ADVANCES IN THE PULSED INDUCTIVE THRUSTER DRIVE SYSTEM

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Abstract

NASA studies show that high power spacecraft coupled with electric propulsion systems are the keys that will unlock the solar system to cost effective exploration. The Pulsed Inductive Thruster (PIT) is especially attractive for these power intensive missions because of its demonstrated megawatt level performance, electrodeless design and variable repetition rate. However, inherent in this design are a number of critical issues that affect lifetime and reliability. A new look at this thruster has led to solutions that overcome past limitations with new and simpler methods. These solutions utilize circuit topologies which reduce the dI/dt requirements on switching, simplify the power circuits, and provide energy recovery at a minimum of 25%, while minimizing the number of components in the power train and will be described.

Introduction

In recent NASA studies, it is clear that high power spacecraft coupled with electric propulsion systems are the keys that will unlock the solar system to cost-effective investigation. However, only a limited number of electric propulsion concepts have been identified that can potentially support the high power requirements of NASA's future missions. Included in this cadre are the magnetoplasmadynamic (MPD) thruster, the variable specific impulse magnetoplasma rocket (VaSIMR), advanced ion and Hall-effect thrusters, gas fed Pulsed Plasma Thrusters, and the pulsed inductive thruster (PIT). The PIT is especially attractive for these power intensive missions because of its demonstrated megawatt level performance, electrodeless design and variable repetition rate. Of all the electric propulsion concepts it appears to be the one most likely to achieve both high thrust and high Isp. Either solar or nuclear power sources can supply the power to the PIT and a wide range of propellants can be used. TRW has developed the PIT over the last 40 years with strong support from NASA and the USAF. The Mk V unit was completed in the 1990s and demonstrated an Isp of 7000 s and single-shot efficiencies of 50% of the energy in the part of the discharge that can produce thrust.

The operational design of the Mark V is to inject a pulse of gaseous propellant that flows to the surface of a flat spiral drive coil. A very high rate-of-rise current pulse is passed through the coil at up to 30 kV potential. This current pulse creates a strong azimuthal electric field which converts the propellant into plasma which is axially accelerated by the resulting magnetic field to provide thrust. Repetitive pulsing is needed to provide the integrated thrust for the system. The Mk V was tested only in the single-shot mode. Inherent in this design are a number of critical issues that affect lifetime and reliability as the pulse rate and number of pulses increase. These include the propellant injection valve, high voltage operation in space, the extremely high value of the rate of current rise (dI/dt) in the current pulse that seriously impacts the switch and capacitor lifetime, uniform firing for all switches, large number of separate components, uniformity of the propellant spread across the induction coil, erosion of materials and thermal rejection requirements. All of these items are amenable to incremental engineering improvement, taking advantage, for example, of today's solid state switches and improved valves. No existing switch technology or capacitor technology provides a heritage that can lead with high confidence to the long life performance parameters set forth for deep space missions.

However, a new look at the design can lead to solutions that overcome past limitations with new and simpler methods. The primary approaches are to utilize circuit topologies which reduce the dI/dt requirements on switching, simplify the power circuits, and provide energy recovery at a minimum of 25%, while minimizing the number of components in the power train. In this paper, we will discuss several circuit topologies that will alleviate some of the concerns expressed above. In the end, we will discuss a new design that permits the system to operate efficiently within the constraints of present day switch technology so as to minimize risk and achieve long lifetimes. Most of the technologies being proposed for our design are at least at NASA TRL 6. Initial examination of the masses involved indicates an alpha value of 6.

Furthermore, the system concept promises to have substantially reduced complexity compared to previous concepts.

The requirements for long life deep space missions are daunting: switch lifetimes on the order of 10^{10} pulses will be required at peak currents of 15 kA and rise times (dI/dt) on the order of 30 kA/?s at standoff potentials of up to 30 kV, if the current circuit topologies are used. In past designs, erodable spark gap switches were used, but their lifetime is seriously limited to a few million cycles, approximately 5 orders of magnitude below long life deep space mission requirements. The obvious approach to overcome those limitations is to use modern solid state switches, but the high dI/dt required will limit their lifetimes at these high standoff potentials. Furthermore, no recovery of the unused energy in the pulse has been demonstrated for PIT.

