this reasoning becomes immediately apparent when the cumulative number of component parts that are absolutely needed for such a channel of power conversion (without redundancy) is compared to a single module system. It may, of course, be indicated to divide the system for a given power capacity into a number of modules to meet certain reliability requirements. However, the number of these modules should not be dictated by the physical limitation of switching devices, but chosen for maximum reliability.

The vulnerability of an electronic switching element in the form of a power transistor was predicated primarily on the effects of two assumptions:

1. The switching element is being used to forcibly interrupt established currents in circuits which include leakage or distributed inductances, and has, therefore, to tolerate the associated cyclically recurring adverse transient effects.
2. The coupling of these circuits to the adjacent - generator and ion engine - systems is such that any variation in the behavior of these systems will proportionally affect the stressed imposed on the switching component.

These effects are compounded by:

3. The inability of the transistor to tolerate more than very moderate excursions of current beyond its rated values, even during short time intervals.
4. The lack of suitable devices with ratings that would permit construction of single module multikilowatt converters of conventional design.

It appears on the surface that it is necessary to develop power transistors for use in larger converters, that is, if one insists to apply them in conventional circuit configurations. Another approach which overcomes the discussed limitations is presented in the following.

II. The Load Insensitive Series Converter

A. Desired Switching Characteristics

A solution of the problem, as exposed in the preceding section, is indicated by the cause of the adverse effects on switching elements, stated under 1 and 2 above. A functional mechanism has to be devised for that purpose in which:

- 1a. The switching element closes and opens in the presence of insignificant or zero current flow in the associated circuits.
- 2a. The characteristic behavior of these circuits is such that the stresses on the switching components are only moderately affected and up to a predictable limit at times when the behavior of the adjacent - generator and ion engine - systems undergo significant variations.

Satisfaction of these two requirements removes the necessity for substantial derating of switching elements in converter circuits for technical reasons. Furthermore, the maximum stresses imposed on the components can then be predicted with certainty; this certainty permits a meaningful estimate on the life expectancy of the switching elements based on test data acquired under analogous conditions of operation. An electronic functional mechanism which satisfies these requirements is presented in the following.

B. Functional Philosophy

The series converter is a system that uses series resonant LC circuits for the transformation and transfer of electric power from the source of electric energy to the load (4, 5). In so doing, it performs the functions of voltage scaling and stabilization (6, 7), within one single process. The symbolic circuit diagram of such a converter is shown in Figure 4. Switch CR_{11} closes at a time when capacitor C_{11} is discharged. As a result, a current will flow from source e_s through switch CR_{11} , inductor L_1 , transformer X and capacitors C_{11} and C_{12} . This circuit is devised to be highly underdamped, since transformer X reflects capacitor C_o shunting its secondary winding, into the primary circuit. The ensuing current i_1 , shown in Figure 5, assumes accordingly a sinusoidal waveform until it tends to reverse its direction. At that time, the thyristor CR_{11} opens by itself, following its intrinsic behavioral character. The primary circuit comes accordingly to rest and remains inert for a time interval T_d to permit thyristor CR_{11} to recover to a forward voltage blocking state. Switch CR_{12} is energized next and another half sinusoid of current flows through transformer X in the reverse direction, again followed by an interval T_d which completes one work cycle of the converter.

These currents charge the output filter capacitor C_o recurrently such that it maintains a desired average voltage level V_o . This level is, of course, perturbed by a "ripple" within prescribed limits of tolerance. The rate of charge of this capacitor is determined by (1) the preprogrammed output voltage V_o and (2) by the current demand of the load. The frequency of operation of this system ranges accordingly from zero at no load to a maximum which is limited by maintaining an efficient ratio between the rms value i_{rms} and the average value i_{av} of

the current. This ratio

$$\rho = (\pi / 2 \sqrt{2}) \sqrt{1 + T_d/T_k}$$

increases with increasing ratio T_d/T_k and the ohmic losses in the linear elements of the circuit increase with the square of ρ (3, 8). The thyristor recovery time interval T_d and the system efficiency requirements thus limit the maximum frequency of operation.

