High-Voltage Power Switching for a Conducting Tether

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The ElectroDynamic Delivery Express (EDDE) is an autonomous space vehicle that can maneuver throughout low earth orbit without using fuel. EDDE uses solar power to drive multi-ampere currents through a kilometers-long aluminum conductor, creating a force normal to both the conductor and the local magnetic field that drives the space vehicle. The tether spins at about 8 times/orbit. This stabilizes its dynamics and also allows a wider range of electrodynamic thrust directions as it spins. The current circuit is closed through the ambient plasma around the conductor. To provide complete control of the orbit, the high-voltage current must be switched repeatedly as a function of the orbital position, to modulate the force on the conductor. This paper describes our solution to this power switching and control problem. Arcing from the conductor to the ambient plasma is a potentially serious problem. To reduce the possibility of arcing, the solar arrays are distributed along the conductor length to reduce the peak potential between the conductor and the local plasma. If arcing does start, it can be quenched by electrically isolating the tether segments upstream of the arcing section, using high-voltage control switches in each power module. This makes it feasible to pull the arcing segment positive to quench the arc. Each power module includes an "H-bridge" so the solar array can drive current through the tether in either direction. Turning the bridge off isolates the conductor segments and array from each other, to help quench arcs from both the array and the conductor. The bridge also includes a shunt switch so tether current can bypass the solar array. This lets EDDE continue operating despite failed power switches or mis-aimed solar arrays. Effective control of current and arcing requires communication between the modules. This can be done optically, or with RF signals transmitted along the conductor, superimposed on the drive current. The entire space vehicle electrical system and switching circuitry are simulated on the "Virtual Test Bed" at the University of South Carolina to demonstrate system performance and design optimization.

I. Introduction

As shown in Figure 1, electrodynamic tethers use the electromagnetic force generated by a current through a long conductor in the earth's magnetic field to generate net forces that cause orbit changes. At one end of the conductor is a

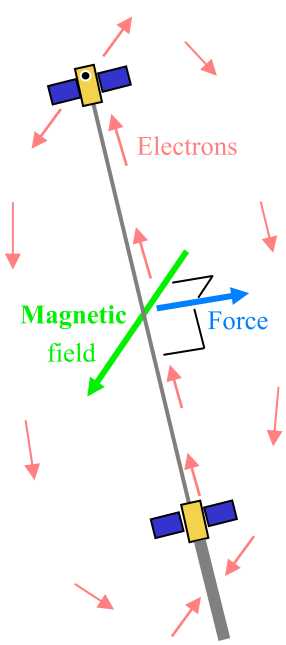

Figure 1. Electrodynamic loop and force

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collector to absorb electrons from the ambient plasma; at the other end is an electron emitter to eject electrons. The current flows through the long conductor and returns through the ambient plasma around the conductor. The force on the conductor can be in either direction, depending on the current flow direction in the conductor. If it flows with the EMF induced by orbit motion through the earth's magnetic field, then power is generated and the orbit decays. If power is available, it can be used to create a current in the other direction. In this case, orbit boosting is obtained, and external power must supply a voltage equal to the EMF plus all other voltage drops in the overall current loop: electron collection, conduction, emission, and external cross-field conduction.

Under an Air Force SBIR contract[1], we designed a spacecraft called the ElectroDynamic Delivery Express (EDDE) that can maneuver throughout low Earth orbit by controlling the current in its conducting tether[2]. By switching the current as a function of orbital position and spin plane and phase, the EDDE spacecraft can adjust its spin state and all 6 elements of its orbit: altitude, inclination, node, eccentricity, line of apsides, and epoch. For simplicity, a bang-bang control system is used that simply reverses the current direction in the conductor at the appropriate times in each spin. The tether spin stiffens the tether against distributed perturbing forces, and allows a wider range of thrust directions around the orbit than do "hanging" tethers[3]. The spin can be near the orbit plane or normal to it (other planes take more effort to maintain). The solar arrays are centrifugally stabilized, and track the sun only around the tether axis.

II. Current Control System

The general operating strategy is to drive current in one direction for about half a spin, and then in the other direction for the next half-spin[4]. The net effect is a force whose average direction is nearly that of the force halfway through each half-spin. Adjusting the length of each cycle allows adjustment of the switch phasing over several spins, to provide the most useful thrust vector as the magnetic field and desired thrust direction both slowly change around each orbit. Changing the duty cycle away from 50/50 can affect the spin rate and spin plane, and also affects tether bending modes. Varying how much of the tether length is used to carry current will have even more effect on spin and bending modes. If the most effective time for control is far from a switching time, the control opportunity might be neglected: most dynamics build up slowly and have many opportunities for control. Each time the current is reversed (16X/orbit, for an 8X/orbit spin), and at other times around each spin, the current can be briefly held off, to allow more accurate estimation of EMF and unperturbed plasma properties. Accurate EMF data allows a state-estimator algorithm in the control computer to estimate the spin plane and phase. This improves control capabilities.

Performance might improve if we use small batteries to save energy collected near the switching times and use it closer to the middle of each half cycle, when thrust is more valuable. This should be easier to justify if EDDE spins faster than 8X/orbit, since that reduces the amount of energy to be stored. But fast spins increase the tether reinforcement mass needed. The battery currents and required cycle life would be very high, so ultracapacitors may be more appropriate than batteries. It is not clear whether it makes more sense to invest marginal masses in larger solar arrays or ultracapacitors for partial-spin energy storage. We plan to study this in upcoming work.