Theory of the Pulsed Inductive Thruster:

The basic theory of pulsed inductive electromagnetic mass drivers of which the Pulsed Inductive Thruster (PIT) is a special case, has been described by a number of investigators[1-4]. Bernardes and Merryman[1] described a unique technique for accelerating large masses to high velocity with efficiencies greater than 60% which also allowed the recovery of a minimum of 25% of the unused energy. Similarly, Dailey and Lovberg[5] reported PIT thrusters capable of efficiency greater than 50% but did not employ a circuit topology that would allow energy recovery. Further, the facility in which the tests were conducted was small and as a result it is probable that field induced currents in the nearby chamber walls affected the accuracy of the results. It is also difficult to see how energy recovery can be accomplished in the Marx configuration described by Dailey and Lovberg.

All of the theories described in the references give a reasonable description that allows some optimization of performance. In general, the coupling between the "mass to be accelerated" and the drive circuits is such that the energy imparted must be delivered in a characteristic length of about 0.1 D where D is the diameter of the drive coil. Electrically, this length corresponds to roughly the spacing where the coupling between the propellant and the drive coil becomes small and further acceleration of the plasma by residual fields is negligible. Ideally, the power system would deliver a "video pulse" corresponding exactly to the time that the propellant gas is resident in the characteristic length. This presents a tradeoff between the speed of the drive circuit and the diameter of the drive coil for efficient conversion of the electromagnetic energy to kinetic energy in the propellant. All other factors being equal, the faster the drive circuits, the easier it is to work with small drive coils. However, the values needed for dI/dt and I, as described in the current embodiments of PIT[3] tend to produce characteristic times on the order of microseconds that drive the design to larger drive coils. The ultimate efficiency of the PIT is limited to the losses in heating and ionizing the propellant gas[3]. They also show that the losses decrease as the diameter increases. The theories described in the references show that:

? It is necessary to operate at high voltages to achieve high dI/dt and I
? For a given circuit design, there is an optimum diameter for the drive coil that will maximize the conversion efficiency from electromagnetic to kinetic energy
? Losses in the propellant due to heating are reduced as the diameter of the drive coil increases
? It is possible to recover significant energy not used in the drive process thereby increasing the system efficiency to values greater than 70%

Each of these factors places constraints on the design of the power train especially within the context of the life considerations within the vacuum of space. However, these theoretical descriptions clearly indicate that high efficiencies are possible.

Energy Recovery Circuit Topologies:

We have examined three basic circuits that would allow the recovery of significant energy not used in the primary PIT cycle. The first of these was described by Bernardes and Merryman[1] and in the embodiment they built would recover 25% of the unused energy from the drive cycle. Figure 1 shows the basic circuit.

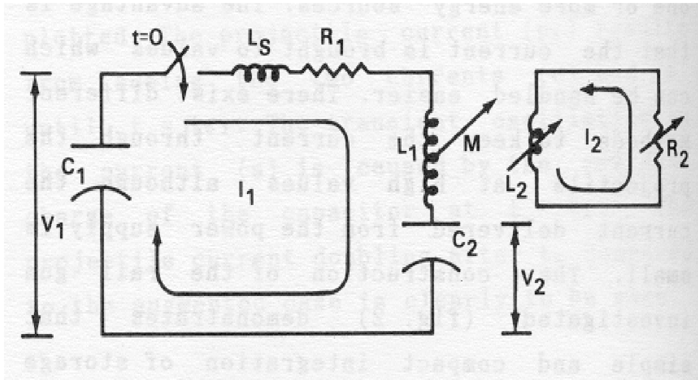

Figure 1: Dual Resonant Energy Transfer System for PIT Applications

In practice, capacitor C_1 is charged to the desired voltage and subsequently discharged by the switch. Since the capacitor C_2 is initially uncharged, energy is resonantly transferred when the switch is closed at t = 0 and if there are no losses in the circuit, the transfer is 100%. The circuit shown in figure 1 is exactly that which would be used in a PIT design, with L_2 and R_2 characteristic of the propellant in its ionized and driven state. Equations 1-3 below describe in detail the circuit shown in figure 1.