It is emphasized that the maximum internal frequency of operation is not limited by destructive heat generated in switching devices as discussed before, but by considerations of overall systems efficiency for a given thyristor recovery time T_d . Currently available devices with otherwise qualifying characteristics require recovery time intervals of approximately 10 μ sec. An inversion frequency $f_i = 10$ kHz corresponds then to a ratio $T_k/(T_k + T_d) = 0.8$, resulting in a value $\rho = 1.24$. The corresponding curve in Figure 6 indicates a steep rise of ρ^2 for $T_k/(T_k + T_d) < 0.8$. The thus indicated effect on the efficiency points to the need to reduce the recovery time T_d for purpose of increasing the internal frequency beyond 10 kHz.

C. Effects of Forced vs. Natural Current Flow Termination

The photograph of a trace on the oscilloscope, indicating the power dissipation in a thyristor as a function of time is presented in Figure 7. This thyristor operates within a series resonant circuit of the previously described type. A comparison of this dissipation curve with that of a switching power transistor shown in Figure 3 reveals the almost complete absence of the power dissipation peaks observed in the transistor dissipation curve. If the transistor dissipation curve were ideal - without the peaks - then the frequency of operation could be increased indefinitely, yet the average power dissipation would remain constant for an invariant average current and a fixed on-off switching ratio. However, the peaks add a fixed amount of energy dissipation per cycle to the former intrinsic dissipation component, and this addition per cycle is independent of the frequency of operation for a given circuit. The product of energy as contained under each peak and the number of events per second, constitutes a dissipation component that is proportional to the transistor switching frequency of operation. This characteristic behavior of switching processes was predicted earlier (9) and was recently verified (3). The results of recorded average power dissipation in power transistors are presented in Figure 8. The graph indicates the power dissipation near zero frequency for various current levels, by intercept of the straight line "curves" with the ordinate. The linear increase of power dissipation with frequency is verified by the straight line character of the graph.

Conversely, the average power dissipation curve of the thyristor operating in the discussed series resonant circuits shows only a very moderate increase with higher frequencies of operation. The slope of the thyristor curve for 7.7 A peak current is approximately 1/40 of that of the transistor curve for the same current. The thyristor average dissipation curve indicated by a dotted line in Figure 8 starts with a higher "zero" frequency value than its transistor counterpart, but soon crosses this line. These data illustrate the impracticality of application of forced current turn-off processes for high frequency power converters; they also indicate the promise of efficient operation of series converters

at higher frequencies. The feasibility of a functional mechanism with switching elements that close and open in the presence of insignificant current flow, as indicated under Ia before, has thus been demonstrated.

D. A Source Voltage Insensitive Nonlinear LC Oscillator

A highly underdamped LC circuit, as discussed with reference to Figure 4, would necessarily cause substantial excursions of the capacitor voltage v_{c1} at the junction of capacitors C_{11} and C_{12} (6). The amplitude $v_{c1}(t_k)$ of these voltage variations eventually reaches the value

$$v_{c1}(t_k) = (Q/\pi) (e_s/2 - v_2)$$

where

Q = the "quality" of the resonant circuit in the conventional sense

e_s = source voltage

v_2 = primary transformer voltage as reflecting the output filter voltage of capacitor C_o .

Any disturbance of the precarious balance between the difference of e_s and v_2 - which are of appreciable magnitude - would result in excursions of v_{c1} that will impose unacceptable stresses on the converter circuit components. This is avoided by removing energy from inductor L_1 at a time when v_{c1} reaches its intended maximum value. As a consequence, the flow of energy into capacitors C_{11} and C_{12} is immediately arrested and the voltage excursion $v_{c1}(t_k)$ is confined accordingly. The voltage wave shape of v_{c1} that ensues under these conditions is illustrated in Figure 9(a).

