TWO-PRIMARY MST SYSTEM

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The purpose of this note is to explain the rationale behind the use of two primaries on the MST poloidal field system and to estimate the amount of iron required for the guard core and current transformers. This is an update of an earlier PLP (955) by Kerst on the same topic.

To the extent that the MST vacuum vessel is many skin-depths thick, the placement of the poloidal-field primary is immaterial except where it crosses the poloidal gap in the vessel wall. At that location, one desires the primary current distribution to match the poloidal distribution of plasma image currents in the wall at toroidal locations away from the gap so as not to create a field error (a radial field entering the gap). In principle this could be done with a single primary except for the fact that some of the primary current is required to magnetize the iron core even in the absence of plasma, and this magnetizing current must be placed in the correct position on the iron to prevent an error at the gap that has the time-dependence of the magnetizing current. The problem becomes especially severe when the core is driven deeply into saturation.

One solution is to employ two primaries, one to provide the magnetizing current, and the other to couple to the plasma, each with the proper poloidal distribution so as to avoid field errors at the poloidal gap. For this scheme to work properly, one must demand that essentially all the magnetizing current flow in one winding and all the plasma current flow in the other. For this purpose, special iron-core current transformers are employed. In addition, a guard core is used to ensure that any field that soaks through the vacuum vessel wall is trapped in the iron and prevented from filling the room with magnetic field.

From the standpoint of understanding the two-primary system, it is useful to consider the iron core, the magnetizing winding, the continuity winding, and the poloidal field winding as a set of nested toroids as shown in figure 1. The current transformers (CT) link the continuity winding and the poloidal field winding in such a way as to force their currents to be nearly equal and opposite. The difference current thus flows through a high-impedance path because of the inductance of the iron-core current transformers. The guard core (GC) performs a similar function in forcing the current in the vacuum containment vessel (VCV) walls to be nearly equal and opposite to the plasma current.

This complicated system can be simplified by a topological distortion in which the poloidal gap (PG) is widened to better illustrate the fact that the continuity winding and VCV wall encircle the current transformers and guard cores but not the main core, as shown in figure 2(a). Since a current transformer