$$V_{C_2} ? \frac{V_0}{2} ? 1 ? e^{?t/2?} \cos ? t ? ? \frac{1}{2? t} ? e^{?t/2?} \sin ? t ? \tag{1}$$

$$V_{C_1} ? \frac{V_0}{2} ? \frac{V_0}{2} e^{?t/2?} ? \cos ? t ? ? \frac{1}{2? t} ? \sin ? t ? \tag{2}$$

$$\text{where } ? ? \frac{L}{R} \text{ for } R ? 0$$

For this circuit, V_{C2} and V_{C1} alternately are V_0. For the lossless case, i.e. where R is zero, the maximum voltage on C_2 is the initial charge voltage. The energy transfer efficiency is given by:

$$? ? \frac{1}{4} \left(1 ? e^{??/2??} \right)^2 = 1 \text{ at Max V} \tag{3}$$

In the proposed PIT embodiment, energy is lost due to the propellant acceleration, with what remains being transferred to C_2. In the far term, resonant transfer will occur back into C_1 and eventually, half of the remaining energy will be resident in each capacitor, minus any circuit losses. In this way, half of the unused energy is available for the next drive cycle. Obviously, the energy in one of the capacitors will have to be discharged so that the process can be continued with the initial conditions. Neither capacitor sees voltage reversal in the discharge cycle.

By adding fast recovery diodes and an additional switch to the basic circuit, it is possible to recover almost all of the energy not used in the drive circuit. We have made a "breadboard" circuit at roughly 100^{th} scale and verified this technique. This approach necessarily doubles the capacitor mass but is still an option since it also allows high repetition rates to lower the value of alpha if an acceptable long life switch technology which can function at the requisite dI/dt and I can be found. A further disadvantage is the need for a power supply that can supply the requisite drive voltage on the order of 30 kV.

In a second energy recovery circuit topology, Strickland et.al.[6] developed a solid state modulator to deliver pulses of 25 kW to an inductive load from a 2.5 kW power supply. This circuit is shown in figure 2 and is a simplified H-Bridge which employs opening and closing of switches to affect recovery. In operation, capacitor C is charged from the High Voltage Power Supply, HVPS, capable of the requisite average power. When fully charged,

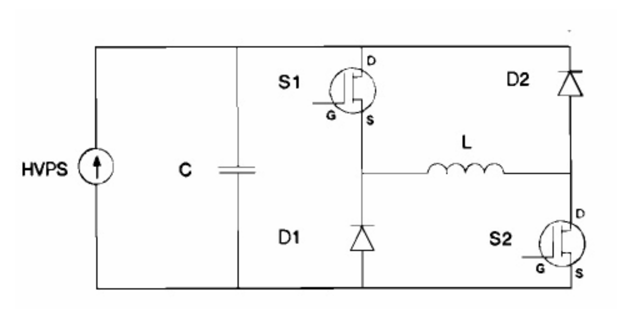

Figure 2: H-Bridge Circuit Topology for Energy Recovery for PIT Applications

switches S_1 and S_2 are closed allowing current to flow through the inductor L (in the PIT circuit, this is the drive coil). When the voltage is reduced to zero, switches S_1 and S_2 are opened, forcing the current flowing through L to flow back to capacitor C, through diodes D_1 and D_2, recharging it to some fraction of the initial charge voltage as determined by the energy used in the load. Strickland et.al.[6] used MOSFET switch arrays but GTO and MOS controlled Thyristors would also serve adequately as switches. The load for the unit was 27 µH and it was operated at repetition rates as high as 10 kHz.