One way to achieve the indicated transfer of energy from inductor L_1 to the load is illustrated in the circuit diagram shown in Figure 10. Inductor L_1 is split into two halves L_{11} and L_{12} and each of these is provided with a secondary winding W_{21} and W_{122} respectively. Secondary switches S_{21} and S_{22} initiate conduction whenever the voltage of the associated secondary inductor windings increases beyond the output voltage V_o . This removes the energy from inductors L_{11} and achieves the intended purpose in arresting further increase of capacitor voltage v_{c1} . The instant when switches S_{21} close can be varied, thus establishing a means to control the magnitude of $v_{c1}(t_k)$. As a matter of fact, one can use the magnitude of the signal v_{c1} to act on switches S_{21} accordingly and pre-determine its excursions.

The voltage and current waveforms in inductors L_{11} are shown in Figures 9(a) and (b). The voltage differential Δv_L impressed on inductor L_{11} remains constant for two source voltages $e_{s1} < e_{s2}$ and could under these conditions thus be kept constant anywhere between these two limits (6).

It follows that the amplitude I_a of each half sinusoid of the current waveform of i_1 can be kept constant for any input voltage e_s within design limits. It can be shown that the ratio i_{rms}/i_{av} of i_1 varies only moderately as long as $I_a(e_{s1}) = I_a(e_{s2})$. The result is, that the efficiency of operation of this

system is independent of variations of the input voltage. This is a unique property for a solid state power converter, as a matter of fact, for any electric apparatus.

A consequence of this peculiar characteristic is a complete insensitivity of the switching components of the system against considerable input voltage variations. This is stated in other terms as saying that the current level in the switching elements is unaffected by substantial (2:1) variation of the input voltage.

A converse situation exists if the system is progressively overloaded, and its output terminals are eventually short circuited. The latter case constitutes obviously the extreme and should cause the maximum component stresses. The amplitude I_a is determined by the initial voltage on the inductor terminals Δv_L and the admittance of the series resonant circuit. The admittance of the LC circuit is only slightly affected when capacitor C_0 is short circuited, because C_0 constitutes an apparent ac short circuit under any condition since $C_2 \gg C_1$; C_2 is the capacitance C_0 as reflected into the primary circuit and $C_1 = (C_{11} + C_{12}) / C_{11}C_{12}$. The magnitude of I_a is thus, in practice, proportional to Δv_L . The reflection v_2 of the output voltage V_0 into the primary circuit is substantially smaller than Δv_L (3). It follows that an elimination of v_2 (by short circuiting the systems output terminals) will result in an increase of I_a by a ratio:

$$I_a \text{ (short circuit)} / I_a = 1 + v_2 / \Delta v_L$$

where

$$v_2 / \Delta v_L < 1$$

Evidently will I_a and i_{rms} increase by less than a factor of two, depending upon design parameters, whatever the output terminal conditions.

It has been demonstrated that the system will, under static or dynamic conditions, not impose stresses on its switching components that exceed the steady state stresses by a factor of two, even when the system output terminals are short circuited. This behavior is rooted in the fact that the discussed nonlinear LC oscillator will limit the acceptance of energy from the source such that its resonant current cannot rise beyond the indicated level. The corresponding circuit operation manifests itself in a prolonged discharge cycle of the energy stored in inductor L_{11} . The corresponding current waveforms are indicated in Figure 11. The requirement for a self-protecting electronic converter system as previously stated under 2a is thus satisfied.

