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Pulse shaping techniques for mega ampere current on Atlas pulsed power machine

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PULSE SHAPING TECHNIQUES FOR MEGA AMPERE CURRENT ON ATLAS PULSED POWER MACHINE

by

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Bachelor of Engineering in Electrical and Electronics Engineering
Madras University, India
2001

A thesis submitted in partial fulfillment of the requirements for the

Master of Science Degree in Electrical Engineering
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Entitled

"Pulse Shaping Techniques for Mega Ampere Current on Atlas Pulsed Power Machine"

is approved in partial fulfillment of the requirements for the degree of

Master of Science in Electrical Engineering

[Signatures of Examination Committee Chair and Dean of the Graduate College]
ABSTRACT

Pulse shaping techniques for mega ampere current on Atlas pulsed power machine

by

Pradeep Kumar Reddy Koppula

Dr. Yahia Baghzouz, Examination Committee Chair
Professor of Electrical and Computer Engineering
University of Nevada, Las Vegas

Atlas is one of the world’s largest pulsed power systems designed by Los Alamos National Laboratory (LANL) to perform high energy density experiments in support of weapon-physics and basic research programs. The current pulse generated by Atlas is a damped sinusoid that rises to nearly 30 MA in 6 microseconds as it flows through the load (target). The models developed here evaluate the Atlas reconfiguration in order to obtain a compressed pulse with a much faster rise-time for magnetic compression experiment, and another expanded current pulse with a much slower fall-time for driving very heavy liners. Comparative studies of various types of switches that can be implemented on Atlas have been examined. The simplified models representing the Atlas reconfiguration are simulated using the PSpice circuit simulation tool to obtain accurate wave shapes based on time varying parameters.
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CHAPTER 1

INTRODUCTION

Atlas is one of the largest pulsed power generators designed and built by Los Alamos National Laboratory (LANL) [1]. It is used as a driver for hydrodynamic experiments in support of weapons-physics investigations for the Science-Based Stockpile Stewardship Program of the National Nuclear Security Agency (NNSA). The experimental data developed is needed to improve computer models for nuclear weapon performance and reliability without nuclear testing [2].

Pulsed power machines like Saturn, PBFA-Z and Procyon, which are designed to drive light weight liners, are used for radiation purposes [3]. Driving these light weight liners in compression experiments requires a current that rises to its peak value at a much faster rate of 0.5 microseconds. This liner collides itself on axis, converting kinetic energy into soft x-rays [4]. On the other hand, Shiva Star and Pegasus II, designed to drive heavy liners, are used for hydrodynamic experiments with low current of about 5 MA. Driving these heavier liners requires the current to decay at a much slower rate after reaching the peak to compress the sample materials to high pressures when hitting the target. Atlas is capable of driving both light and heavy liners. In the Atlas machine, high-energy density conditions are developed by delivering nearly 30 MA of current in a 4-6 μs time frame. The basis of pulsed power implosions is the magnetic interaction between
the flowing electric charges that make up an electric current (i.e., Lorenz's forces). Atlas is capable of achieving shock pressure exceeding 30-Mbar in several centimeter cube volume for hydrodynamic experiments. Light and heavy liner experiments require some Atlas reconfigurations in order to obtain desired current pulse shapes. The work presented in this thesis shows some circuit models of Atlas, when equipped with switches, generating the above mentioned current wave shapes.

Organization of the thesis

In Chapter 2, a brief overview of the Atlas pulse power system, operation, and an equivalent circuit model representing its present configuration is shown. Various parameters of the Atlas machine are described in detail. In Chapter 3, Atlas pulse shaping methods are described along with a literature survey on the possible switches that can be employed on the Atlas machine. It is determined that most of the switches have either low amperage rating or longer switching time than needed [5]. In Chapter 4, modified circuit models that achieve pulse compression by using a plasma opening switch close to the load, and pulse expansion by using the crowbar switch near the source-end of the transmission line, are described. Simple physical models which describe the switch performance are studied.

Due to the time-dependent nature of the switches and the load parameters, simulations are conducted using PSpice. This software is used to predict the system performance for various parameter values.

The work presented in this thesis indicates that the current pulse obtained by the present configuration can be conditioned to meet the needs of a wider array of liner sizes.
and weights. The rise time of the current wave shape was significantly reduced by using a plasma opening switch (POS). Similarly, the current fall time was expanded by using a shunt crowbar switch.
CHAPTER 2

DESCRIPTION AND OPERATION OF ATLAS PULSED POWER MACHINE

The Atlas pulsed power system is a facility developed for studying material properties and high energy density experiments under extreme conditions. The description and operation of the facility is described in detail below.