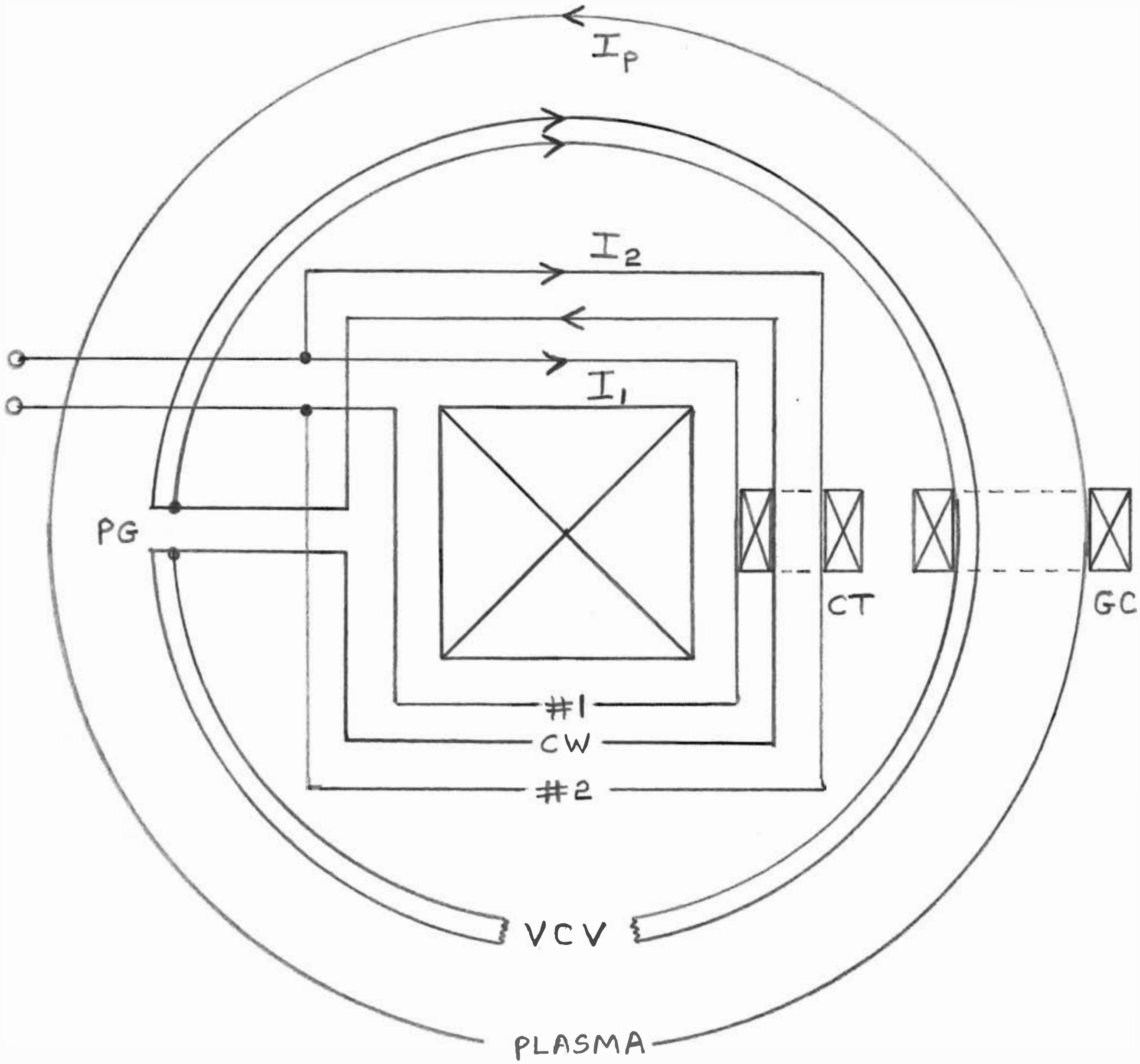


Figure 1

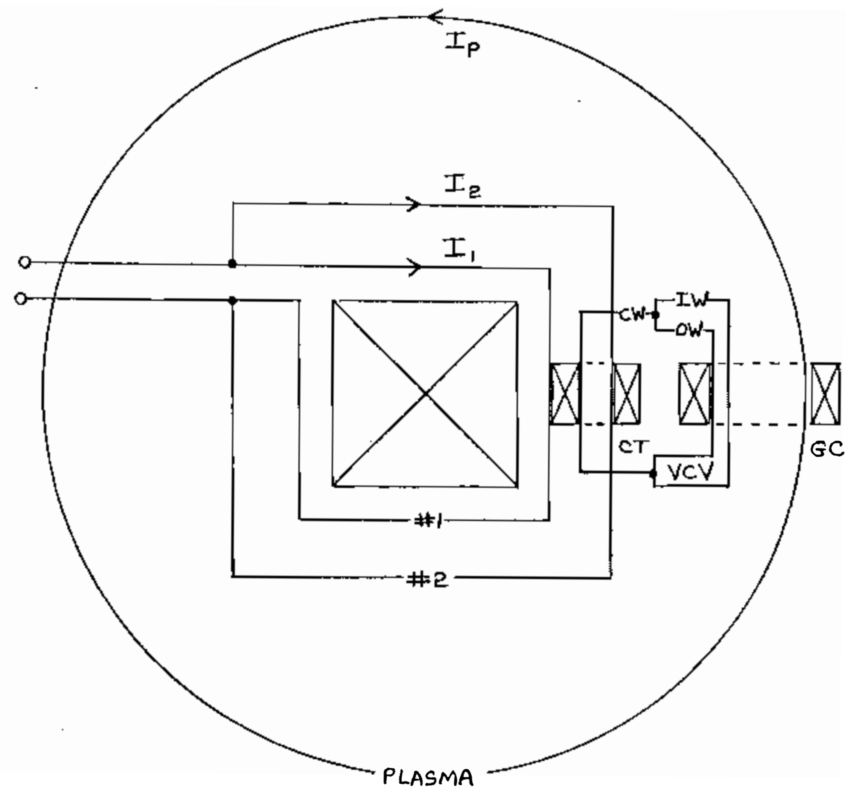


Figure 2(a)