E. Rugged Switching Components

The series resonant circuits of the discussed inverter-converter lend themselves uniquely for operation with thyristors as switching elements. Current conduction is initiated by triggering of the devices; current flow termination is caused by the natural behavior of the circuits and does not require any mechanism for that purpose, as otherwise needed. The thyristor will tolerate current excursions of ten times and beyond of its rated current carrying capacity for short-time intervals, such as approximately ten milliseconds without damage to the

device. The device is, furthermore, available with ratings in excess of 1000 volts and in excess of 1000 amperes, although devices with the higher current ratings would not be suited for operation in excess of a few kHz. However, devices of this type with ratings up to 1000 volts and currents in excess of 100 A that are suited for use in systems with internal frequencies up to 10 kHz are currently available and have been successfully used in series converters. Thyristors with comparable ratings and with recovery times of less than 2 μ sec. that could operate within converter systems with frequencies up to 50 kHz are presently being developed; tests of prototype devices have indicated feasibility.

F. The Electronic Protection System

Simultaneous closing of switches CR₁₁ and CR₁₂ would lead to a catastrophic failure of the converter system. This type of problem is common to dc driven self oscillatory converter systems with thyristor switching devices. There is, however, a significant difference between use of thyristors in series and in parallel inverters. Failure of enforced termination of current flow in the thyristor of a parallel inverter results, unavoidably, in a short-circuit condition and the destruction of the inverter. Prevention of initiation of conduction in the companion thyristor is futile, since it will not terminate the on-going destructive process, unless other precautions have been taken.

Conversely, it is sufficient to prevent initiation of current flow in any of the series inverter's thyristors as long as its companion thyristor continues in the conducting state. The presence of current flow through the individual thyristors is sensed and transformed into an inhibiting signal that prevents any trigger pulse from causing current conduction in the companion thyristor. Current flow in any of the thyristors has to cease eventually because of the series capacitor which cannot sustain a dc current. It follows that no short circuit condition will occur, as long as the electronic protection mechanism functions properly. "Accidental" firing of thyristor can be invariably traced to improperly designed or faulty constructed circuits. This can include inadvertent violation of dynamic device characteristics, failure to appreciate parasitic effects such as leakage inductance or distributed inductance and capacitance. It includes, furthermore, inadequate protection against noise generated by electromagnetic stray fields and noise conveyed through conductive channels such as ground wires during violent transient conditions. Exposure of the thyristor to radiation effects has shown that the responsiveness of this device to trigger signals suffers in the presence of neutron bombardment rather than to increase its susceptibility to an establishment of current conduction. The thyristor has proven to be an utterly reliable device, when applied properly and used in accordingly designed circuits.

III. Experimental Results

A 2 kW converter was constructed and operated from a 300 volt dc supply line. This system was used to supply the power for the beam of the Jet Propulsion Laboratory's 20 cm ion engine at 2 kV. This converter operated at an efficiency of 95% when fully loaded. The system efficiency as a function of output power is indicated in Figure 12.

The system was provided with an overload protection mechanism that would cause cessation of switch operation whenever the output current would exceed its rated maximum of 1 A by 10%. Approximately 300 m.sec. later operation would be reinitiated automatically and recurrent recycling continue until steady-state operation could be reestablished. This power supply was tested to withstand peak currents up to 1000 A through its short circuited output terminals, prior to integration with the ion propulsion engine.

During recurrent arcing phases of the ion engine it became apparent that this beam power supply could resume operation without delay and without the need for (1) reduction of the other engine functions and (2) a following phase of gradual power build-up. It became, furthermore, apparent that there was no need to interrupt the flow of power for purposes of protecting the power supply when the rated current was exceeded by 10%. The breadboard of the discussed system has a component weight of approximately 4 kg, or 2 kg/kW. This breadboard is, however, not the result of weight optimizing design. A photograph of the experimental system is shown in Figure 13.

The dynamic behavior is that of an unconditionally stable system, as expected from a regulator system with a single element filter. No output voltage overshoots are observed during the turn-on phase or during complete unloading of the fully loaded system. Conversely, there is no transient reduction in output voltage when the full load is imposed on the previously unloaded system.

A complete electronic system with ten output channels and a cumulative power capacity of 2.7 kW is presently under construction. It is intended to control and power a 20 cm hollow cathode ion propulsion engine. The power is derived from a source of electric energy with voltage variations from 200 to 400 volt dc, simulating the output characteristics of a solar panel.