2.1 System description

Figure 2.1 shows a basic view of the Atlas pulsed power system. Spanning nearly 80 ft in diameter, the machine consists mainly of Marx capacitor banks, transmission lines, and the target area, [6] each briefly described below. The Atlas machine was constructed 4 years ago and is expected to perform reliably for 10-20 years. Recently, Atlas was transferred from Los Alamos National Laboratory (LANL), NM, to the Nevada Test Site, NV.

2.1.1 Marx bank and maintenance units

The capacitor banks are considered to be the primary elements that store and deliver the electrical energy used to drive the liner. The power source consists of 96 Marx capacitor banks [7] to store a total energy of nearly 23 MJ at rated conditions. These banks are arranged in 24 modules, each containing four capacitor banks connected in a
series. These modules are housed in 12 separate oil tanks, symmetrically arranged in around the target chamber. A stainless steel resistor is interconnected between two centre capacitors in the Marx module to limit fault currents and capacitor voltage reversal. Two

![Atlas pulse power system](image)

**Figure 2.1: Atlas pulse power system [6]**

low-inductance pressurized gas switches, known as rail gaps, connect all four capacitors in a series [8]. The Atlas machine consists of 192 switches, i.e., two switches for each Marx module, with 120-kV maximum voltage, 330 kA conduction current and 3-coulombs of charge transfer.

Each capacitor bank is charged to around 60 kV, thus the module has an erected voltage of 240 kV. The capacitor bank can handle a maximum voltage reversal of about 90 kV, but the engineers of Los Alamos Laboratory limit the voltage to 68 kV to 70 kV.
This allows the maximum voltage of the Marx capacitor bank to be less than 200 kV, instead of 240 kV. Figure 2.2 below shows one of the 12 Marx tanks and its basic components, like tri-plate transmission lines, the load protection switch, and the target chamber. The maintenance unit consists of two stacks of Marx modules mounted, and they can be independently removed from the system. Each maintenance unit consists of a capacitor charging system, a railgap trigger system, and a data acquisition module.

![Figure 2.2: Atlas pulse power system basic components][40]

In case of misfiring, current is transmitted from the cable header to the load protection switch through the high voltage, coaxial cables. The purpose of the switch is to protect the liner from damage due to misfiring. The other end of the load protection switch is connected to the vertical triplate transmission line system.
2.1.2 Triplate transmission line system and load protection

The Marx modules are connected to the power flow channel (PFC) located outside the target chamber through 24 parallel triplate transmission lines, designed with minimum inductance [9]. The aluminum triplate conductors are around 6 m long, with an inter electrode gap of 2.03 cm, and the height of the transmission lines decreasing from 1.75 m at the switch end to 0.32 m at the target end. The centre conductor of the triplate is 2.6 cm thick, and the outer conductors are 1.6 cm thick. These transmission lines must withstand a discharge voltage of 220 kV, and should carry 1.3 MA of current under normal discharge.

2.1.3 Load protection switch

The load protection switch should protect the load assembly from prefire current from the Marx modules, allowing the modules to discharge individually or collectively so that the load is not subjected to significant voltage or current. The load protection switch will remain closed during charging. When the charge is full, these switches open in approximately 250 ms, and are arranged near to the maintenance unit.

2.1.4 Target chamber

The target chamber houses the target/liner assembly and provides vacuum confinement for the experiment [10]. The target chamber is around 2 m in diameter. The liner in the target chamber implodes due to the magnetic interaction between the flowing electric charges that make up an electric current (i.e., Lorenz’s forces). High pressure is created in the target chamber due the liner impact. The amount of energy trapped and
dissipated in the target chamber is more than 12 MJ. Figure 2.3 below shows the target and the liner assembly. A wide variety of experiments are done in the centimeter cube volume, like high pressure adiabatic compressions, experiments on dense strongly coupled plasmas, material response at very high strains, and magnetized fusion experiments.

![Figure 2.3: Cylindrical liner and the target [6]](image)

2.2 Equivalent circuit of Atlas machine

The simplified lumped model of the Atlas machine is shown in figure 2.4 below:

![Figure 2.4: Lumped model of the Atlas machine](image)
where \( C_1 \): capacitance of Marx generators,

\( L_1 \): header inductance,

\( R_1 \): series resistor to limit voltage reversal,

\( R_2 \): shunt resistor to prevent parasitic ringing between transmission line capacitance,

\( L_1, L_2 \): transmission line inductance,

\( R_3 \): transmission line resistance,

\( L_3 \): inductance of power flow channel,

\( L_4 \): variable inductance of imploding liner.

