Performance Effects of Adding a Parallel Capacitor to a Pulse Inductive Plasma Accelerator Powertrain

Kurt A. Polzin and Amy D. Sivak
NASA-Marshall Space Flight Center, Huntsville, AL, 35812, USA

and

Joseph V. Balla
The Ohio State University, Columbus, OH, 43210, USA

kurt.a.polzin@nasa.gov

Pulsed inductive plasma accelerators are electrodeless space propulsion devices where a capacitor is charged to an initial voltage and then discharged through a coil as a high-current pulse that inductively couples energy into the propellant. The field produced by this pulse ionizes the propellant, producing a plasma near the face of the coil. Once a plasma is formed if can be accelerated and expelled at a high exhaust velocity by the Lorentz force arising from the interaction of an induced plasma current and the magnetic field. While there are many coil geometries that can be employed to inductively accelerate a plasma, in this paper the discussion is limit to planar geometries where the coil take the shape of a flat spiral. A recent review of the developmental history of planar-geometry pulsed inductive thrusters can be found in Ref. [1]. Two concepts that have employed this geometry are the Pulsed Inductive Thruster (PIT)[2,3] and the Faraday Accelerator with Radio-frequency Assisted Discharge (FARAD)[4].

Pulsed inductive plasma accelerators possess many demonstrated and potential benefits[1,3], providing motivation for continued investigation. The electrodeless nature of these thrusters eliminates the lifetime and contamination issues associated with electrode erosion in conventional electric thrusters. Also, a wider variety of propellants are available for use when compatibility with metallic electrodes is no longer an issue. Pulsed inductive accelerators have demonstrated operation on propellants like ammonia, hydrazine, and CO_2, and there is no fundamental reason why they would not operate on other propellants like H_2O. It is well known that pulsed accelerators can maintain constant specific impulse I_{sp} and thrust efficiency η_t over a wide range of input power levels by adjusting the pulse rate to maintain a constant discharge energy per pulse. In addition, these thrusters have demonstrated operation in a regime where η_t is relatively constant over a wide range of I_{sp}. Finally, thrusters in this class have operated at high energy per pulse, and by increasing the pulse rate, they offer the potential to process very high levels of power to provide relatively high thrust using a single thruster.

Pulse circuits for inductive thrusters have in the past typically been limited to a simple, ringing RLC configuration like that shown in Fig. 1A,B. However, as the field develops the circuit topologies are becoming much more are becoming more complex[5]. In this paper, we proceed with an investigation of the circuit shown in Fig. 1C where a second capacitor with value less than or equal to C_1 is inserted downstream of the switch. There are two observations that have motivated the investigation of this particular configuration. The first is a set of data where the efficiency of a thruster increased when the capacitor C_2 was inserted[6]. Unfortunately, the value of C_1 was also increased when C_2 was added and previous work has shown that this could also increase the efficiency[7]. The authors also noted in Ref.

[6] that the voltage across C_2 could be approximately double that across C_1 when $C_2 << C_1$. This result was interesting because it implied that the voltage and commensurate current rise rate in the coil could be increased by adding C_2. A higher current rise rate can, in turn, produce stronger electromagnetic fields at the coil face and potentially lead to better inductive ionization of the propellant[5].

There exists a 1-D pulsed inductive acceleration model that employs a set of circuit equations coupled to a one-dimensional momentum equation. The model was originally developed and used by Lovberg and Dailey[2,3] and has since been nondimensionalized and used by Polzin *et al.*[7,8] to define a set of scaling parameters and gain general insight into their effect on thruster performance. In this paper we modify the acceleration model to account for the presence of C_2 in the system, and then nondimensionalize the equation set to identify any new nondimensional scaling parameters that might arise for the new circuit topology. The current rise rate through the coil is computed for various cases, and it is used as a proxy for the ability of the coil to inductively ionize the propellant. Finally, we gauge the potential benefits or detriments the addition of C_2 imposes on thruster efficiency and I_{sp}.

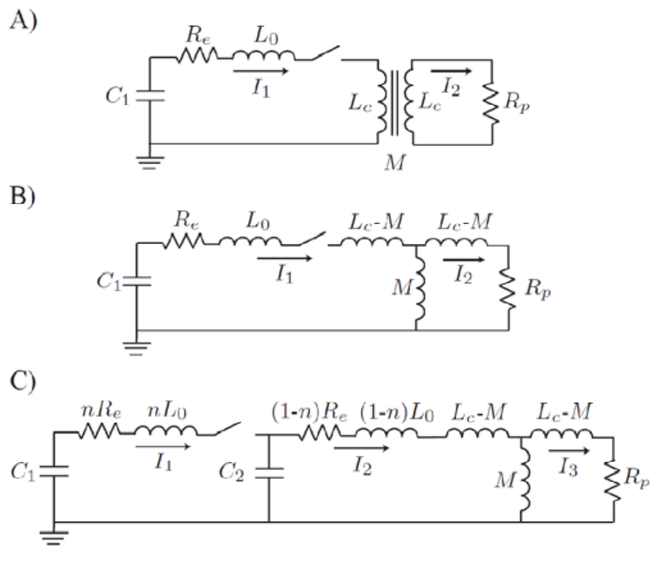

Figure 1. A) General lumped-element circuit model and B) equivalent circuit model of a pulsed inductive accelerator (after Ref. [2]). C) Equivalent electrical circuit model of an accelerator with a second, parallel capacitor.