A. Damping Strategy

Electrodynamic thrusters develop instabilities when energy is pumped into conductor dynamics[5]. This can occur even at constant current[6], but is usually worse due to current variations forced by the environment. Furthermore, the magnetic field is seldom aligned exactly as needed, so modulating current to obtain a desired effect usually excites undesired modes. Limiting the undesired dynamics requires persistently draining energy out of the system.

Our feedback control strategy starts with an ideal reference frame moving and rotating with the ideal tether motion we want (no bending, an ideal spin rate and plane, etc.). We then take the tether state inferred by the state estimator algorithm, compute the tether motion relative to the ideal reference frame, and compute the "error EMF" caused by motion relative to the ideal frame. If that error EMF actually drove the current, then we would get passive eddy-current damping of the undesired motion. But the actual EMF is not the same as the error EMF, so we must actively mimic the effect of an error EMF. We do this by specifying a current schedule that correlates with the error EMF.

Constraints on ED force direction limit how much each mode can be driven or damped each instant, but on timescales >1/4 orbit, all modes are accessible. The main goal is a long-term trend of damping any dynamics with effects large enough to observe. Periodic EMF variations in a spinning system make all large dynamics clearly observable, including skip-rope. The required average control current is usually small. The slow growth rate of most of the dynamics and the cumulative nature of damping makes this strategy very tolerant of periods when problems with the power, data acquisition, or control systems make active stabilizing control temporarily unavailable. Control of the tether dynamics is more effective than in previous methods[7].

With EDDE's "use it or lose it" power strategy, the performance penalty due to control currents is generally smallest if current reductions or reversals occur near switching times. Then ED forces can be large but the force component in the desired direction is smallest, so penalties for changing the force magnitude are small.

III. Power Switching System

B. Tether Power Management

Our initial plans were to use DC/DC converters between the solar arrays and the tether. But the DC/DC converters could actually outweigh our lightweight flexible solar arrays. So we now plan on a less efficient but far lighter voltage-control concept. The arrays operate direct-coupled to the tether, but each array consists of 4 sub-arrays that can be connected in parallel, in series, or 2x2. (This requires only 6 diodes, 3 MOSFETs, and 3 isolated gate drivers.) This should allow an average efficiency >75% that of peak-power efficiency, over an 8:1 voltage range, even with switch losses. This is less than the ~90% available with wide-range DC/DC converters, but the controls are so much lighter that the overall power system has much higher useful output per unit mass. Adding a small amount of ultracapacitor storage may allow us to significantly increase both the average efficiency and also its average utility, by moving small packets of energy from periods of peak availability to periods of peak value.

Each power module includes an "H-bridge" so the solar array can drive current through the tether in either direction. Turning the bridge off isolates the tether segments and the array, to help quench arcs from either the array or the tether. The bridge also includes a shunt switch so tether current can bypass the solar array. This lets EDDE continue operating despite failed power switches or misaimed solar arrays. It also allows EMF-driven "drag-mode" operation at night. The switches are all soft-switching solid-state devices for low EMI and long cycle life.

The overall energy efficiency of EDDE is modest, because of the combined effects of one-axis tracking, direct-coupled array use at off-ideal voltages, and "use it or lose it" power management. These features reduce efficiency, but they reduce complexity, mass, and cost far more, so they greatly improve EDDE's overall system performance.

C. Circuit Schematics for EDDE Power Control

The power processing for EDDE is as simple and direct as possible, subject to the need to operate the system in five states—a "current off" mode for diagnostic and other purposes, and currents in either of two directions for either of two operating modes: solar-array-driven, and shunted (i.e., EMF-driven). We plan to use high-voltage solid-state switches rather than relays. Spinning ED thrusters can require switch lives of 100,000-200,000 cycles, which is beyond the rated life of many relays. Solid-state switches should also allow much faster, more deterministic, and smoother switching, allowing better coordination of switching of multiple power modules. Miller-capacitance effects will help synchronize current turn-on and turn-off for multiple power modules operating in series. (But synchronized or carefully-sequenced switching commands are needed to minimize peak local voltages.) Note also that the heat capacity of the switches allows us to use them briefly in linear mode. This can stimulate low-frequency plasma dynamics, and may have scientific and/or engineering value as part of an EDDE flight experiment.

Figure 2 shows a possible DC-isolated charge pump that can provide a ~17 V gate drive to a power IGBT or MOSFET whose negative side is at a far different voltage than the low-level logic voltage driving the charge pump. Not shown in the circuitry would be some sort of "Gate Voltage OK" signal back to the logic, perhaps from an LED in series with Zener D6. Note that this circuit is only DC-isolated: AC voltage variations across C1-C4 will tend to cause additional charge pumping. Zener D6 prevents the voltage on C5 from exceeding ~17 V (vs. the allowable gate drive voltage of 20 V). There will be 7 MOSFETs and 2 high-current IGBTs in the overall circuit, but two of the MOSFETs can use one charge-pump circuit, so we will need 8 charge pumps for each power module.