The values of the parameters above are as follows: \( C_1 = 816 \, \mu\text{F} \), \( L_1 = 2.6 \, \text{nH} \), \( R_1 = 1.875 \, \mu\Omega \), \( R_2 = 50 \, \text{m}\Omega \), \( L_2 = 6.2 \, \text{nH} \), \( R_3 = 10 \, \mu\Omega \), \( L_3 = 13.2 \, \text{nH} \).

The liner inductance \( L_4 \) varies according to the following physics-based model. The equations which govern the liner motion and subsequent variable inductance under the \( J \times B \) forces, which include the liner’s mass, current flowing through the liner, liner’s radius and liner’s height, are [11]

\[
m \ddot{r}(t) = -\frac{\mu_0 i(t)^2}{4\pi r(t)} \tag{Equation 2.1}
\]

\[
L = L_0 + \Delta L(t) = \frac{\mu_0 H}{2\pi} \times \ln\left(\frac{r_o}{r(t)}\right) \tag{Equation 2.2}
\]

\[
L_0 = \frac{\mu_0 H}{2\pi} \times \ln\left(\frac{r_{out}}{r_{in}}\right) \tag{Equation 2.3}
\]

\[
I = \frac{1}{L} \int_0^t \dot{V} \, dt \tag{Equation 2.4}
\]
where \( m \) is the liner mass,

\( i(t) \) is the current through the liner,

\( r(t) \) is the liner radius at time \( t \),

\( H \) is the liner height,

\( \mu_0 \) is the permittivity of free space,

\( r_{out} \) and \( r_{in} \) are the initial liner outer radius and inner radius, respectively.

Equations (2.1) and (2.2) are used to measure the liner’s radius, velocity, acceleration, kinetic energy, electrical action and variable inductance with respect to time. From equation (2.1), one can observe that the force on the liner is proportional to the square of the current through it. Aluminum is treated as the best liner material, as it provides the highest velocity for a given thickness. Table 2.1 below shows the values referring to the beginning of the melting \( Q_{mb} \), the end of the melting \( Q_{me} \), the beginning of vaporization \( Q_v \) and the burst \( Q_b \) of the aluminum.

<table>
<thead>
<tr>
<th>Constants</th>
<th>Velocity coefficients ([ \text{A}^2 \text{s/m}^4 ])</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Q_{mb} )</td>
<td>( 2.52 \times 10^{16} )</td>
</tr>
<tr>
<td>( Q_{me} )</td>
<td>( 3.20 \times 10^{16} )</td>
</tr>
<tr>
<td>( Q_v )</td>
<td>( 4.86 \times 10^{16} )</td>
</tr>
<tr>
<td>( Q_b )</td>
<td>( 6.58 \times 10^{16} )</td>
</tr>
</tbody>
</table>

Table 2.1: Various constants of aluminum

If the load inductance were fixed at \( L_0 \), then the current can easily be derived analytically by standard circuit analysis techniques such as Laplace Transform. If one
further ignores the high shunt resistance $R_2$ (figure 2.4 simplified to a second-order RLC circuit), the current can be described by:

$$i(t) = \frac{V_0}{\alpha L} e^{-\alpha t} \sin(\omega t)$$

(Equation 2.5)

Where $\omega = \left( \frac{1}{L_I C_1} - \frac{a^2}{2} \right)^{1/2}$ and

$$a = \frac{R_T}{2L_T}.$$

Here $R_T = R_1 + R_3,$ $L_T = L_1 + L_2 + L_3 + L_4,$ and $V_o$ is the initial capacitor voltage. However, due to the time-dependent inductance of the load, a more exact circuit solution requires computational techniques or circuit simulation tools such as Pspice.

A Pspice model was created by Kurlinski [12], and incorporates equations (2.1) (2.2) in order to model the liner's radius, velocity, kinetic energy, electrical action and variable inductance, shown in figure 2.5.

![Figure 2.5: Pspice Model of Variable inductance](image)

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Figure 2.6 shows the basic Atlas current wave shape for a typical liner, without any additional pulse shaping elements (with $H=2\text{cm}$, $r_{out}=5.13\text{ cm}$, $r_{in}=5\text{ cm}$):

![Figure 2.6: Atlas current wave shape](image)

Here the current was observed reaching the peak current of 27MA in about 6 μsec, with an initial capacitor voltage of 190.8 KV. In practical applications, the liner should reach target at maximum current in order to achieve optimal efficiency.