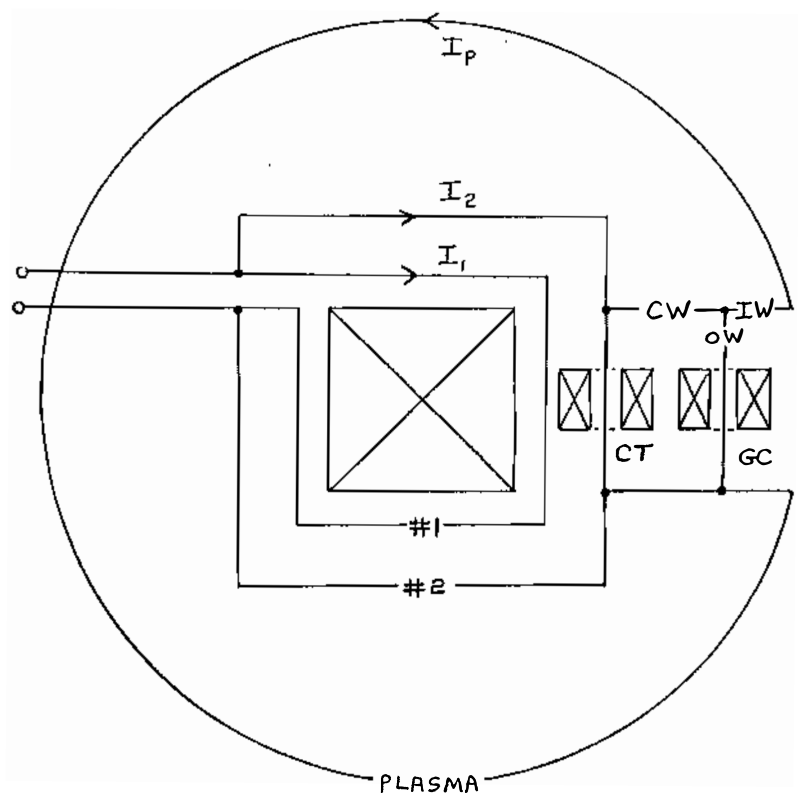
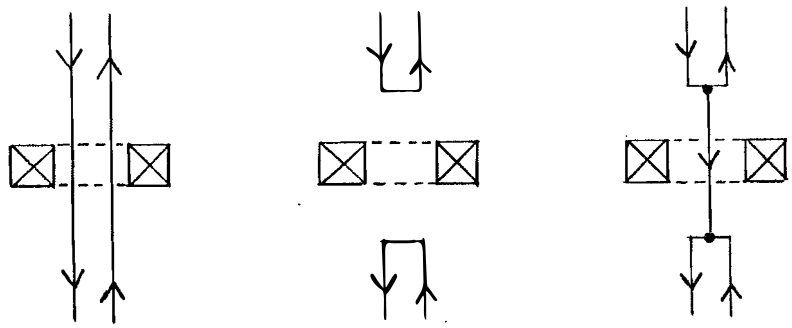


Figure 2(b)

behaves so as to force the net current linked toward zero, its effect can be represented as follows:



real case ideal equivalent real equivalent

The ideal equivalent is appropriate to the case in which the inductance of the current transformer is infinite (no magnetizing current), and the real equivalent includes the possibility of a non-zero magnetizing current linking the transformer. Using these rules, the circuit in figure 2(a) can be transformed into that in figure 2(b).

From figure 2(b) the electrical equivalent circuit of figure 3 is obtained. In this representation, C is the poloidal-field capacitor bank, R_0 is the resistance of the transmission line to the machine, R_1 is the resistance of the magnetizing winding (primary 1), and R_2 is the resistance of the poloidal field winding (primary 2). All resistances and inductances are referred to their single-turn values (that is, divided by the square of the turns-ratio). The capacitance C is also transformed to its single-turn value (multiplied by the square of the turns-ratio). L_1 is the leakage inductance of primary 1

