An Inexpensive Ohmic Transformer Firing Circuit for the CDX-U Spherical Torus

T. Munsat, R. Majeski

Princeton Plasma Physics Laboratory, Princeton, NJ 08543

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Abstract

We have designed and modeled a simple, efficient circuit for delivering power to the CDX-U ohmic transformer solenoid. Inexpensive electrolytic capacitors are used to provide the bulk of the stored energy. One small high-voltage oil-filled capacitor bank is used in the ignitron-based circuit.

Several design objectives are met, including the production of a solenoid current waveform well suited to the breakdown and ohmic current-drive of a tokamak plasma, making efficient use of the available loop volt-seconds. The electrolytic capacitors are protected from reverse-bias conditions, and the ohmic solenoid is protected from voltages above 1 kV, well within the voltage rating, under normal operation and any forseeable fault conditions.

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1. Introduction

Toroidal plasma devices (tokamaks, reversed-field-pinches, stellarators, spherical tori) have traditionally driven plasma current by using the transformer action of a centrally-located solenoid to induce a toroidal loop voltage. The loop voltage drives current through the conducting plasma ring, which also provides plasma heating based on the finite resistivity of the plasma. Because of the inherent time-limitation of ohmic plasma current drive and the upper limit of ohmic heating imposed by decreased plasma resistivity at high temperature, fusion devices will eventually rely on other (steady-state) methods of current drive and heating such as radio-frequency waves, neutral beams, etc. That said, ohmic transformers remain an important method of heating and current drive for all existing toroidal plasma experiments.

Plasma initiation and breakdown have been demonstrated to follow Townsend avalanche models, and efficient tokamaks traditionally require loop voltage of 2-5 V for plasma initiation[1,2]. Ohmic current drive is generally sustained with 1-2 V loop voltage, depending on plasma resistivity. CDX-U uses either electron-cyclotron-resonance heating (ECH) or a hot-filament for preionization, and typically requires loop voltage of ~3 V for plasma breakdown. As the plasma current increases, the plasma is ohmically heated, and the electron density also increases. As the plasma temperature rises, the resistivity decreases, and thus lower loop voltage is required in the later stages of the discharge to maintain or even increase the total plasma current while continuing to heat the plasma and build up the electron density.

Based on this loop voltage requirement, it is desirable to construct a system which provides the highest loop voltage at the very beginning of the pulse, to insure strong plasma breakdown. Because the ohmic drive is dependent on a solenoid current ramp, an inherent limitation on the pulse length is based on the maximum current and/or power dissipation tolerances in the solenoid conductor. It is desirable that a driving circuit for an ohmic solenoid provide positive loop voltage for as long as possible within this limitation.

2. The CDX-U Device

CDX-U is a spherical torus (ST) with $R \approx 34$ cm, $R/a \geq 1.5$, $\kappa \leq 1.6$. The power systems for the toroidal and poloidal field coils have recently been upgraded from capacitor banks to power supplies, which provide 2.3 kG toroidal-field on-axis as well as the corresponding vertical and shaping fields necessary to maintain plasma equilibrium. Typical plasma parameters include $n_e(0) > 10^{19}$ m^{-3}, $T_e(0) \approx 150$ eV, and pulse lengths of ~20 ms. The ohmic-heating solenoid is powered by capacitor banks, because of the inherent advantage of swinging the current from negative to positive (to minimize the I^2R dissipated power) and the difficulty of achieving the double-swing with the available high-current supplies. Since all other systems are run from DC power supplies, the limiting factor on plasma pulse length is the duration of the positive loop voltage provided by the ohmic-solenoid waveform.

The bulk of the available CDX-U capacitor banks are electrolytic, so an important requirement in a driving circuit is to keep the capacitors from becoming reverse-biased. CDX-U has traditionally used a circuit which imposed a transient (<15 ms) reverse-bias on the electrolytic capacitors. This is a condition which can act to degrade the lifetime of the capacitors, especially as the pulse length is extended, and has therefore been eliminated with this design.

The CDX-U ohmic solenoid[3] was designed to hold off ~2 kV across the leads. In a low-aspect ratio machine, it is particularly difficult to access the 'center stack', which houses the inner legs of the toroidal-field coils and the ohmic solenoid. It is therefore extremely important to avoid causing internal damage to the center-stack from over-voltage arcing. Special attention has been paid to insure that during normal operation as well as during any foreseeable fault condition the voltage across the solenoid leads does not exceed 2 kV. Fault scenarios are briefly described in section 4.