The effect of the series resistance is clearly seen in figure 2.7 below. Here with the series resistance, the peak reversal voltage is about 87 kV, whereas without the series resistance the peak reversal voltage is about 140 kV. It is determined that series resistance $R_1$ is very critical for the protection of the capacitor by damping the voltage reversal.
R2, the shunt resistor, was found to limit the parasitic ringing between the capacitance of the transmission line and the inductance of the Marx modules.
CHAPTER 3

PULSE SHAPING TECHNIQUES

Although there are many methods for shaping the pulsed power current waveform, the possible methods for shaping the Atlas machine waveform are limited. The main reason is the inability to handle enormous currents and voltages by the existing pulse shaping devices. Another reason is that the Atlas machine occupies a limited amount of space, which eliminates other methods for shaping the pulse that require large space.

3.1 Need for pulse shaping techniques for Atlas machine

There are two categories of experiments carried out on the Atlas machine. The first category involves driving the thin liners for soft x-ray production, and the second involves driving the heavy liners, in which the current stays for a longer time at the peak. The heavy liner experiments were primarily done to investigate the properties of materials at extreme pressures and temperature, in order to study the hydrodynamic behavior of the imploding systems and magnetized target fusion (MTF). In magnetized fusion experiments, the properties of the materials at high strain under various shock loading circumstances were investigated, along with the issues of liner instabilities, motion of interfaces undergoing differential acceleration, and hydrodynamic flows in complicated geometries. Imploding liners of speeds greater than 1cm/\mu s are used for
compressing the fusion target that has magnetized, preheated plasma. The main requirements for heavy liner experiments are that the inner surface of the liner attains high velocity, and it remains unmelted and has a smooth uniform drive.

3.2 Types of pulse shaping techniques carried on Atlas machine

A literature survey was carried out to explore new pulse shaping techniques. Prior to the switching technology, spark gaps were used. Switching emerged as a better technique after considerable amount of research. When we attempt to shape the current waveform of the Atlas, the important factor to be considered is the placement of the switch in the power flow channel. The following methods were studied for shaping the Atlas current pulse.

3.2.1 Drift Step Recovery Diodes (DSRD)

Drift step recovery diodes are the fast semiconductor opening switches, and when used along with silicon avalanche shapers (SAS) [13], can reduce and sharpen the rise times of the waveform. Silicon avalanche shapers are the fast closing switches. When DSRD is used with the SAS, the output voltage of the DSRD rises up to an order of 3kv/ns during the Marx erection process. Their low power rating makes them unsuitable for use in the overall circuit model of the Atlas machine.

3.2.2 Nonlinear capacitors and IGBT

Nonlinear capacitors
The BaTiO₃ non-linear capacitor [14] is a ceramic capacitor mainly used for voltage amplification. These switches can reduce capacitance values to about one tenth of original value after passing a certain amount of electrical energy. The nonlinear capacitors are unsuitable for the Atlas machine because the peak voltage is around 10 kV, and peak current is around 10s of kilo amps.

Insulated gate bipolar transistor (IGBT)

An insulated gate bipolar transistor is a diode based opening switch, used only in the range of few KAs. Since the Atlas machine requires switches that can handle mega amperes of currents, an IGBT is unsuitable.

3.2.3 High power transformer

Another option for pulse shaping of Atlas current is the installation of the high power transformer that can handle Mega ampere currents [15]. Because of the limited space, creation of such small transformers is very unlikely.

3.2.4 High-Power MOSFETs and Fast-Switching Thyristors

The performance of high power MOSFETs and fast-switching thyristors was investigated for their use in opening switches in inductive storage systems (ISS). The parallel and series configurations of power MOSFETs show a negligible current imbalance and a symmetrical voltage sharing during the commutation phase, making it unsuitable for use in the Atlas pulse power machine [16].
3.2.5 Blumleins circuit

Blumleins circuits [17] are the pulse forming network used to create pulses up to 50 MW with voltage stability with 0.03%. These Blumleins, along with the Photo conductive switching, provide faster output pulse rise times. They can provide nano second pulses at powers approaching 100 MW with rise times faster than 300 picoseconds. If a shaped pulse was required from the generator, Blumleins would replace the peaking capacitor.

3.2.6 Reversed switched dinistors (RSD)

Reversed switched dinistors were developed to allow greater switching currents than thyristors [18]. Therefore, it was a very useful addition to pulse power engineering. However, their permissible operational modes and complicated triggering have yet to be studied. An optimal configuration for different operational modes of switch needs to be studied. The study should involve performance parameters like maximum permissible voltages, peak current, maximum transferred energy, and charge per one shot before being used on the Atlas machine.