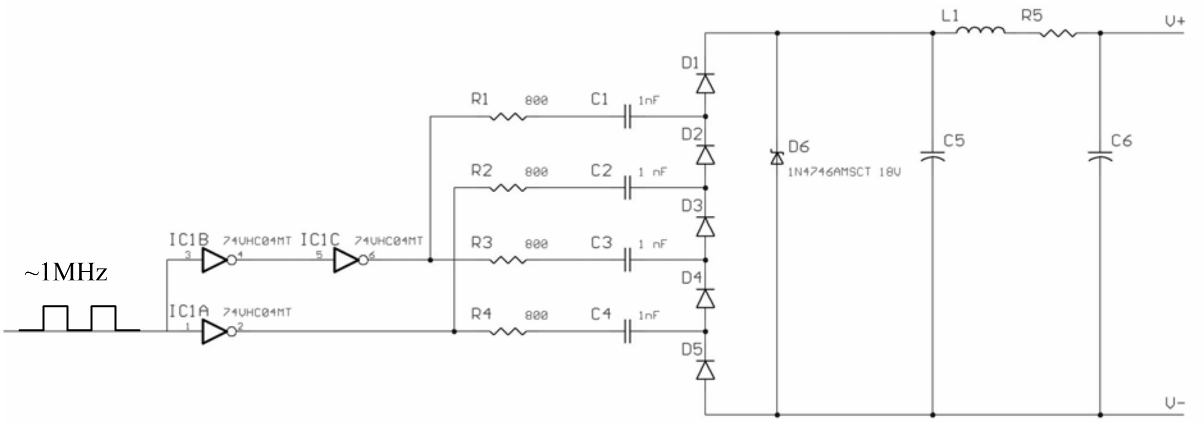

Figure 2. DC-isolated charge-pump for MOSFET and IGBT gate drive (one of 8)

To run the conductor bi-directionally as required with a spinning conductor (or even a hanging one, for many maneuvers), some sort of "H-bridge" drive circuit is required, to couple the solar array to the conductor. The schematic for that circuit is shown below on the right side of Figure 3 below:

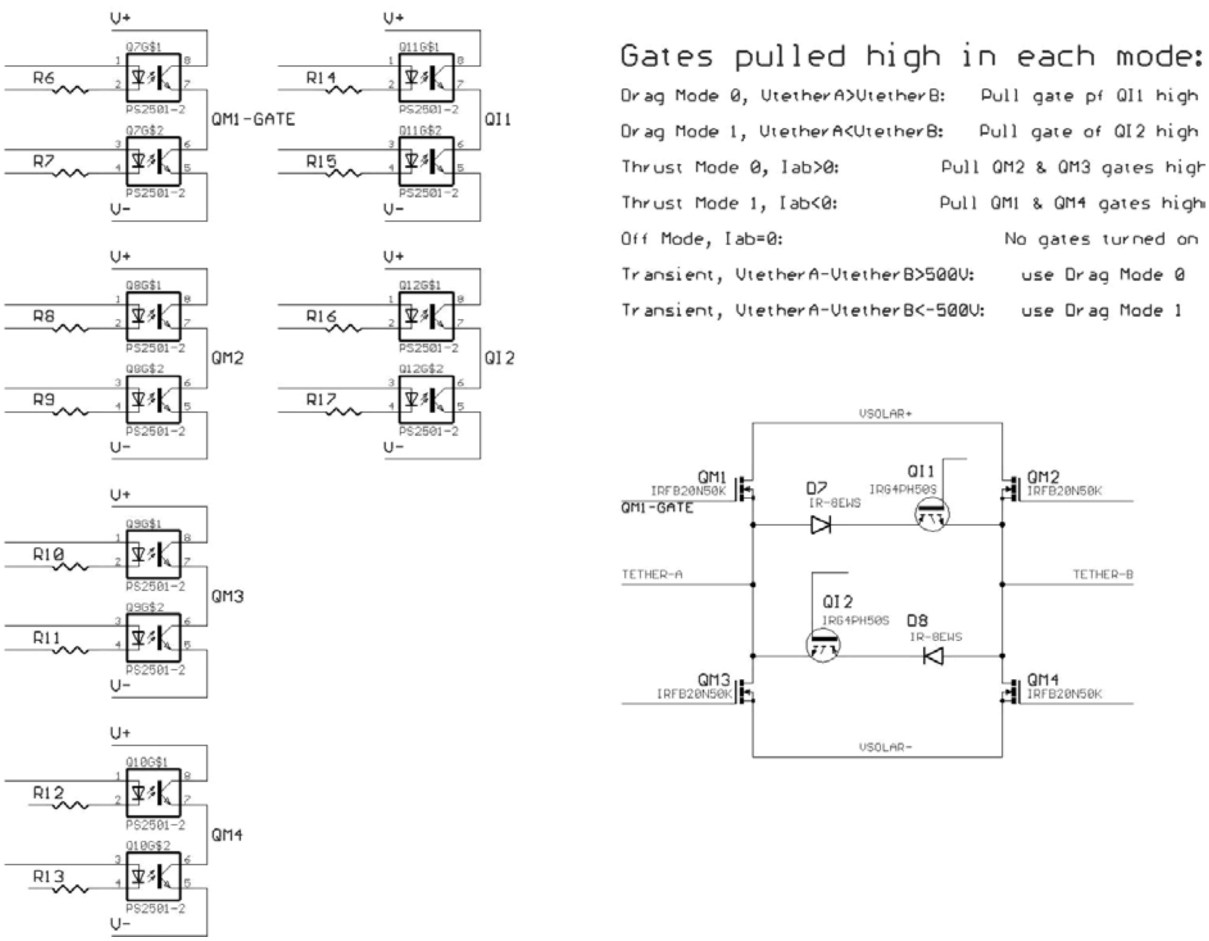

Figure 3. Opto-Isolated gate drive circuits, and H-bridge with IGBT-controlled shunts