3. Ohmic Solenoid Driving Circuit

The circuit which drives the ohmic solenoid is shown in figure 1, with the elements described in table I-a. The firing sequence is described in table I-b. The circuit is composed of 2 electrolytic capacitor banks (C1, C3), one oil-filled capacitor bank (C2), 3 ignitrons (IG1-IG3), one damping resistor (R2), and the ohmic solenoid itself (L_{SOL}, R_{SOL}). Modeled time traces of the relevant voltages and currents shown in figure 2 (a-c). Each of the electrolytic banks is matched to a blocking diode (D1, D3) to keep the bank from becoming reverse-biased. The basic description of the circuit is that C1 and C3 are biased in opposite directions with respect to the solenoid, and thus provide positive and negative current ramps, respectively. The oil-filled bank C2 provides a voltage spike which shuts off IG1, thus isolating C1 from the second stage of the firing sequence.

At t=0, the first ignitron IG1 is fired, which allows C1 to discharge, bringing the current through the solenoid to 38 kA. This is the "precharging" phase of the current, which produces negative loop voltage (proportional to the negative of the solenoid current slope), which is not used to drive plasma current. Pre-ionization of the tokamak plasma should begin near the positive current peak, at t~9 ms. During this initial current ramp, the voltage is held fixed on C2 and C3 by the non-conducting ignitrons IG2 and IG3.

At the positive solenoid current peak, at t=10 ms, IG2 is fired, which allows C2 to discharge. This immediately opens IG1, and current from C2 is sent through C1. This is perhaps the most critical step in the action of the circuit, allowing current to flow through the solenoid in both directions as necessary while not reverse-biasing either of the two electrolytic capacitor banks.

The solenoid current ramps down from its peak of 38 kA to 0 kA by t=19.4 ms. During the initial 2-3 ms of the rampdown, the voltage difference across C2 swings from +3000V to -550V (the initially-negative side of C2 goes to ground, while the initially-positive side goes to -550V relative to ground). After this rapid voltage reversal of C2, the inductively-driven current through the solenoid flows through D2 and acts to additionally charge C3 (from its initial charge of 350V to around 415V). The voltage on C3 reaches a maximum as the solenoid/D2 current reaches zero, at t=19.4 ms.

At t=19.4 ms, IG3 is fired. The current path is exclusively through the solenoid, C3, and IG3. The solenoid current reaches a peak of -36.5 kA at t=40 ms, as the voltage across C3 reaches zero. At this point the positive loop voltage in the vacuum vessel reaches zero, and the ohmic current drive has ended. The solenoid current then exponentially decays, damping on the resistance of the coil, with a characteristic L/R time of 23 ms.

Though the timing of the IG3 firing is optimally set precisely when the solenoid current passes through zero, small deviations will only act to degrade the waveform, and will not damage the circuit elements. If IG3 is fired before the solenoid current passes through zero, it will not begin to conduct, since the bias will be in the wrong direction (before 19.4 ms, current is still flowing through D2). Because of this criterion, either the ignitron will have to be kept open through the solenoid cross-through time, or it will have to be fired slightly after 19.4 ms. If IG3 is fired more than a few hundred μs after t=19.4 ms, a voltage spike of several hundred volts is formed across the solenoid, as the solenoid current is held at 0 until IG3 is fired. A detailed analysis of this situation is addressed in section 4.

The loop voltage produced by the solenoid is simply given by the mutual inductance M of the solenoid with the current-carrying channel of plasma inside the vacuum vessel. Measurements of the existing ohmic current-ramp and loop voltage provide a value of M=1.2 μH, which can also be written as 1.2 V·ms/kA. The modeled loop voltage, which is simply $-M\frac{dI_{SOL}}{dt}$, is plotted in figure 1b.

The loop voltage peaks at the beginning of the discharge, and decreases thereafter. In the past, CDX-U has used a simpler, double-swing sinusoidal firing configuration, which has the disadvantage of wasting valuable volt-seconds before the loop voltage reaches a critical level for breakdown (~3V). Clearly this new configuration immediately achieves a voltage well beyond the threshold voltage, and then falls off as the plasma current grows. Configuring the time-history of the loop voltage in this way makes efficient use of the available capacitor energy.