3.2.7 Plasma Opening Switch

The plasma opening switch (POS) can be used for switching multi-MA currents with typical rise times of 0.1 μs to a load within 10 to 100ns. Because of this, they are used in light liner experiments. The main purpose of driving the light liner is to create high power x-ray radiation sources [19]-[22]. When large current is sent through the liner for a long time, the liner reaches the melting point before vaporizing and finally bursting into
plasma. As the liner become thinner, the current density, the electrical action increases, and improves the production of the x-rays [23]-[26]. In order to produce high acceleration to the liner, current pulse is shaped to allow greater current through the liner before implosion. To shape this current pulse, an opening switch was placed parallel to the load. This pulse shaping system was referred to as an inductive energy storage system because the system depends on releasing the capacitor’s energy to the circuit as current. The important part in opening the switch is diverting almost all the current, in a few hundred nano seconds, to the load. Plasma opening switches that can handle 5MA have been built and tested on machines like the ACE4 generator [27]. It has been experimentally shown that POS is better than the fuse option due the following constraints (1) POS allows closer placement of the switch to the load, thus providing a favorable inductance distribution [5]; (2) Fuse option is inefficient due to significant resistance loss during conduction; (3) POS option shows promise but has scaling issues; (4) Modeling of these switches is extremely difficult (physics not well understood).

3.2.8 Crowbar switch

Heavy liners with small diameters require a higher rise time current to obtain maximum compression at impact. The important parameters of the heavy liner can be assessed by considering the kinetic energy of the liner. As the liner kinetic energy increases, more energy will be passed on to the target. The energy available for the target is compressed to fusion conditions for MTF experiment.

Magnetic compression experiments and many plasma physics experiments require crow bar switches that have low resistances and short switching times [28]. One thing
that should be kept in mind during the design of the crowbar switch is to have low inductance [29], as it effects the L/R decay time of the current.

Because of high reliability, low resistance, precise delay time, and the simplicity of operation, the crowbar switch can be used on the Atlas machine for driving the heavy liners [30]-[32]. The crowbar switch, placed at the source end of the transmission line, releases maximum current to the load followed by a non-oscillating current decay. Crowbar switch can be modeled by a variable resistor that ideally exhibits a step decrease from infinity to zero.
4.1. Atlas reconfiguration for current compression

Atlas reconfiguration for current compression using the light liner requires current to rise to its peak at a faster rate, probably in the order of microseconds. A plasma opening switch is supposedly the best option.

Plasma opening switch (POS)

Because of the load stability issues, the lightweight liners were accelerated at a rate nearly one order of magnitude faster than heavy liners. Also, heavy liners with small diameters require a higher rise time current to obtain maximum compression at impact. The most common way to obtain a higher faster current pulse was inductive pulse compression, where some of the electrostatic energy stored in the capacitor banks was converted into magnetic energy by allowing temporary current flow in the LC circuit. This was achieved by discharging the capacitor through an inductor while shorting out the load with a switch. Then, the switch was opened when maximum current through the inductor was reached, and the current was transferred to the load.

The biggest problem is finding an opening switch capable of interrupting tens of mega-amps in time scales of a few hundred nanoseconds, while withstanding voltages of
mega volts. A plasma opening switch (POS) was the best candidate for such extreme currents and voltages [34]. The POS is basically plasma that is rapidly injected by a number of plasma sources into the vacuum gap between the output conductors of a pulsed power generator. In the POS, the plasma will not conduct any generator current towards the load during the conduction phase of the plasma opening switch. During the opening phase, the generator current was allowed to pass towards the load. Figure 4.1 below shows conduction and the opening mechanisms of the plasma opening switch.

Figure 4.1: Conduction and opening of the plasma opening switch [41]

The switch opens when the resistance of the switch becomes high compared to the resistance during the conduction. POS was previously developed on the facilities like ACE-4, Hawk, and Decade; properties like peak conduction current, plasma density, storage current rise time were investigated. The use of the POS between the generator and the load improves the rise time of the load voltage and the current. Here, an attempt was made on the Atlas machine by placing the plasma opening switch parallel to the load. Conduction and opening mechanisms were investigated. Figure 4.2 below shows the...
basic Atlas machine with the plasma opening switch, represented by a L-R circuit.