This topology readily demonstrated energy recovery of 81% but issues such as lifetime and so forth were not considered. This circuit topology should be capable of scaling to the 25-50 kW range. The switches would still have to provide the necessary dI/dt and I for energizing the PIT drive coil. The unique feature of this circuit is that only one storage capacitor is used and never sees a voltage reversal. Losses are primarily due to "hard shut-off" of the switch array. As in the Bernardes and Merryman circuit[1], the HVPS must continuously provide a high voltage of approximately 30 kV to charge the capacitor C.

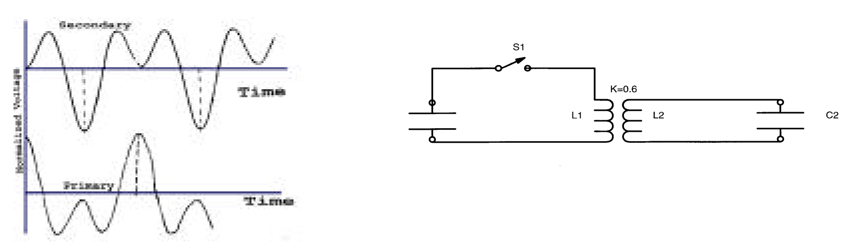

Figure 3: Double Resonant Pulse Transformer and Voltage Waveforms and Schematic for a Coupling factor of K = 0.6. Dotted Lines Represent Points of Complete Energy Transfer.

The third circuit that we studied appears most adaptable to the PIT thruster and is based on a dual resonant pulse transformer (DRPT). Figure 3 shows a simple schematic of the DRPT and the wave forms in both the primary and secondary sides of the circuit. The theory of operation of these devices is amply covered in reference 7. Equations 4 and 5 illustrate the secondary voltage as a function of time for a dual resonant pulse transformer.

$$V_{C_2} = \frac{V_0}{2}\sqrt{L_2 / L_1}\, e^{-t/\tau'} \left[\cos\left(\frac{\omega t}{\sqrt{1+K}}\right) - \cos\left(\frac{\omega t}{\sqrt{1-K}}\right)\right] \tag{4}$$

$$\text{Where} \quad \tau' = \frac{4L_1L_2}{R_2L_2 + R_1L_1}\left(1 - K^2\right) \tag{5}$$

For a coupling factor K of 0.6, there is complete energy transfer from the primary to the secondary and back to the primary side of the circuit periodically. Note the phase relationship and the fact that the energy stored in the primary circuit is resonantly transferred to the secondary, and as time progresses, back to the primary side of the DRPT. This fact forms the basis of energy recovery for our proposed power train.

For electrical pulses which are a few microseconds in duration, dual resonant pulse transformers (DRPT) offer a more compact and reliable method of achieving high voltages than the more commonly used Marx generators. This type of transformer has a low voltage capacitor, C_1, capable of storing all of the energy needed for a pulse. This capacitor is connected in series with an appropriate switch, S_1, and the primary of the DRPT that has an inductance L_1. The secondary side of the DRPT similarly has secondary inductance L_2 and a capacitor C_2. The condition for dual resonance is essentially that:

$$L_1C_1 = L_2C_2 \tag{6}$$

Making $L_2 > L_1$ requires that $C_2 < C_1$ if dual resonance is to be maintained. Neglecting losses, by conservation of energy, the voltage on C_2 must increase if L_2 is greater than L_1. It is obvious that any voltage multiplication factor can be in principle achieved. It can be shown[7] that for a coupling factor K of 0.6, complete energy transfer from the primary side of the transformer to the secondary side occurs on the second cycle of oscillation in the secondary. The coupling factor of 0.6 allows for considerable spacing between the primary and secondary sides of the DRPT. This is advantageous for vacuum insulation. Any arcing between primary and secondary does not destroy the DRPT and in the vacuum of space, it will recover as soon as the gasses formed in the discharge dissipate. For a perfectly tuned transformer, the only losses are those associated with the primary switch and the resistive losses of the windings. It is possible to readily achieve efficiencies greater than 90% in a carefully designed system. The literature is filled with examples of applications of this technique.[8-11].