4. Fault Modes

Of particular importance in a low-aspect machine such as CDX-U are the engineering specifications of the center-stack, because of the limitations imposed by the geometry of the system. The CDX-U ohmic solenoid was designed to hold off ~2 kV between the leads, so it is important that during normal operation as well as during any foreseeable fault condition this voltage does not exceed 2 kV.

Considering the charging voltages of the various capacitor banks, the most dangerous fault mode is when IG2 fires, discharging the 3000V oil-filled capacitor bank, but IG3 fails to fire. Figure 3 shows the solenoid current and voltage under this condition. As the current in the solenoid goes to zero, the voltage across the solenoid simply drops to zero as the voltage across the non-conducting IG3 rises to 410V, (which corresponds to the 410V held by C3, with the negative side at ground). Diode D2 effectively shorts out the induced voltage across the solenoid as the current is terminated at 19.4 ms, thus protecting it from any voltage spikes or oscillations.

A second fault mode which is worth addressing is that in which the voltage spike from C2 fails to shut off IG1. In this case the solenoid current waveform is ruined, in that the zero-crossthrough second stage of the solenoid current is replaced by a slow resistive decay to zero. When IG3 is fired, a short-circuit current path exists through IG3, IG1, D1, and C3. The current spike through D1 reaches a peak of several hundred kA, enough to destroy most power diodes. Based on this condition, a protection circuit should be built which inhibits IG3 from firing if IG1 hasn't been shut off, which will serve to protect D1 under this fault condition.

5. Discussion

Given the difficulty of producing a high current, double swing current waveform with a rectified power supply, capacitor-bank driven circuits for the ohmic solenoid are the obvious choice. We have designed and modeled a simple driving circuit which meets the multiple design requirements of the CDX-U ohmic power system. The solenoid current produces a loop voltage which peaks at the beginning of the plasma discharge, facilitating breakdown, and slowly ramps down as the plasma current and temperature increase over the course of the discharge. This time sequence provides an efficient use of loop volt-seconds, which is the limiting factor on plasma discharge duration. The electrolytic capacitors used in the circuit are not reverse-biased during any part of the firing sequence. Fault-mode modeling indicates peak voltage across the solenoid well within the design limits. This circuit should be useful as a design basis for any small toroidal plasma device.

Figure Captions

Figure 1. The ohmic solenoid driving circuit.

Table I. (a) Values of the circuit elements. (b) Firing times of the three ignitrons.

Figure 2. Normal operation: (a) Solenoid current trace. (b) Loop voltage trace. (c) Capacitor voltage traces.

Figure 3. Fault mode: (a) Solenoid current trace. (b) Solenoid voltage trace.

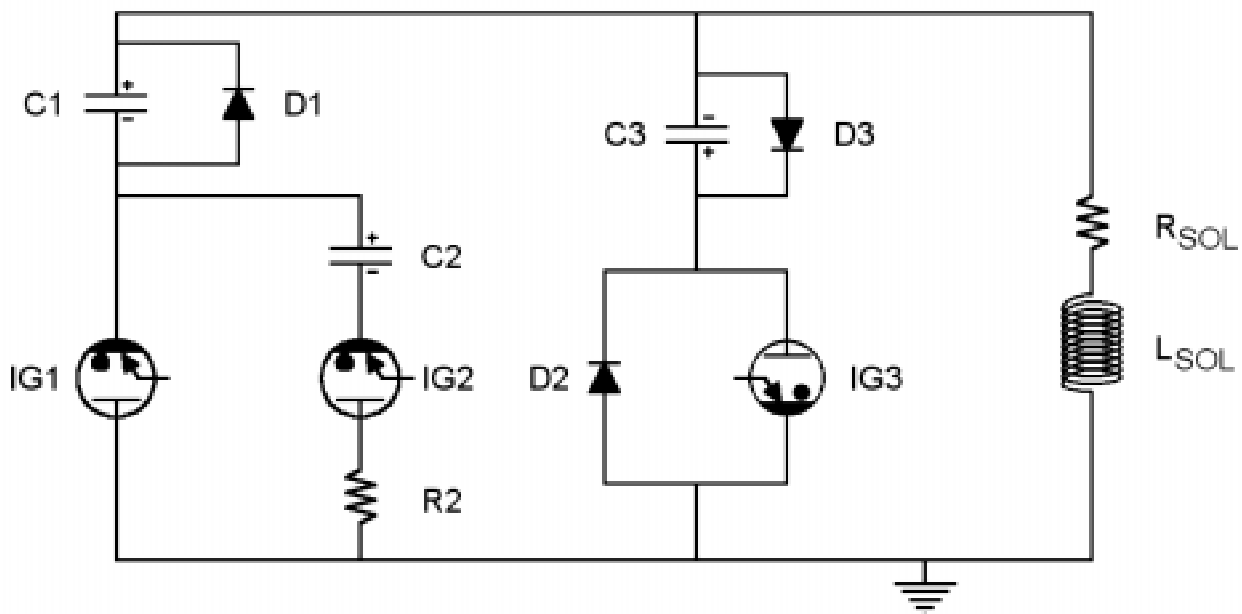

Figure 1.