![Atlas machine with plasma opening switch](image)

Figure 4.2: Atlas machine with plasma opening switch

Herein, energy initially provided by the capacitor was transferred to inductors $L_1$ and $L_2$, with the circuit being completed by $L_5$ and $R_4$. When the current in $L_2$ reaches its peak, the POS switch is opened (i.e., $R_4$ was increased to a large value) thus energizing the load. Obviously the circuit performance depends on how the increase in impedance of the POS takes place. Under ideal conditions, the switch resistance exhibits a step increase from $R_4 = 0$ to $R_4 = \infty$, and its inductance $L_5$ is constant. If one further ignores $R_2$ and fixes $L_4$ to its initial value $L_0$, analytical solutions of the current can be easily derived as follows: Prior to opening the switch, the capacitor current was described by equation (2.5) with $L_T = L_1 + L_2 + L_5$. The peak current was reached at

$$t_p = \frac{\arctan(\omega/a)}{\omega}$$

(Equation 4.1)
where $a$ and $\omega$ are defined in equation (2.5). The peak value $I_p$ of this current was simply obtained by evaluating equation (2.5) with the inductance change above at time $t_p$. Immediately after the switch opens, the amount of current transferred to the load can be approximated by

$$I_0 = \frac{L_1 + L_2 + L_5}{L_1 + L_2 + L_3 + L_6} I_p$$

(Equation 4.2)

Theoretical modeling of the plasma opening switch and various equations relating to the switch resistance, flow impedance, time dependant of the POS switch gap, etc., were studied and implemented on the PSpice design of the Atlas machine.

In figure 4.2, $L_5$ and $R_4$ are the variable inductance and resistance of the plasma opening switch. The variable resistance mainly depends on the flow impedance [35] given by $Z_f$

$$Z_f = \frac{V_{sw}}{(I_{AU}^2 - I_{CD}^2)^{1/2}}$$

(Equation 4.3)

Where $Z_f$ is the flow impedance,

$I_{AU}$ is the Anode current upstream of the POS,

$I_{CD}$ is the cathode current downstream of the POS, and

$V_{sw}$ is the switch voltage.

Here flow impedance was assumed to rise linearly from zero to 0.14 $\Omega$ in 100 nanoseconds. The flow impedance concept was mainly used to measure the degree to which the POS is open. The net current flowing in the plasma opening switch was given by $I_{sw} = I_{AU} - I_{CD}$. The resistance in terms of the flow impedance [36] is determined by the following equation,
The main advantage of the flow impedance concept is that it differentiates the difference between the anode current and the cathode current. Anode current is the current coming from the source side, and cathode current is the current from the load side. The flow impedance can also be derived according to the time dependant POS gap, which is allowed to rise linearly to a specific value in a specified time and was given by:

\[ Z_f = 30D_{cr}(t) \]

(Equation 4.5)

Where \( D_{cr}(t) \) is the time dependant plasma opening gap, and \( R_c \) is the radius of the cathode of the POS. The POS gap is assumed to form at the cathode [37]. The value of the plasma opening gap in the above equation can be calculated using:

\[ D_{cr}(t) = 8500F_{cr} \frac{R_c}{I_{AU}} (\gamma^2 - 1)^{1/2} \]

(Equation 4.6)

Where \( F_{cr} \) is dimensionless, and its value is around 1.6 for voltages ranging between 1 and 3 MV, and \( \gamma \) is the ratio of the electron energy to electron rest energy. The rate of the inductance change in the plasma opening switch was calculated according to the snowplow model [38] during the conduction phase. To account for the plasma motion, the inductance was assumed to increase from 1.25 to 2.1 nH during the conduction time. The switch was assumed to open when the snowplow model reaches the end of the plasma fill region according to the assumed \( Z_{flow} \) model. The snowplow motion was given by the equation
\[ F = \frac{d}{dt} \left( M_{sp} \frac{dX_{sp}}{dt} \right) \]  

(Equation 4.7)

Where \( M_{sp} \) is the snowplow mass,

\( X_{sp} \) is the snowplow axial location.

The position of the snowplow can be calculated by

\[ \frac{dX_{sp}}{dt} = \frac{1}{10r} \sqrt{\frac{Z}{\pi M_i n}} \left\{ dt \left[ I^2 dt \right] \right\}^{\frac{1}{2}} \]  

(Equation 4.8)

Where \( I \) is the current,

\( Z \) is the ion charge state,

\( M_i \) is the ion mass,

\( n \) is the Plasma electron density.