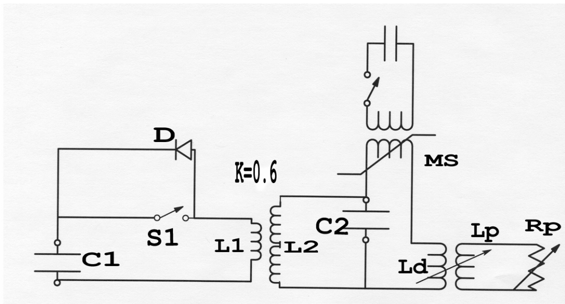

Figure 4: Circuit diagram for candidate PIT thruster

We are using the DRPT as the basis of a PIT driver with energy recovery. This circuit has the distinct advantage that the circuit geometry can be divided into a slow and a fast section. Figure 4 shows the circuit. The "slow" high voltage multiplication section of the circuit consists of a dual resonant pulse transformer as described above. The value of the capacitor C_1 is chosen to store the total energy for a pulse at the operating voltage desired. For the PIT, this would be in the range of 5-10 kV. The DRPT can be adapted to any spacecraft line voltage capable of the requisite power.

On the primary side of the DRPT, since it is resonant, choosing L_1 determines the circuit oscillating frequency, ??, which, depending on L_1, can have any number of values. Because the maximum current I in the primary is directly proportional to the charge voltage V, and to $(C_1/L_1)^{0.5}$, it is possible to control the maximum current to be within the long-life regime for the switch. Similarly, dI/dt is proportional to the same parameters times cos (? t). Where ? is proportional to $1/(C_1L_1)^{0.5}$ and can be controlled to allow dI/dt to be within the long-life regime for the switch used in the primary side of the circuit. Since $L_1C_1 = L_2C_2$, the circuit parameters and their choice obey the same laws in the secondary side of the DRPT. If $L_2 > L_1$, the square root of (L_2/L_1) determines the maximum voltage on C_2. Note that $C_2 < C_1$ and must be able to withstand the high voltage. Note also from the section on the DRPT, in the absence of losses, all of the energy initially stored in the primary side of the transformer is transferred to the secondary side on the second swing of voltage.

The DRPT itself is air-core construction with the primary usually wound outside the secondary and separated from it by some centimeters. The exact spacing is chosen to yield a coupling factor of 0.6 or this can also be achieved by tuning inductors. Since there is no solid insulation, this construction lends itself readily to vacuum insulation and if there are failures, the windings would tend to be self healing. The design and construction of these transformers is straightforward and amply described in previous references.

Up to this point, the circuit dynamics are slow enough to allow operation in the long-life regime for the requisite switch and capacitor technologies. Referring to figure 4, all of the energy is resonantly transferred to the capacitor C_2 on the second swing of the voltage. At this time, the core of the magnetic switch MS saturates and the inductance of the switch changes by approximately 1000 in a time scale that can be designed to be on the order of a few nanoseconds as described in references cited in the section on switching. The energy stored in C_2 suddenly sees a low impedance path through the drive coil L_d and subsequently discharges with high current I and at a high dI/dt. The pulse compression that occurs can be at least an order of magnitude and several stages can be added in series if further compression is warranted. The requisite condition for this to occur is that the drive coil inductance is much less than the inductance of the secondary of the DRPT. This will be the case since the ionization of the propellant gas reduces the drive coil inductance by the mutual inductance between the drive coil and the conducting gas sheath and the experimenter has control of the value of L_d. L_p and R_p represent the propellant gas in its dynamic state. Magnetic switches have been operated at dI/dt and I far in excess of that called for in the PIT thruster and will be discussed subsequently.