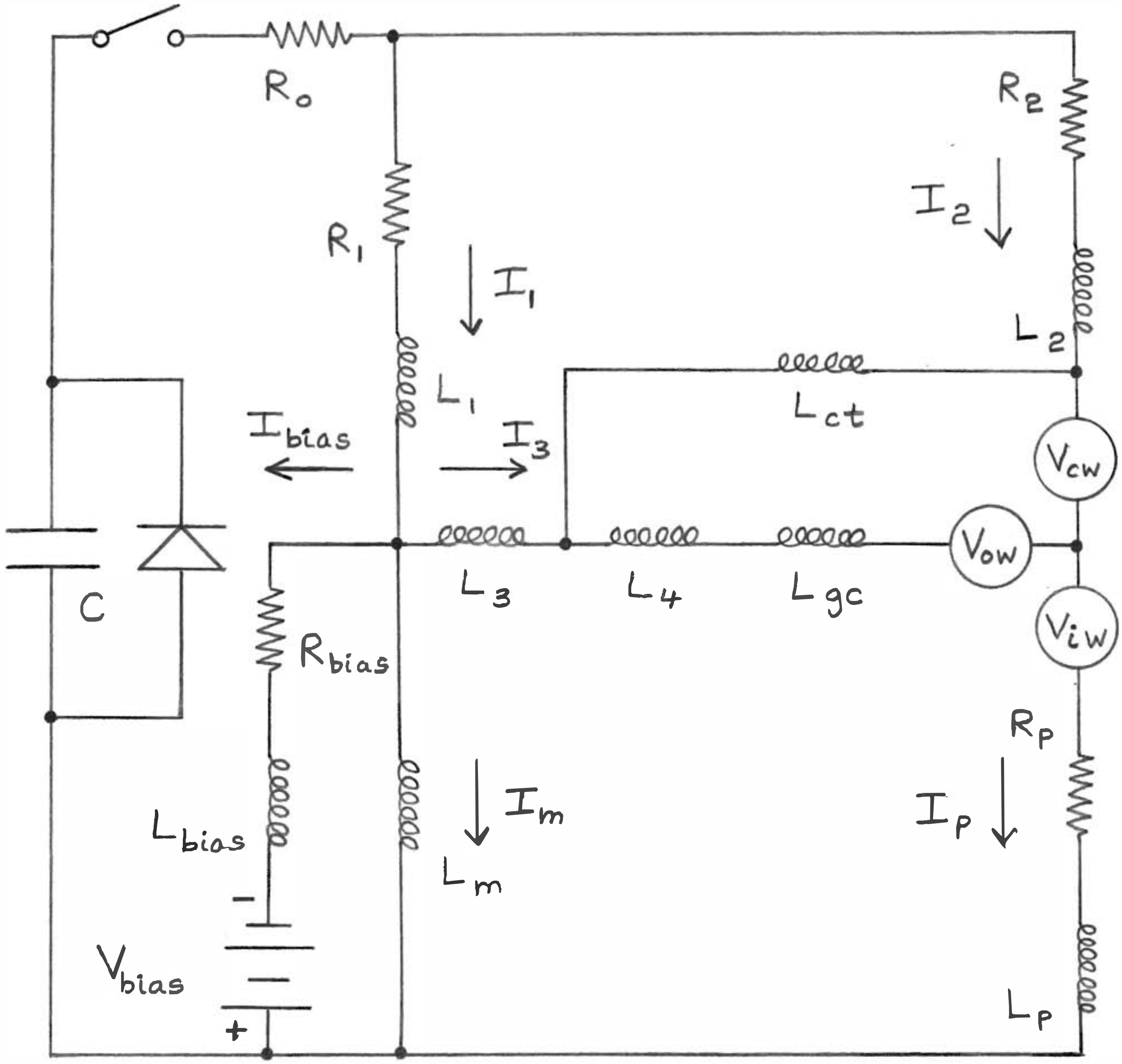

R₀
R₂
I₂
R₁
I₁
L₂
L₁
L_ct
I_bias
I₃
V_cw
L₃
L₄
L_gc
V_ow
C
V_iw
R_bias
R_p
I_m
I_p
L_bias
L_m
-
V_bias
+
L_p

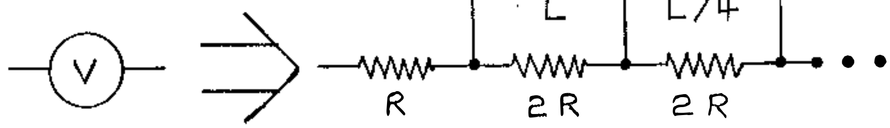
Figure 3

(that is, inductance resulting from any flux generated by primary 1 that does not encircle the vacuum vessel in the poloidal direction). L_2 is the leakage inductance of primary 2 (that is, inductance resulting from any flux generated by primary 2 that does not link the continuity winding). L_3 is the inductance of the space between the continuity winding and the magnetizing winding, ignoring the current transformers. L_4 is the inductance of the space between the poloidal field primary and the outer wall of the VCV (the hole through the doughnut), ignoring the guard core. L_{ct} is the inductance of the current transformers, and L_{gc} is the inductance of the guard core.

The magnetizing inductance L_m is modeled with the expression

$$L_m = 1 \ / \ 12.1(|I_m|+1)$$

where I_m is the magnetizing current. The plasma is modeled as an inductor L_p in series with a resistor R_p, where for simplicity we take L_p constant and adjust its value to give the same peak current and volt-second consumption as does a more detailed model in which the interaction with the toroidal field circuit is included (see PLP 1010). The resistance is assumed given by R_p = const/I_p (see PLP 978), where the constant (loop voltage) can be adjusted to cover the range of plausible plasma resistivities. The quantities V_{cw}, V_{iw} and V_{ow} represent, respectively, the voltage drop in the continuity winding, the inner surface of the VCV wall and the outer surface of the VCV wall. These are modeled with equivalent circuits as shown below [see D. W. Kerst and J. C. Sprott, Journ. Appl. Phys. 60, 475 (1986)]:



Also included in the circuit is the bias system whose voltage source V_{bias} drives additional reverse magnetizing current I_{bias} through a choke of inductance L_{bias} and resistance R_{bias}. The bias winding is assumed to be tightly coupled to the magnetizing current winding.