The six circuit fragments on the left of Figure 3 show opto-isolators. The logic (left) side of each circuit is connected to the flight computer, while the right side is driven by one of the charge pumps shown on the previous page, to actively pull the isolated transistor gate high or low, at rates determined by the gate capacitance, isolator drive current, and current transfer ratio.

The diagonally opposite transistors (QM1 and QM4, or QM2 and QM3) are turned on depending on the current direction required. We use MOSFETs to couple the solar array to the conductor, because at low currents (up to several amps) they have lower conduction losses than IGBTs. However in the "drag" mode (which bypasses the solar array), we need to conduct up to 10-12 A. Here we are better off using an IGBT, both because of the higher voltage ratings available (1200 V) and the low conduction losses at high current (~1.2 V at 12 A). Note that efficiency is not much of an issue in drag mode, but component overheating is. IGBTs have very high capabilities but cannot handle reverse biases, so the shunt circuit consists of two IGBTs, each in series with a blocking diode to protect them from reverse voltage. Each IGBT will each have to dissipate up to ~15 W during peak drag episodes, and its diode will dissipate similar power. By comparison, the MOSFETs in the low-current paths involving the solar array will usually dissipate <1 W each.

The final aspect of the power management circuitry that deserves attention is the series/parallel switching of the solar array. That is shown below in Figure 4. Three more opto-isolated gate drive circuits (not shown) are needed to control Q_{SOL}1-3.

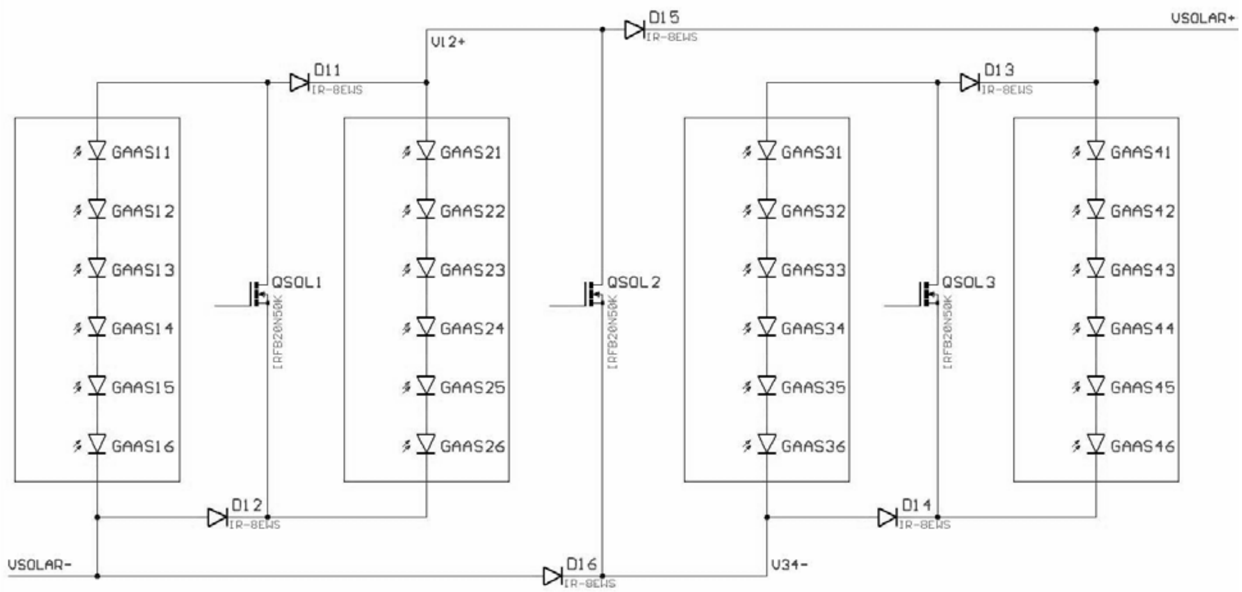

Figure 4. Series/parallel switching of 4 solar array strings

The conventional photocurrent in an illuminated solar cell flows against the direction of the diode arrow, with forward conduction "leakage" in the other direction becoming significant if the cell voltage approaches the open-circuit voltage. So each string of 6 solar cells (labeled GaAsNN) tries to pump conventional current up the array. Each string of 6 GaAs photodiodes is a simplified representation of 1/4 of the solar array for that module. This 1/4 array might contain two parallel strings of ~90 GaAs single-junction cells in series. Together those two parallel strings might provide ~80 V at ~1.6 A at peak power. Four such sub-arrays could provide 1.6 A at 320 V if connected in series, or 3.2 A at 160 V in 2 parallel strings of two, or 6.4 A at 80 V when all wired in parallel. (These nominal voltages do not include the 1-2 V drops in the control circuitry.)