The nondimensionalized equation set can be written as

$$\frac{dI_1^*}{dt^*} = \frac{1}{n}(V_1^* - V_2^*) - \psi_1 I_1^*$$

$$\frac{dI_2^*}{dt^*} = \frac{\left(L^* V_2^* + (M^* I_2^* + I_3^*)\, {}^{dM^*}\!/_{dt^*} - \psi_2 L^* M^* I_3^* - (1-n)\,\psi_1 L^* I_2^*\right)}{\left[\left((1-n)L^* + 1\right) - (M^*)^2\right]}$$

$$\frac{dI_3^*}{dt^*} = M^* \frac{dI_2^*}{dt^*} + I_2^* \frac{dM^*}{dt^*} - \psi_2 L^* I_3^*$$

$$\frac{dV_1^*}{dt^*} = -I_1^*$$

$$\frac{dV_2^*}{dt^*} = C(I_1^* - I_2^*)$$

$$\frac{dM^*}{dt^*} = -\frac{1}{2} e^{\left(-z^*/2\right)} v_z^*$$

$$\frac{dz^*}{dt^*} = v_z^*$$

$$\frac{dv_z^*}{dt^*} = \frac{\left[\alpha (I_2^*)^2 e^{(-z^*)} - \rho^* f(z^*)(v_z^*)^2\right]}{m^*}$$

$$\frac{dm^*}{dt^*} = \rho^* f(z^*) v_z^*$$

where the starred quantities represent dimensionless properties and L^*, ψ_1, ψ_2, α, and C are the similarity parameters of the system. The set is solved by parametrically varying the values of α and C and using the final velocity to calculate the thrust efficiency. Additionally, the equation set can be used to calculate the time history of the current rise rate dI_2^*/dt^* and commensurate inductive voltage drop across the inductive coil. These data are presented in Fig. 2. This paper will discuss the observed trends in these data and draw conclusions regarding the efficacy of adding a second capacitor for inductive preionization, as well as examine the effects on pulsed inductive plasma thrusters performace.

References

[1] K.A. Polzin, "Comprehensive review of planar pulsed inductive plasma thruster research and technology," *J. Propuls. Power*, **in press**, 2011.

[2] R.H. Lovberg and C.L. Dailey, "Large inductive thruster performance measurement," *AIAA J.*, **20**(*7*):971, 1982.

[3] C.L. Dailey and R.H. Lovberg, "The PIT MkV Pulsed Inductive Thruster," TRW Systems Group, Tech. Rep. NASA CR-191155, Jul. 1993.

[4] E.Y. Choueiri and K.A. Polzin, "Faraday Accelerator with Radio-Frequency Assisted Discharge (FARAD)," *J. Propuls. Power*, **22**(*3*):611, 2006.

[5] K.A. Polzin, "Scaling and Systems Considerations in Pulsed Inductive Plasma Thrusters," *IEEE Trans. Plasma Sci.*, **36**(*5*):2189, 2008.

[6] C.L. Dailey, "Pulsed Electromagnetic Thruster," TRW Systems Group, AFRPL-TR-71-107, 1971.

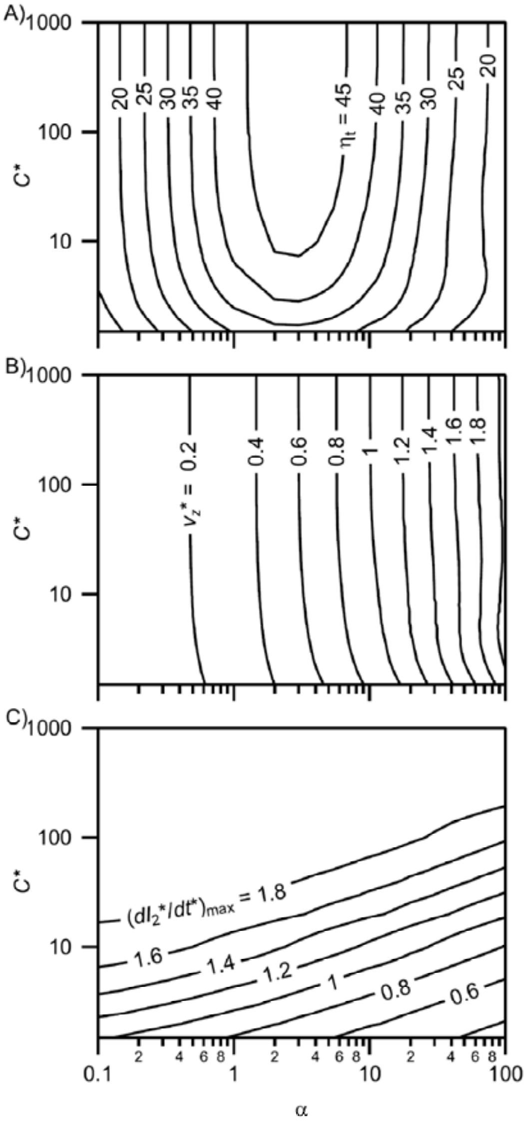

Figure 2. contour plots of (A) efficiency, (B) nondimensional velocity and (C) maximum value of dI_2^*/dt^* as a function of α and C.

[7] K.A. Polzin and E.Y. Choueiri, "Performance optimization criteria for pulsed inductive plasma acceleration," *IEEE Trans. Plasma Sci*., **34**(*3*):945, 2006.

[8] K.A. Polzin, Faraday Accelerator with Radio-Frequency Assisted Discharge (FARAD), Ph.D. Dissertation, 3147-T, Princeton Univ., Princeton, NJ, 2006.