The magneto hydrodynamics (MHD) conduction limit of the POS was given by the equation

\[ \int I^2_{MHD} dt^2 = \frac{100 \pi r^2 I^2 M_i n}{Z} \]  

(Equation 4.9)

Here \( l \) is the POS plasma fill length. MHD conduction limits mainly occur when the motion of the ion is not negligible and when \( J \times B \) forces displace or distort the plasma. This result in the formation of the low density region from where the opening starts occurs by erosion mechanism. The axial displacement \([39]\) of the plasma, due to the magnetic force, was given by the following equation

\[ \Delta z = \frac{\mu_0 Z}{8\pi^2 r^2 l_o M_i n_e} \int \int I^2 dt^2 \]  

(Equation 4.10)
The plasma opening switch is said to open when the resistance increases to a high value compared to the resistance during the conduction. The current at which the POS opens is known as the critical current, and this current mainly depends on the voltage across the POS gap. The critical current was given by

\[ I_c = \frac{2\pi m_e c}{e\mu_0} (\gamma^2 - 1)^{\frac{3}{2}} \frac{r}{D} \approx 8500(\gamma^2 - 1)^{\frac{3}{2}} \frac{r}{D} \]  

(Equation 4.11)

Where \( D \) is the gap size,

\( m_e \) is the electron mass, and

\( \gamma \) is the relativistic factor.

The complete model of the Atlas machine with

\( C_i = 816 \mu F \), Capacitance of Marx generators,

\( L_i = 2.6 \text{ nH} \), header inductance,

\( R_i = 1,875 \mu \Omega \) series resistor to limit voltage reversal,

\( R_2 = 50 \text{ m}\Omega \) shunt resistor to prevent parasitic ringing between transmission line capacitance,

\( L_2 = 6.2 \text{ nH} \), transmission line inductance,

\( R_3 = 10 \mu\Omega \), Transmission line resistance,

\( L_3 = 13.2 \text{ nH} \), inductance of power flow channel,

and variable inductance of imploding liner according to the physics-based model is given in figure 2.5, and the physical parameters of the plasma opening switch are simulated using the PSpice simulation tool.
A more accurate representation of the current pulse was obtained through computer simulations of the basic equations relating to the switch resistance, flow impedance, time dependant of the POS switch gap, etc.

The resistance of the switch given in the equation (4.4) can be modeled by using different parts available from the library of the PSpice simulation tool.

\[
\frac{I_{\text{AU}} + I_{\text{CD}}}{I_{\text{AU}} - I_{\text{CD}}} \times \sqrt{\text{ABM2}} \times \text{Zf}
\]

**Figure 4.3: Resistance calculation**

In modeling the resistance of the plasma opening switch, the anode and cathode currents are divided by using the part ABM2. To obtain the resistance of the POS, the square root of the ABM2 output value is multiplied by the value of the Zf, shown below. The Zf value of the POS was calculated by using equation (4.5) and equation (4.6). The PSpice model for calculating this value is shown below. The value of the \( D_{\text{crit}}(t) \) is calculated by using the equation 4.6 to obtain flow impedance.
Critical current which is the current at which the switch opens, was calculated by using the equation (4.11).

The storage current and the output current are shown in the figure 4.6. The bump in figure 4.6 shown is mainly due to the liner impact. In here, the plasma opening switch was allowed to open at 3.8 μ sec. It was found that the load current is less compared to the storage current. The load current is observed to reach to its peak in about 100 nS.
Figure 4.7 is the magnification of the load current at the time of switching of the plasma opening switch.

Figure 4.8 shows the resistance of the POS, which varies according to the time. The resistance was observed to vary from zero to 0.30 mega ohms. When the resistance of the switch becomes high, the switch opens, allowing the current to flow towards the load. The critical current was observed to be around 20MA at the time of the opening of the switch. This current mainly predicts how much current passes through the switch at the time of opening of the switch, as shown in figure 4.9. Figure 4.10 shows the change of the radius of the liner due to the impact.

The impedance of the switch was found to rise from zero ohms to 0.14 ohms in 100ns. This can be observed from the graph shown in figure 4.10. The inductance of the switch was allowed to increase from 1.25 to 2.1 nH during the conduction phase, which accounted for the plasma motion in POS region shown in figure 4.12. Figure 4.13 shows the compressed atlas current pulse when the switch is opened at around 6 μsec. Here we can see the switch current, load current, and the capacitor current. Note that the rise time for load current is now over 10 times faster than the one obtained in the present Atlas configuration without the addition of the POS.
Figure 4.6: Load Current

Figure 4.7: Magnification of the Liner Load Current
Figure 4.8: Resistance of the Plasma opening switch

Figure 4.9: Critical current of the Plasma Opening Switch
Figure 4.10: Radius of the liner

Figure 4.11: Flow impedance of the POS
Figure 4.12: Variable inductance of the POS

Figure 4.13: Compressed Atlas Current Waveshape

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4.2 Atlas Reconfiguration for Current Pulse Expansion

The Atlas reconfiguration for current expansion using the heavy liner requires current to decay at a much slower rate after reaching the peak current in the hydrodynamic experiments. The Crowbar switch is assumed to be the best option to achieve this.