If all 3 transistors are open (gates low), then the conventional current flows in parallel from Vsolar- through the 4 arrays and diodes D11-16. If Q_{SOL}2 is closed, the current on trace V12+ can flow down through it to V34-, where it goes through the two other strings. Then the array provides half the current but at up to twice the voltage. Finally, if Q_{SOL}1 and $_{QSOL}$3 are also closed, then the current follows a full serpentine path through all 4 strings, providing ¼ the current at up to 4X the voltage. Note that the arrays work at less than peak efficiency at most voltages, but averaged over the full range, the losses are well under 20% (and can be much less if ultracapacitors are added to the circuit).

The above schematics do not include various additional features that will be required for accurate sensing of conditions and protection against transients. As part of follow-on work, we would estimate the performance of these circuits using SPICE or similar programs, and we would fabricate and test these circuits under a range of conditions to verify suitability.

The efficiency loss (and resulting heat dissipation) in these components is small. The charge pumps will take milliwatts (except during power-up and during brief diagnostic tests in the linear region). The MOSFETs will dissipate well under a watt each, and the solar array diodes a bit more. It is only the IGBTs and their series diodes that will dissipate large amounts of power (up to ~30 W/module). That is a heatsink issue more than an efficiency issue, since many kilowatts will be dissipated in "drag" mode anyway, mostly in the long conductor.

IV. "Virtual Test Bed" Simulation

The entire electrical system and the switching circuitry of EDDE were modeled on the Virtual Test Bed[8] platform of the University of South Carolina, which required development of new models for the electron collector, electron emitter, and ambient plasma. The switching circuitry model was built from standard parts. The complete system model is shown in figure 5:

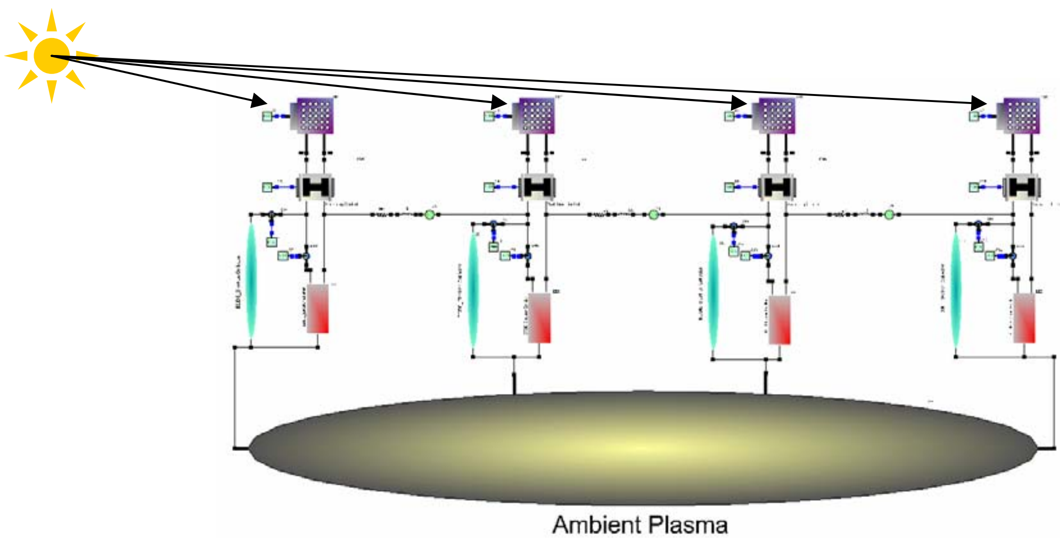

Figure 5. VTB schematic, showing the EDDE configuration

Power Modules

Each power module consists of a solar array, a switching module, and the high voltage tether control switches for isolation of the power modules in the event of arcing. The model of the solar array module is a "hierarchical device" in VTB, which means that it wraps up a more detailed model which is shown later (in Fig 9). The solar array model generates the voltage required to drive the current through the tether segment. This solar array is connected to the tether segment through the switching control module. High voltage control switches are connected in the power module for isolation of this power module or tether segment when arcing occurs between the tether segment and plasma. The electron emitter and electron collector are connected with the help of controlled switches which gives an option for electron emission or collection at the end of the tether segment where this power module is connected.

The power modules, electron emitter and the electron collector are connected at each end of the tether segment. Figure 6 shows this configuration. This enables current through the tether segment to be switched in any direction desired, and enables any tether segment to function independently though with a reduced thrust. The tether segment is represented by a series combination of resistance, inductance and a voltage source which represents the EMF induced by motion of the tether segment through the earth's magnetic field.

Several such tether segments are connected together and the switch configuration is arranged so as to drive the current in the desired direction for a particular tether segment at any instant thus electrons can be emitted to or collected from the ambient plasma at either end of any segment, by switching the appropriate emitter and collector in the power modules. This concept is shown in Figure 7.