Although the electrical circuit is rather complicated, it is possible to make several general observations. The current I_3 represents the current that is being improperly transferred from one primary to the other and is thus the current that causes the field error. The relative field error is determined by the ratio I_3/I_p, which we would like to make no larger than a few percent. The worst case occurs for $I_m << I_p$, which at early times ($t << L_{ct}/R_2$) requires L_{ct} and L_{gc} to be the order of 100 times L_2. The flux in the current transformers in this worst case is given by

$$\Phi_{ct} = L_2 I_p + \int I_p R_2 \, dt$$

The flux in the guard core is larger than Φ_{ct} by the integral of the voltage drop in the continuity winding. At late times ($t >> L_{ct}/R_2$), I_3/I_p approaches $R_2/(R_1+R_2)$ for $I_m=0$ independent of the inductances. This is the limit in which the current division between the two primaries is determined solely by their resistances, and must be avoided by making L_{ct}/R_2 much greater than the maximum desired pulse length.

If the pulse length T is much greater than L_2/R_2, the flux in the current transformer is approximately $\Phi_{ct} \approx I_pR_2T$. Since $\Phi_{ct} = B_{ct}A_{ct}$, where A_{ct} is the cross section of the iron in the current transformer, the amount of iron required to avoid saturation (B_{ct} less than about 1.5 tesla) is proportional to the resistance of the poloidal field winding. The resistance of the poloidal field winding is inversely proportional to its cross section (in a direction perpendicular to the iron cross section). Consequently, the radial thickness of the iron times the radial thickness of the winding has to exceed a quantity that depends on the geometry and the properties of the materials. If radial space is limited, as it is on the inner leg of the core, the optimal condition is to have the total thickness of the two legs of the iron equal to the thickness of the winding, since the product of two numbers that have the same sum is greatest if the numbers are equal. This condition also optimizes the ratio L_{ct}/R_2. When this condition is satisfied, assuming negligible gaps in the winding and in the iron, the thickness of the winding and the total thickness of the two legs of the iron must satisfy

$$d^2 > 2I_p\rho_2 T \;/\; B_{ct}h$$

For a 1-MA, 40-ms discharge with $\rho_2 = 1.7 \times 10^{-8}$ Ω-m (copper), B_{ct} = 1.5 tesla, and h = 4 m, the result is d > 1.5 cm. This value must be proportionally increased if there are gaps in the winding or in the iron.

A more detailed calculation requires a numerical solution of the equations governing the electrical equivalent circuit. This was done using what is considered a worst case in which a 1-MA, 40-ms discharge has a sufficiently low loop voltage (4 volts) so as to cause negligible magnetizing current. The values taken are from old estimates (April 29, 1986 MST Design Group meeting minutes), but updated to the case with a full 52-cm radius plasma. The values used are listed in Table I. The resulting waveforms are shown in figures 4.

Table I

Values used for electrical circuit modeling of MST with two primaries.

$N = 40$ turns	$R_p = 4/I_p\ \Omega$
$C = 0.084N^2$ F	$L_p = 1.4\ \mu H$
$V_c(0) = 5000/N$ V	$R_{cw} = 1.68\ \mu\Omega$
$R_o = 0.013/N^2\ \Omega$	$L_{cw} = 9.54$ nH
$R_1 = 1\ \mu\Omega$	$R_{iw} = 2.4\ \mu\Omega$
$L_1 = 0.047\ \mu H$	$L_{iw} = 38$ nH
$R_2 = 2.5\ \mu\Omega$	$R_{ow} = 2.4\ \mu\Omega$
$L_2 = 0.025\ \mu H$	$L_{ow} = 38$ nH
$L_3 = 0.02\ \mu H$	$I_{bias} = 24$ kA
$L_4 = 0.3\ \mu H$	$R_{bias} = 0.06/N^2\ \Omega$
$L_{gc} = 8.3\ \mu H$	$L_{bias} = 40/N^2$ mH
L_{ct} = infinite	$V_{bias} = 36/N$ V
$L_m = 1\ /\ 12.1(\lvert I_m\rvert+1)$ H	