A significant fraction (~50%) of the energy stored in C_2 will have been converted to kinetic energy of the propellant gas, and the energy stored in the inductance of the drive coil will try to resonantly transfer back into C_2, reversing the voltage to approximately 0.7 V_M. Since MS has high impedance to reversed current, the energy remaining in the system will be resonantly transferred back into the primary of the DRPT as shown in figure 3, where switch S_1 is still conducting. Total resonant transfer from the secondary back into the primary occurs on the second swing. As the current reverses, it can be transferred to capacitor C_1 through diode D_1. Similar diodes were used in reference 2. This process will take place at the characteristic time scale for the circuit. During this phase of the conduction cycle, there is no current or voltage across the switch S_1 and it can be triggered open with a small pulse. Now all of the unused energy not lost in circuit elements has been transferred back into the capacitor C_1 for use in the next discharge cycle.

Before the next cycle occurs, the reset circuit, inductively coupled to MS, must return the magnetic core to its initial starting place on the B-H curve for the material used. This is a standard circuit technique, not very demanding from an energetic point of view, requiring no more than a few joules to accomplish. It is possible to design the circuit to be self resetting once a set of circuit parameters have been fixed. If the total circuit losses are on the order of 25% of the total energy, and we believe that this is a conservative assumption, and 50% of the initial energy is converted into kinetic energy of the propellant, the remaining 25% will be recovered making the single pulse efficiency for the system approximately 75%.

Power modulators of this type have operated at kilohertz rates and at average powers greater than 20 kW. Thermal management will be the single most limiting factor. This approach provides minimal numbers of components, provides a mechanism for utilizing solid state components within their "long life" regime, minimizes vacuum breakdown concerns, simplifies thermal management, and provides throttleability via control of the pulse repetition rate.

Component Technologies:

There are several critical components that must be available for long duration continuous operation in space. These are discussed below:

Capacitors:

Energy storage capacitors will be essential for all electric propulsion concepts. The requirements placed on the Pulsed Inductive Thruster (PIT) are stricter in that the capacitors must store substantial quantities of energy, be subjected to voltage reversal, and utilized at a repetition rate that may require innovative thermal management techniques to eliminate thermally induced failures. Further, the capacitors must function in the vacuum of space for mission durations of 7-10 years. For pulsed capacitive systems, the system mass is proportional to the specific energy of the storage media and the energy desired in any pulsed event. However, the specific mass in terms of power of the thruster is determined by the pulse repetition rate. Increasing the pulse repetition rate for a given average power reduces the requirements on energy storage mass and results in a trade off between system mass and repetition rate. Table 1 illustrates the approximate state of the art in advanced capacitor technology relevant to PIT.

Table 1: Representative Relevant Capacitor Technologies

Type	Voltage range	Specific Energy J/kg	Life in number of cycles	Comments
Polymer film[12] in oil bath	>30kV	15	$>10^{10}$	Voltage reversal 20% Low esr and esl Require pressure vessel and hermetic sealing
Mica[13]	>10kV	<10	$>10^{10}$	Very low esr and esl Life is specific power limited Suited to vacuum
Ceramic[13]	>10 kV	~10	$<10^{6}$	Low esr and esl Piezoelectric, Limited life Suited to vacuum

From Table 1, it is obvious that the closest capacitor technology to meeting the long lifetime requirements for a PIT thruster is the Film-Foil-Oil capacitor investigated for applications to Laser Isotope Separation Power Modules. The capacitor has limited voltage reversal capability, and a low specific energy. For an average power of 20 kW, assuming 60% efficiency, there is a tradeoff space between total energy stored and pulse repetition rate. Reference 7 tested at a pulse repetition rate of 500 Hz. Life in terms of numbers of charge discharge cycles is given approximately by:

$$L = \sim (E_I / E_m)^8 \tag{7}$$

Where L is the life in numbers of charge-discharge cycles, E_I is the intrinsic strength of the dielectric, and E_m is the maximum working electric field. Reducing the working stress by a factor of two, results in an increase in life of 2^8. At areduced voltage and packaged for space the specific energy should be reduced by half with the result that a pulse repetition rate of 50 Hz should produce a capacitor bank weighing about 100 kg for a average power of 20 kW. Similarly, a pulse repetition rate of 150 Hz would reduce the mass to approximately 30 kg. The other capacitors listed in Table 1, while potentially applicable, have not demonstrated the requisite specific energy or life based on stringent testing. Reconstituted Mica capacitors are highly promising but have demonstrated the requisite life only at low specific energy. They would be suited for applications in space since they contain no oils in their construction. Although there are new capacitor technologies emerging[14] which would provide a higher specific energy, their life and loss mechanisms have not been explored sufficiently to allow considering them for this application.