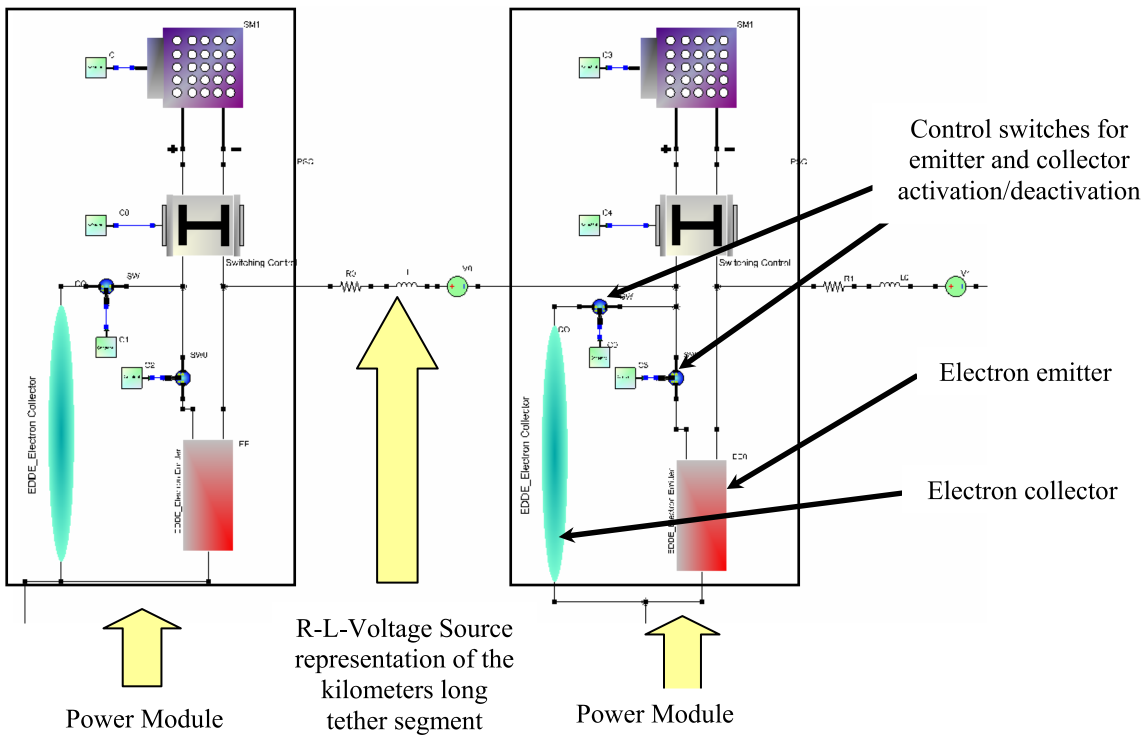

Figure 6. Configuration of single tether segment in VTB

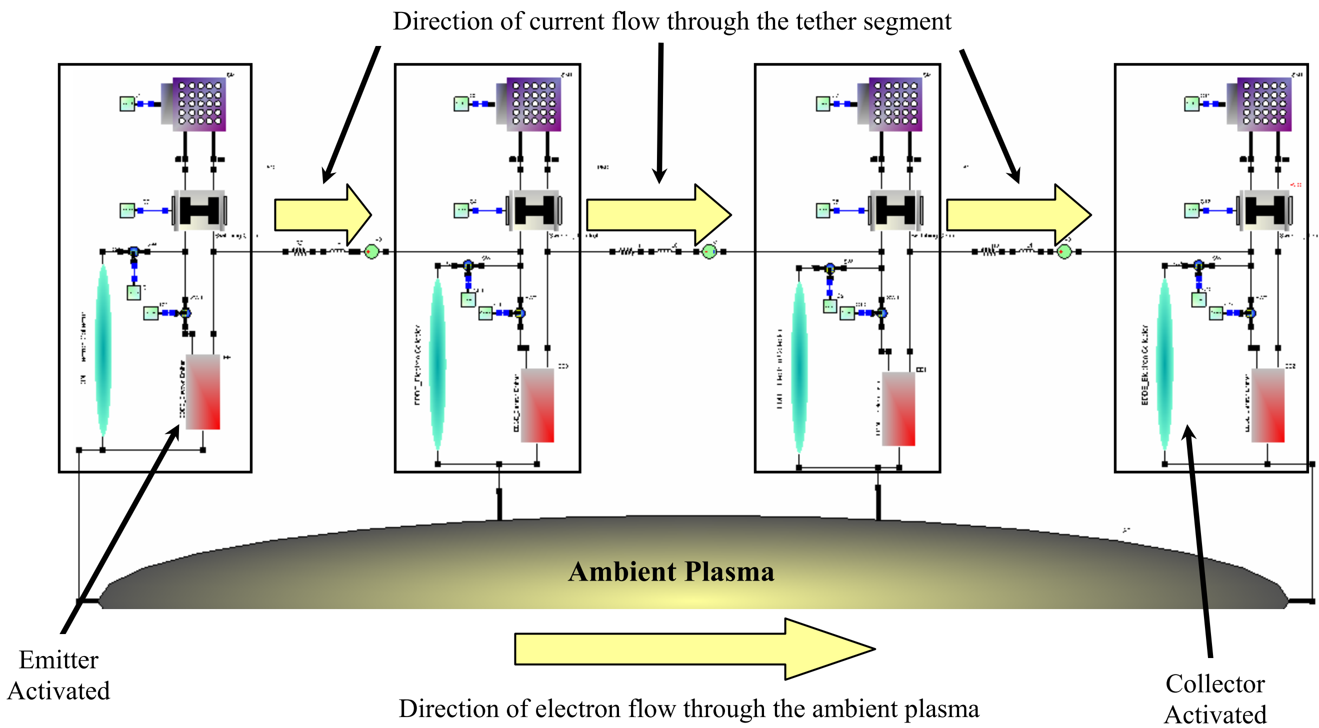

Figure 7. Controlling the direction of current in the tether with switching control

Solar Array Power Module

The solar array power module comprises of four sub-arrays which can be connected in series, parallel or in a 2X2 configuration. The VTB model of this module includes a signal port, as shown in Figure 8, which is used to select the configuration.