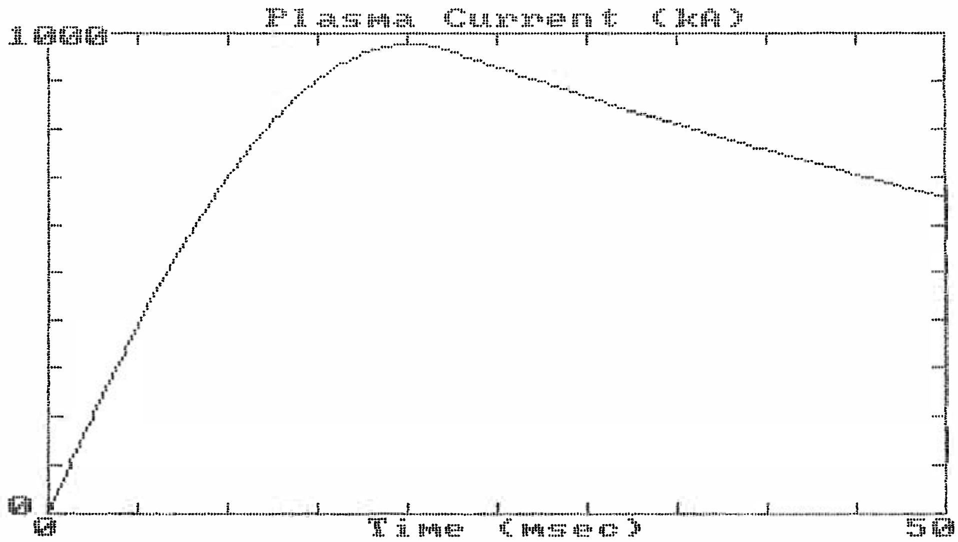


Figure 4(a)

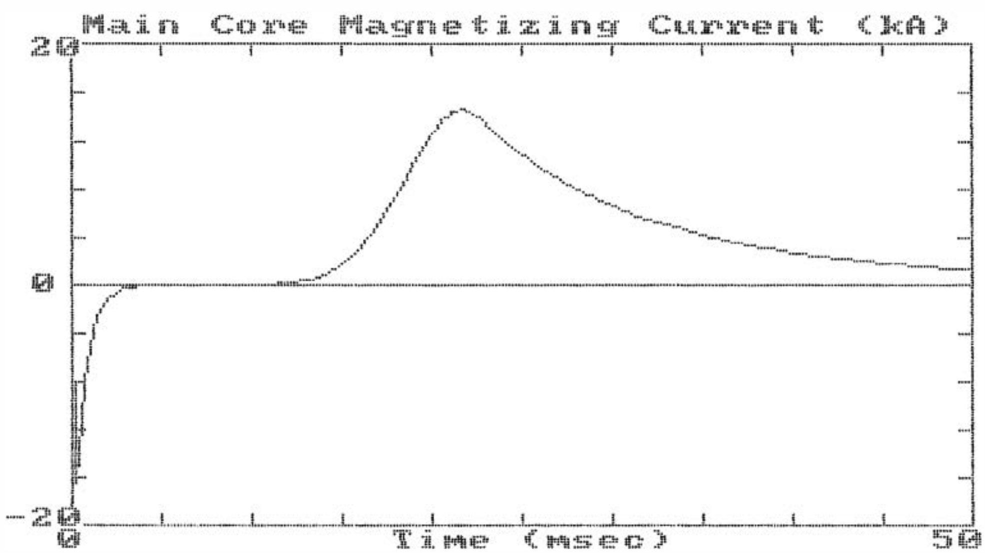


Figure 4(b)

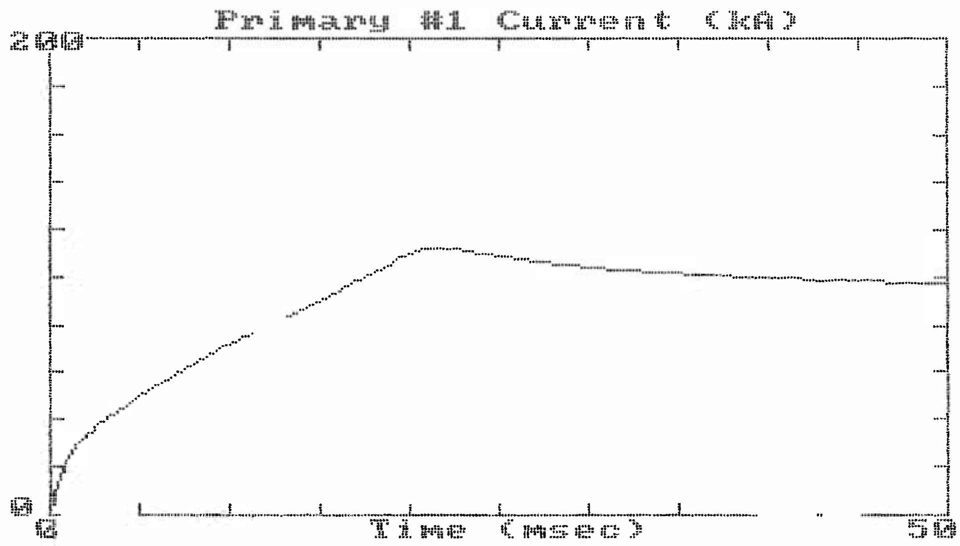


Figure 4(c)