(a)	Element	Type	Value	Charge Voltage
	C1	Electrolytic	412.5 mF	800V
	C2	Oil-filled	5 mF	3000V
	C3	Electrolytic	2200 mF	400V
	R2	-	60 mΩ	-

(b)		IG1	t = 0 ms
	Firing Times:	IG2	t = 10 ms
		IG3	t = 19.4 ms

Table I.

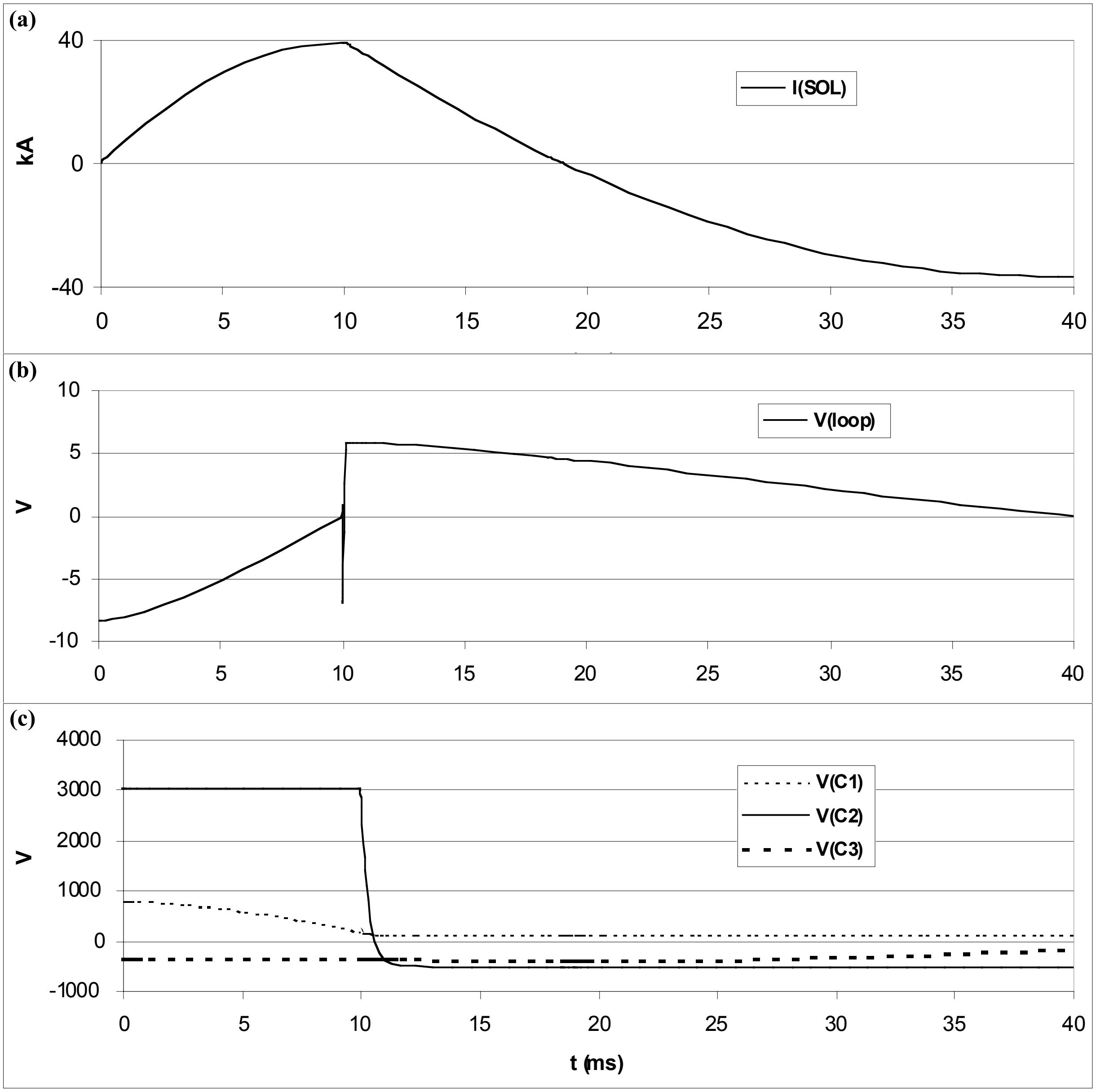
(a)
40
0
-40
kA
I(SOL)
0 5 10 15 20 25 30 35 40
(b)
10
5
0
-5
-10
V
V(loop)
0 5 10 15 20 25 30 35 40
(c)
4000
3000
2000
1000
0
-1000
V
V(C1)
V(C2)
V(C3)
0 5 10 15 20 25 30 35 40
t (ms)