V. Conclusions

The presented electronic converter system was shown to

1. Be electrically rugged because it intrinsically avoids imposition of severe transient peak stresses on semiconductor switching components, otherwise encountered in electronic power converter technology.
2. Be suited for utilization of electrically rugged thyristors as switching elements because of the resonant current turn-off processes which are inherent in the system.
3. Allow construction of single modules with multikilowatt power capacity, because of the current availability of switching elements with ample ratings.
4. Transform the electric energy at efficiencies in excess of 90% which is largely due to the natural current commutation of its internal switches and its operation from conventional voltage levels of several hundred volts.

5. Permit use of efficient and lightweight cabling, and distribution systems at 100 to 500 volt dc (or ac when preceded by a three-phase full wave rectifier bridge).
6. Allow high power densities of equipment such as approximately 0.4 kW/kg with projection of feasibility of further improvement to 1 kW/kg and beyond with the availability of currently developed high-speed thyristors.

The electric ruggedness of the system is rooted in its internal mode of operation, rather than the use of the more stress tolerant thyristor. It is almost ironical that the thyristor used in the series inverter-converter which protects the switching device from harmful transients possesses the ruggedness to tolerate very substantial transient stresses, where there is little need for it, while the transistor with little capacity to tolerate excess currents is exposed to the often violent overloads in the parallel inverter caused by transient phases of ion engine operation.

Design and construction of these systems impose substantial demands on the skills of concerned personnel. Inadequacies manifest themselves in the form of internal short circuits. These can be induced by exposure of the system to sudden changes in external loading conditions. However, the system withstands the most severe externally imposed conditions once it is properly established. A conventional electronic converter is not prone to sudden failure due to design or construction inadequacies because these will, usually, cause a continued process of erosion in the system. But it will fail, eventually, because of any of these inadequacies, while a false confidence may be evoked by initial system performance. This difference in initial behavior of the two types of systems could be interpreted as permitting a more conclusive evaluation of the fitness of the series inverter-converter by means of systems tests before its commission to a given task.

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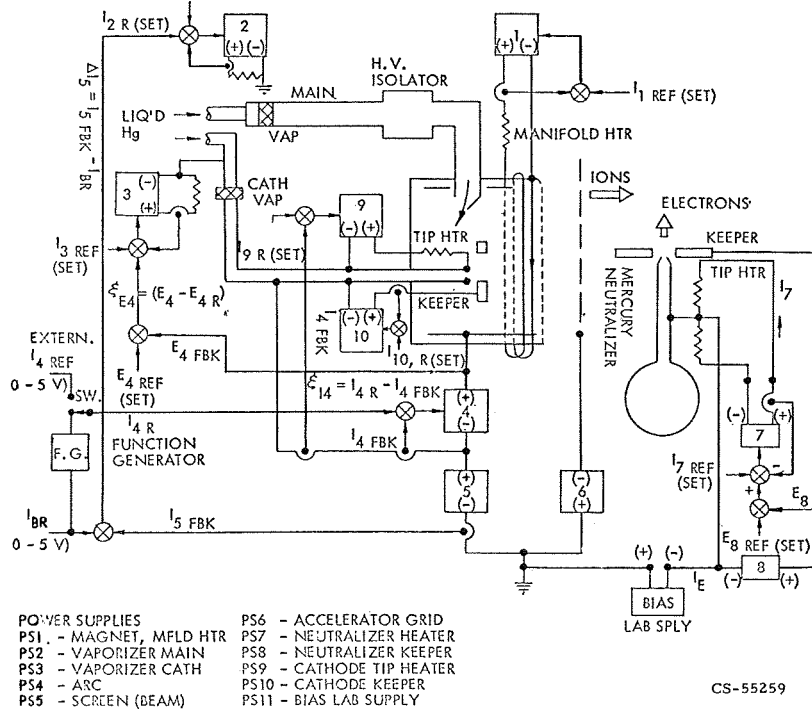


Figure 1. - Symbolic diagram of an ion propulsion engine with its electronic control and power system.