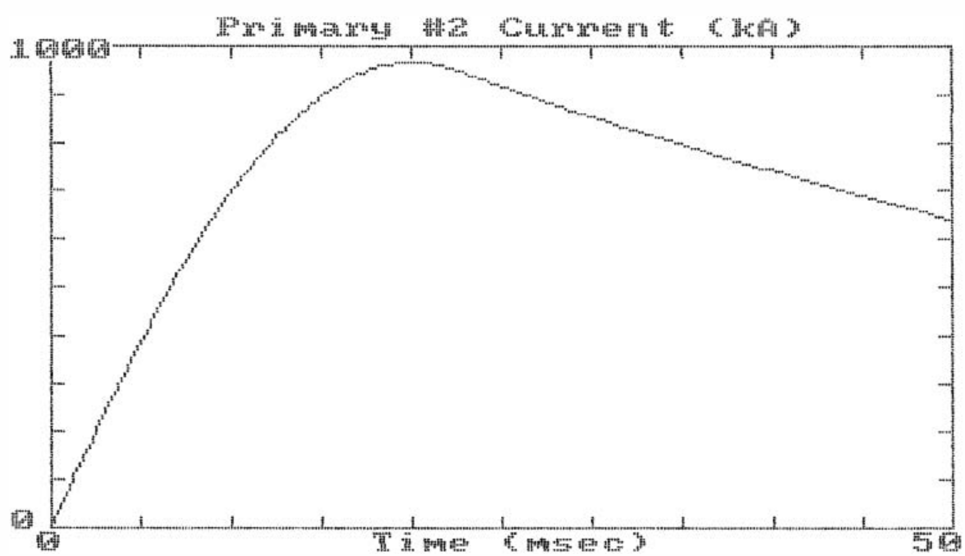


Figure 4(d)

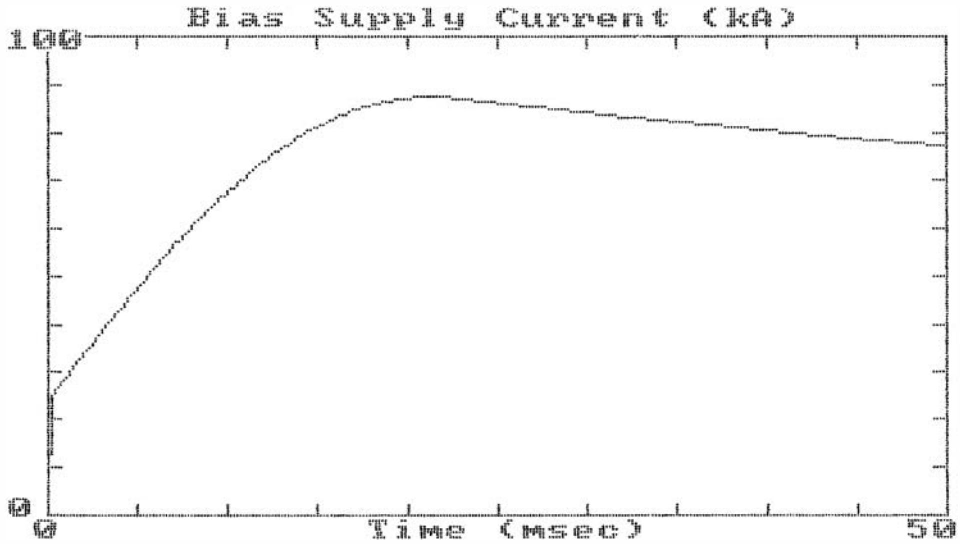


Figure 4(e)