Figure 2.

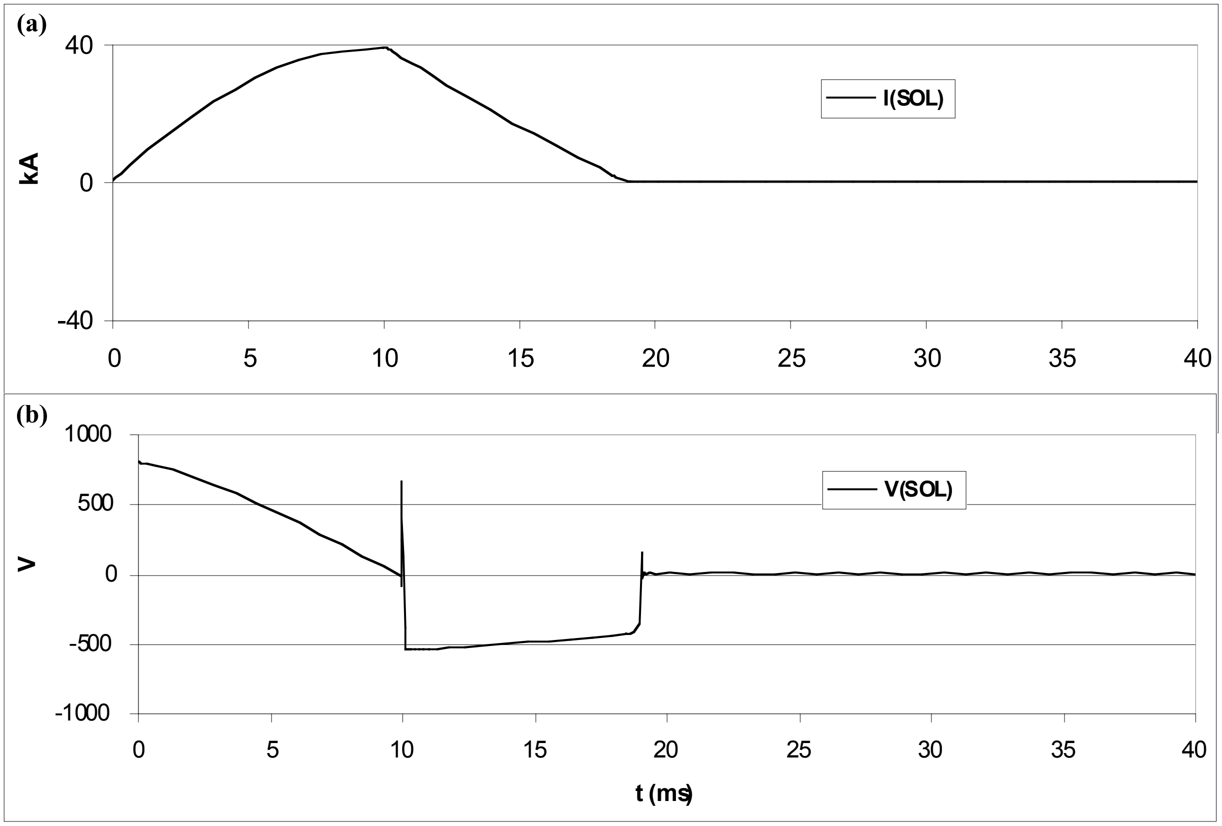
(a)
40
0
-40
kA
I(SOL)
0
5
10
15
20
25
30
35
40
(b)
1000
500
0
-500
-1000
V
V(SOL)
0
5
10
15
20
25
30
35
40
t (ms)

Figure 3.

References

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