Crowbar Switch

Heavy liners are used to either compress sample materials to high pressures, or when driven into a central target, to produce extremely high pressures for hydrodynamic experiments. Optimal operation for these liners is achieved when the time at which the liner hits its target coincides with the current rise time.

Under Atlas' present configuration, heavier liners reach their target well after the current reaches its peak value. This is due to the liner's lower rate of acceleration as defined in equation (2.1). It is noted that the velocity reached by the liner depends only on the integral of the current density squared. In other words, indefinitely large velocities can be obtained by simply applying high current for a longer time. Hence, an Atlas modification that allows the current to stay longer near its peak value is required in order to efficiently implode very heavy liners. One way to achieve this is to allow the normal current flow till it reaches its peak value, and then trap the charge flow through the liner by literally causing a short circuit across its terminals.

In the Atlas case, however, there is no room to install such equipment within the experimental chamber. A more viable location for such a switch is at the connection point between the Marx capacitor banks and the transmission lines. The other issue is the
availability of a switch that can handle tens of mega amps, and convert from a very high resistance to nearly zero resistance at very high speed (i.e., in the order of 1 μs.). These switches are referred to as crowbars, which can be modeled by a variable resistor, and ideally exhibits a step decrease from infinity to zero.

Figure 4.14 below displays the Atlas equivalent circuit with a crowbar, represented by a variable resistor $R_c$, that is placed at the source-end of the transmission line.

![Figure 4.14: Atlas machine with plasma opening switch](image)

An analytical solution of the load current can be obtained again by assuming an ideal switch and ignoring the impact of $R_2$ and changes in $L_4$. Before the crowbar is activated, the load current is described by equation (2.5), and reaches its peak value at $t_p$ which is computed by the equation (4.1). Immediately after the switch is closed, the load current circulates within the mesh to the right as it is "trapped" by the crowbar. The current now decays exponentially, i.e.,

$$I_a = I_p e^{-t/t_l}$$  \hspace{1cm} (Equation 4.12)

where the time constant $t_l$ is computed by

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\[ r_i = \frac{L_2 + L_3 + L_o}{R_3} \]

and \( I_p \) is the initial current right before switching. Similarly, the Marx capacitor current is trapped on the left-side mesh, represented by a second-order RLC circuit. The wave shape of such a current is a damped sinusoid with a much shorter time constant that is equal to \((2L_1/R_1)\).

PSpice simulation was carried out to determine the time dependency of the crowbar switch with variable resistance \( R_c \), and the variable inductance of the load \( L_4 \). Figure 4.16 shows the resulting load and capacitor currents with variable load inductance and switch resistance. This graph is obtained by assuming that the crowbar resistance varied from 1 M\( \Omega \) to 1 m\( \Omega \) in 0.2 \( \mu \)s, and is shown in figure 4.18. Note that the time it takes for the load current to drop to 75% of its peak value is nearly tripled (i.e., from 3 \( \mu \)s in Figure 2.6 to 10 \( \mu \)s in figure 4.17). Figure 4.17 shows the decrease in liner radius due to the imploding liner.

![Graph showing expanded Atlas current waveshape.](image-url)

**Figure 4.15:** Expanded Atlas Current Waveshape.

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Figure 4.16: Radius of the liner

Figure 4.17: Resistance of the crowbar switch
CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The work presented here indicates that the current pulse obtained by the present configuration can be conditioned to meet the needs of a wider array of liner sizes and weights. By using the shunt plasma opening switch on the load side, the rise time of the current waveshape can be significantly reduced. The physics of the plasma opening switch is not well understood, but with the help of the work presented here, the current pulse with a sharp rise time can be achieved to produce high power x-rays.

Similarly, the current fall-time can be expanded by a shunt crowbar switch at the source-side of the transmission line. More work has to be done to understand the behavior of the crowbar switch, when implemented on the Atlas machine. The remaining challenge is to build such fast-acting switches that can handle tens of mega amps and several megavolts.
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