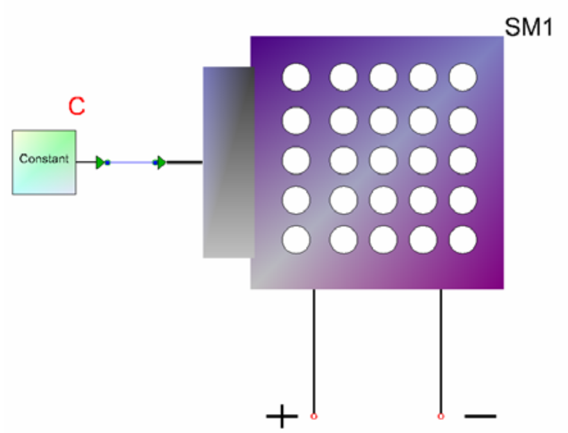

Figure 8. VTB model of solar array power module

The internal schematic diagram of the solar array power module is shown in Figure 9. The solar irradiance model for orbital applications is used to drive the solar arrays.

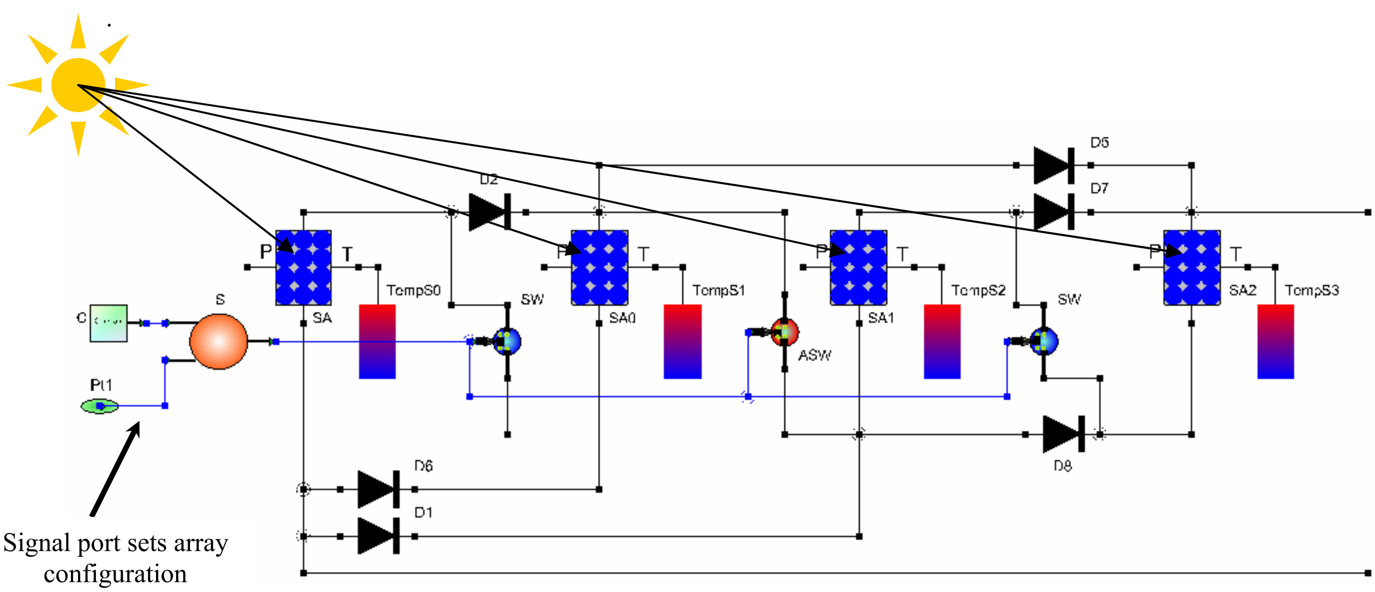

Figure 9. Internal Schematic diagram of solar array power module

Switching Control

The model of the high voltage h-bridge switching control module has four natural ports and one signal port, and has schematic symbol as shown in Figure 10. A command signal can be applied at the signal port to set the power switch configuration to either forward or reverse polarity to control the direction of current in the tether. In case of failed power switches or misaimed solar arrays, a shunt switch is provided to bypass any solar array modules.

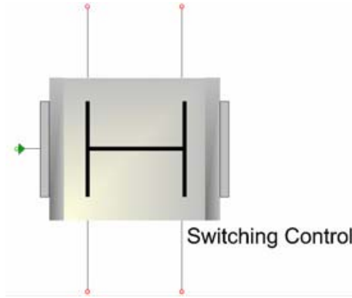

Figure 10. VTB icon for the high voltage power switching module

Figure 11 shows the schematic of the h-bridge switching control module, which also includes bypass and shunt switches to bypass the module in event of failures.