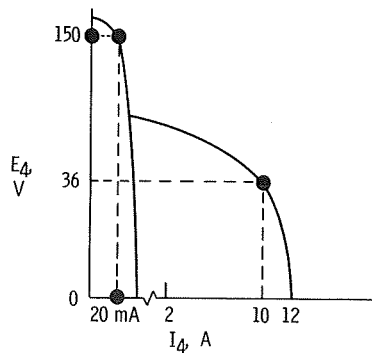


Figure 2. - Volt-ampere characteristic of the power supply for the arc of an ion propulsion engine.

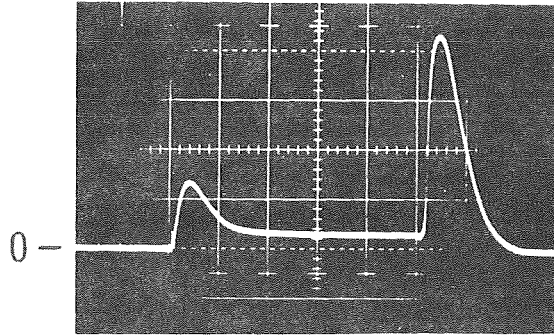
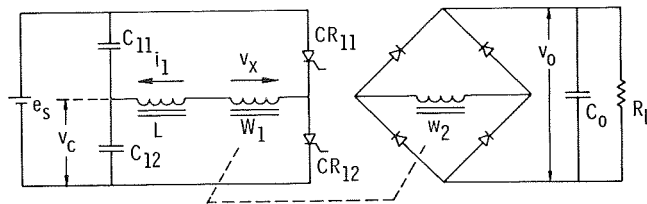


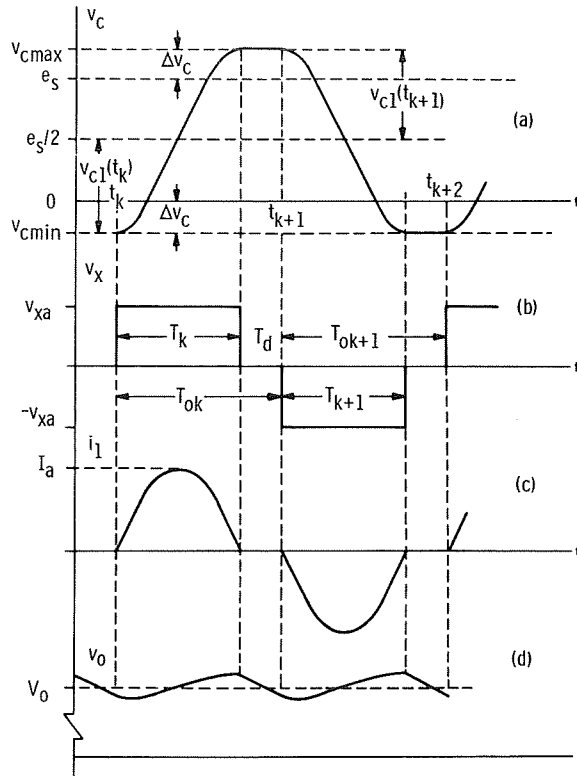
Figure 3. - Waveform of power dissipation in switching transistor with inductive load (10 ohm resistance in series with 10 H inductance).