In all likelihood, a capacitor will have to be custom designed for this application due to the stringent demands for life and reliability. There is sufficient heritage in the literature to give confidence that this capacitor can be developed either in film-foil-oil or using reconstituted mica[15]. In the initial stages, existing capacitor technologies can be used to illustrate the concept and a custom unit designed from the results of the systems analysis.

Switch Technologies:

The switch technology for PIT is extremely demanding. To date, there is no reported switch in the literature capable of meeting all of the requisite parameters necessary for a PIT thruster. Spark gaps and pseudospark switches can meet all of the requisite parameters[16] except life. Similarly, solid state switches while capable of life have never been demonstrated under the stringent requirements for dI/dt and I for PIT. In current embodiments the best solid state switches have hold off levels of approximately 5 kV for an individual element and a dI/dt of less than 5 kA/µs. The literature does contain examples of high dI/dt but life under these conditions is unknown. Table 2 lists candidate switch technologies that could be used in the Pulsed Inductive Thruster. References quoted below are typical of the literature and not intended to be all inclusive. The proceedings of the IEEE International Pulsed Power Conferences and the International Modulator Symposia are rich sources of material for designing the PIT modulator.

Table 2: Candidate Switch Technologies for the PIT

Switch	Voltage, kV	I_{max}, kA	dI/dt, kA/µs	Life, Hz	Comments
Spark Gap[(16)]	>50	>100	>100	$<10^6$ rep 50 Hz	Limited life - fatal flaw
Pseudospark Switch[(17)]	35	20	>20	$\leq 10^9$ rep 500 Hz	Marginal life demo Candidate for PIT
Thyristor[(18)] Si-thyristor[(19)]	~5 ~4	10-80 3.5	~5 95	$>10^9$ rep >100 Hz Unknown	Life acceptable Candidate for PIT
IGBT[(20)]	4.5	6.5	17	Unknown	Possible candidate
PCSS[(21)]	10-200	8	$\sim 10^4$	$\sim 10^8$	Possible candidate
Magnetic[(22-24)]	30-150	>6	>20	$\sim 10^{11}$ rep >1 kHz	Strong Candidate

Solid state switches when operated within acceptable parameter ranges have essentially unlimited life[25]. Similarly, magnetic switches based on saturation of magnetic materials within a core structure have been shown to be essentially limited to insulation failures in the feed circuits rather than in the intrinsic properties of the materials themselves[26]. For our design of the power train for Pulsed Inductive Thrusters, we will employ solid state switching typical of the thyristors operated within their acceptable long life regime and use magnetic saturation switching to provide the requisite switching at high voltage and high dI/dt. In this way, we have eliminated the fatal flaws associated with spark switching and the multiplicity of switches needed in distributed energy stores in a Marx configuration. Finally, high voltage spiral line vector inversion generators[27] also have applicability to pulsed electric propulsion systems. They provide a precisely controllable method for producing high voltage, high power RF pulses with a predetermined rise time in a single dynamic step, requiring only one active component. These systems are under development and will likely have impact on the PIT as well.

Conclusions:

There are several circuit topologies capable of delivering high average power to pulsed thrusters. Most of these suffer from placing extremely demanding requirements on components that must survive for long space voyages. Thus they fall short of usefulness. In this paper, we have evaluated three circuits and have proposed one that should alleviate most of those requirements. In addition, the circuit is simple, reduces the dI/dt requirements on switching and provides at least 25% energy recovery while minimizing the number of components in the power train. The circuit operates efficiently within the constraints of present day switch technology thus minimizing risk and yielding long lifetimes. This design is also based upon components that are mostly commercially available. In our laboratory, we are in the process of building bench top models to confirm our analyses.

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