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

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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 it 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 limited to planar geometries where the coil takes 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\(_2\)O. It is well known that pulsed accelerators can maintain constant specific impulse \(I_{sp}\) and thrust efficiency \(\eta_t\) 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 \(\eta_t\) 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 $C_2 \ll C_1$. 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.

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 and has since been nondimensionalized and used by Polzin et al. 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 $I_{sp}$.

The nondimensionalized equation set can be written as

\[
\frac{dI_1^*}{dt^*} = \frac{1}{n} (V_1^* - V_2^*) - \psi_1 I_1^* \\
\frac{dI_2^*}{dt^*} = \frac{\left(L^*V_2^* + (M^*I_2^* + I_3^*) \frac{dM^*}{dt^*} - \psi_2 L^*M^*I_3^* - (1 - n) \psi_1 L^*I_2^*\right)}{\left((1 - n)L^* + 1\right) - (M^*)^2} \\
\frac{dI_3^*}{dt^*} = M^* \frac{dI_2^*}{dt^*} + I_2^* \frac{dM^*}{dt^*} - \psi_2 L^*I_3^* \\
\frac{dV_1^*}{dt^*} = -I_1^* \\
\frac{dV_2^*}{dt^*} = \zeta (I_1^* - I_2^*) \\
\frac{dM^*}{dt^*} = -\frac{1}{2} e^{-\frac{z^2}{2}} \psi_2^* 
\]

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.
\[
\frac{dz^*}{dt^*} = v_z^*
\]
\[
\frac{dv_z^*}{dt^*} = \frac{\alpha (l_z^*)^2 e(-z^*) - \rho^* f(z^*) (v_z^*)^2}{m^*}
\]
\[
\frac{dm^*}{dt^*} = \rho^* f(z^*) v_z^*
\]

where the starred quantities represent dimensionless properties and \( L^*, \psi_1, \psi_2, \alpha \), and \( C \) are the similarity parameters of the system. The set is solved by parametrically varying the values of \( \alpha \) 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 \( dI_z^*/dt^* \) 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 performance.

References


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