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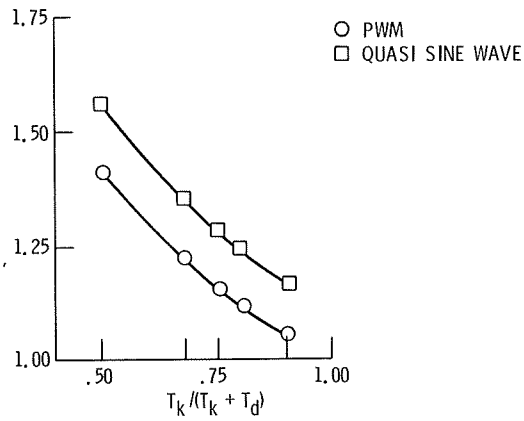
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Figure 4. - Simplified schematic of the load-insensitive series inverter-converter.



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Figure 5. - Characteristic voltage and current waveforms of the load-insensitive series inverter-converter.



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Figure 6. - Current form factor ρ as function of pulse time ratio $T_k / (T_k + T_d)$.

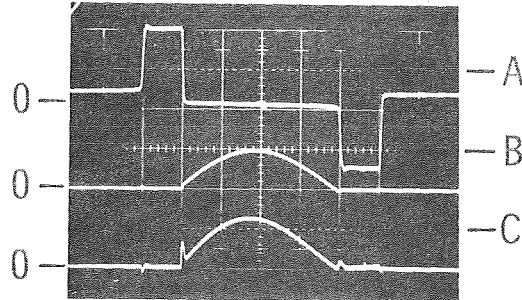


Figure 7. - Waveform of (a) anode to cathode voltage, (b) anode current, and (c) power dissipation of switching thyristor in series resonant circuit.

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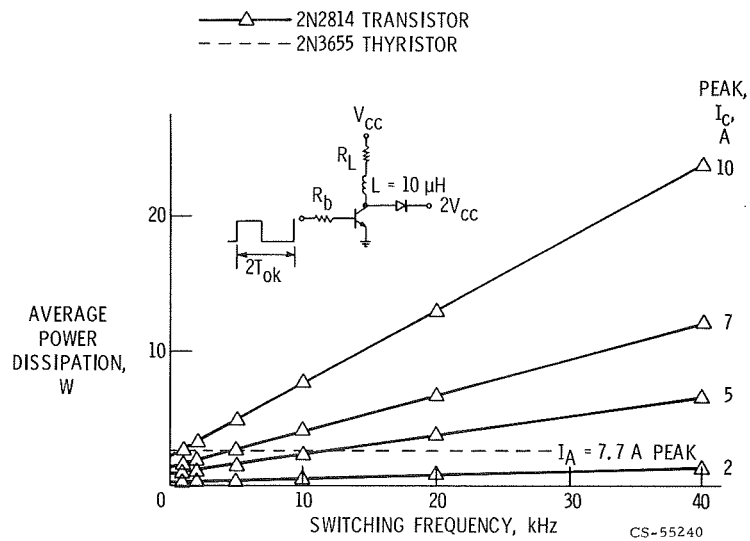


Figure 8. - Average power dissipation in switching elements, versus pulse repetition frequency.