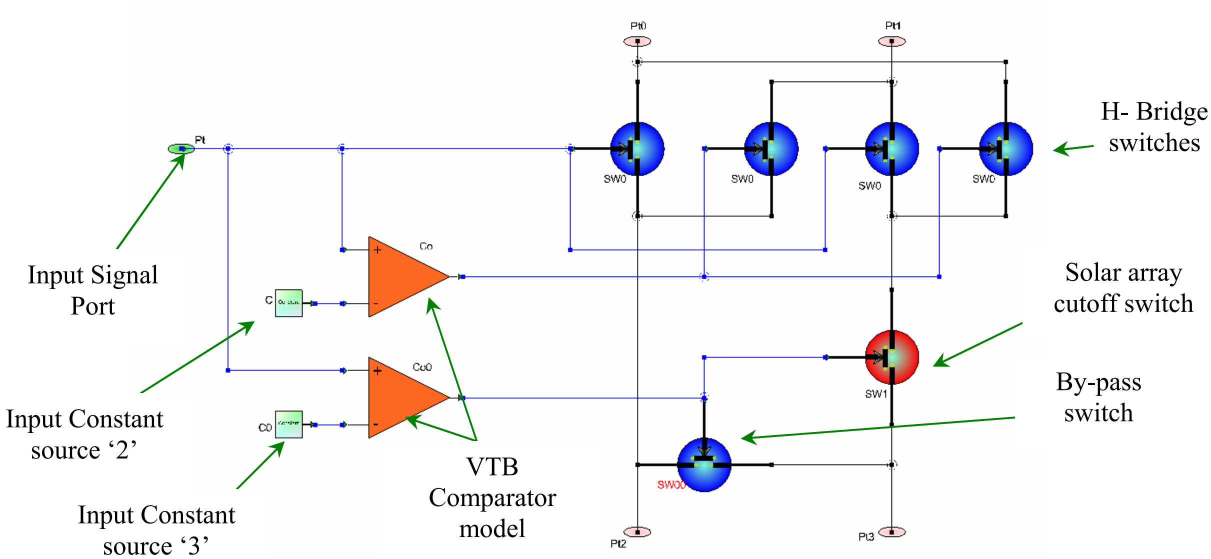

Figure 11. Schematic of the high voltage power switching module

Ambient Plasma, Emitter and Collector

To emit electrons into the ambient plasma, EDDE can use either a hollow cathode (which has a weak dependence of voltage on current) or a thermionic emitter, which has a stronger dependence. If a thermionic emitter is used, the thermionic electron emitter receives heater power from the power module with a control switch for its activation and deactivation. Electron emission from the heated filament is represented by the Richardson-Dushman equation:

$$j_s = AT^2 \exp(-e\varphi_c / kT)$$

The electron collector is also connected to the power module through a series switch for its activation and deactivation, and simulates the resistance of value 2.3 ohms/km offered by a 30-mm wide, 38-micron thick aluminum-foil tape as the EDDE collector. When in drag mode, the EMF leads to electron collection at the furthest end of the emitter, with self-adjusting collection length which varies with the plasma density. A bare-wire design can work in drag mode, but won't work efficiently against EMF, because in such a situation the electron collection will occur near the emitter, which in turn will reduce the working length and thus thrust[9]. EDDE's distributed power is a solution to this problem which pumps electrons against the EMF. In low plasma density, a lower current flows which allows the power system to operate at higher voltage and biases more of the tape positive and hence allows collection along more of the length but still far from the emitter.

The conductivity of the space plasma depends on the local ion density. The equivalent circuit that we can use for the ambient plasma is shown in Figure 12:

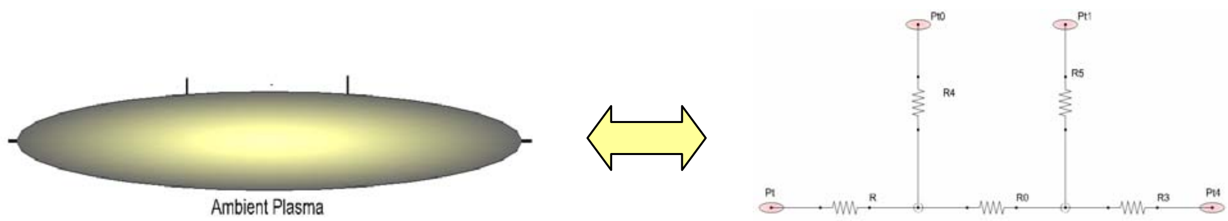

Figure 12. VTB Model for ambient plasma

V. Conclusion

The EDDE operational vehicle concept proposed in this report is the most flexible, high-performance, useful, realistic, and cost-effective electrodynamic thruster vehicle concept proposed to date. EDDE's spinning mode of operation allows far higher performance than possible with any non-spinning electrodynamic thruster; its control law allows minimum-time orbit transfers throughout LEO; and its distributed power and power control improve electron collection, reduce arcing susceptibility and damage, and allow EDDE to promptly de-orbit itself if it is cut or otherwise partially disabled. To complete the high-voltage power switching system development, the next steps are to develop and test the solar-array switching circuits and to refine and test EDDE's current control laws.

Acknowledgments

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