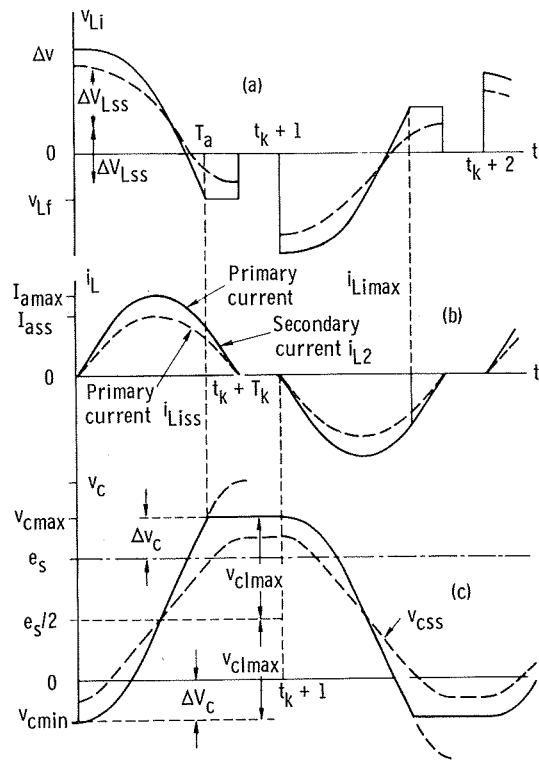
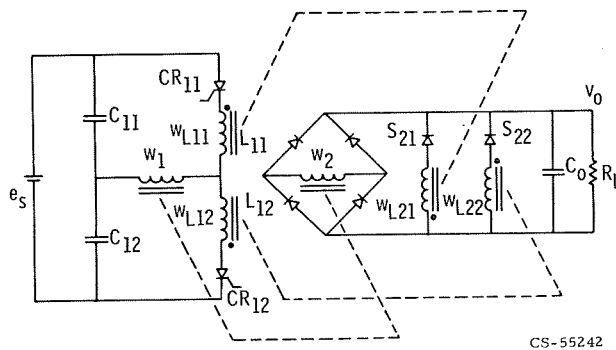
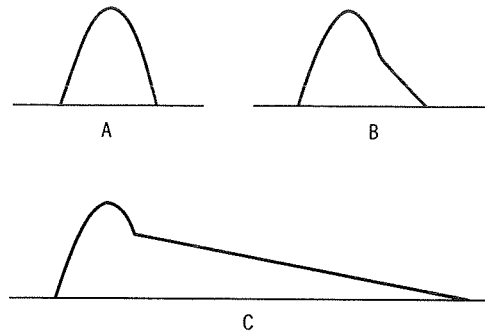


Figure 9. - Voltage and current waveforms associated with inductive energy transfer.



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Figure 10. - Simplified schematic of the load-insensitive, series inverter-converter with inductive energy transfer to the load.



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Figure 11. - Inductor current waveforms (a) without energy transfer through secondary inductor windings, (b) with such energy transfer, and (c) for short circuited system output terminals.

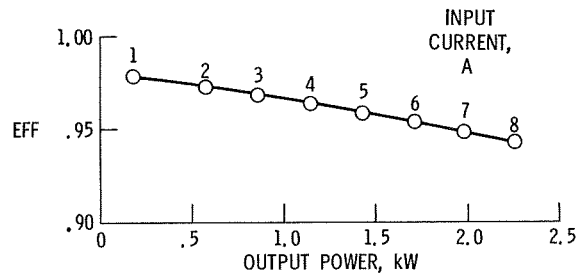
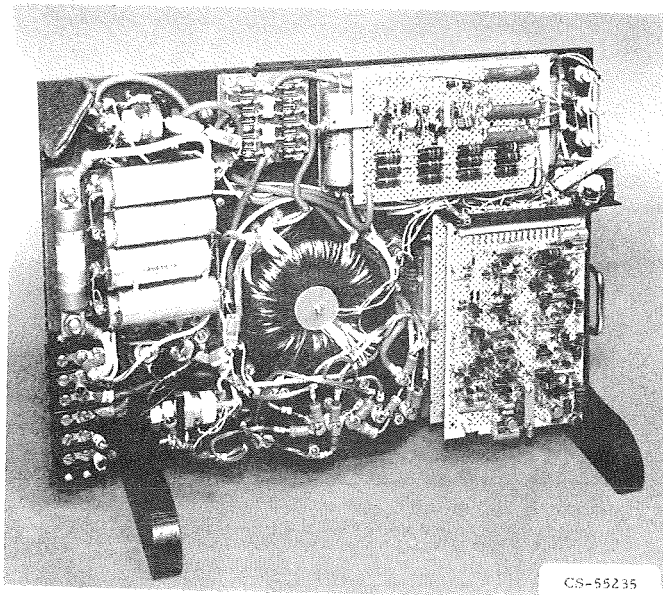


Figure 12. - Efficiency of series inverter-converter as function of output power.

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Figure 13. - Series inverter-converter breadboard.