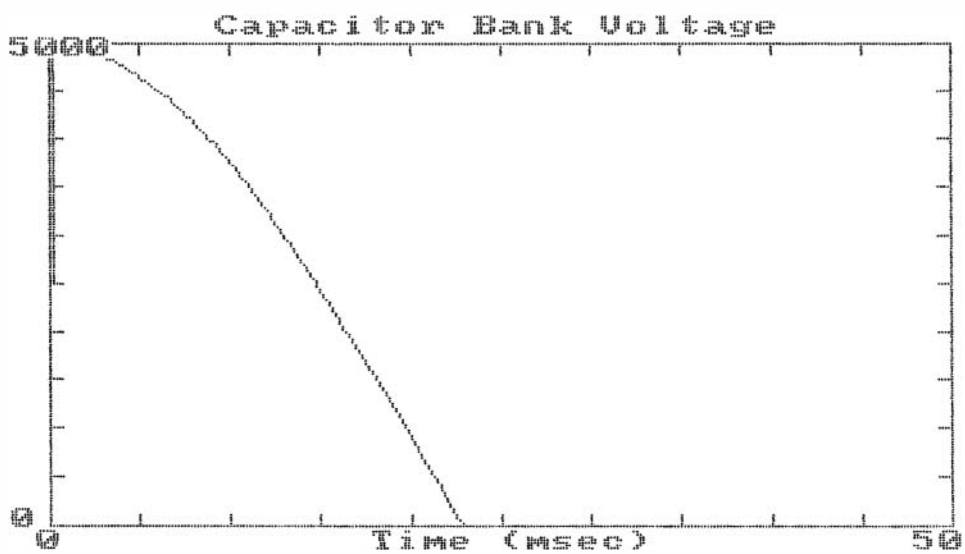


Figure 4(f)

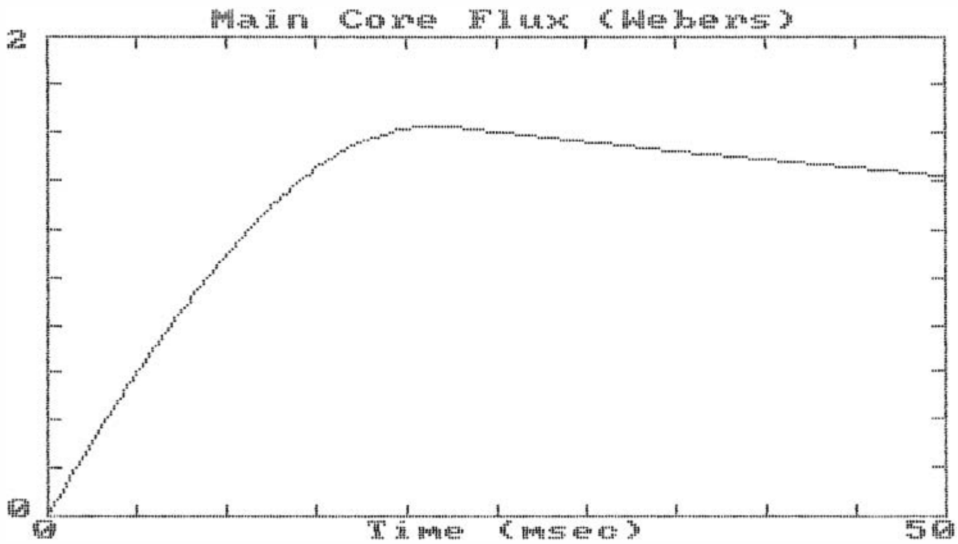


Figure 4(g)

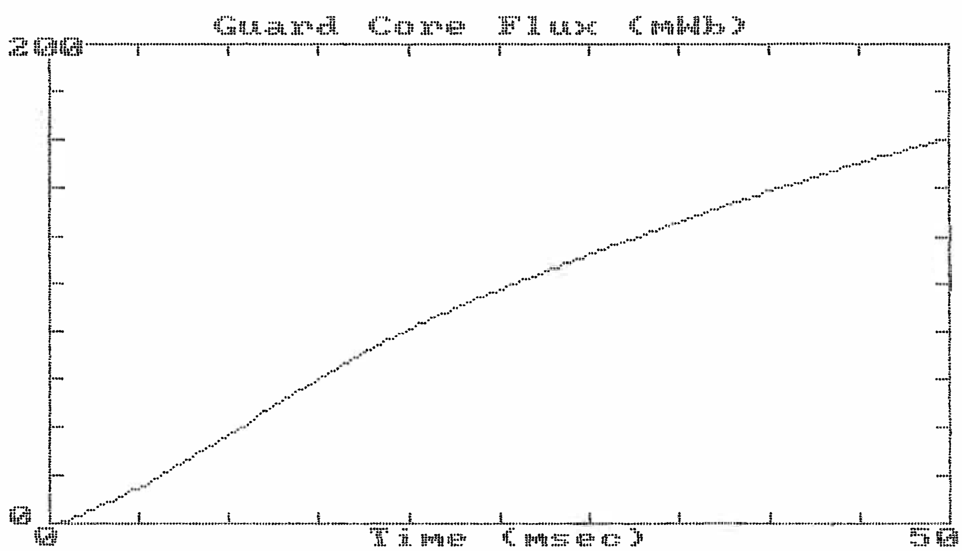


Figure 4(h)

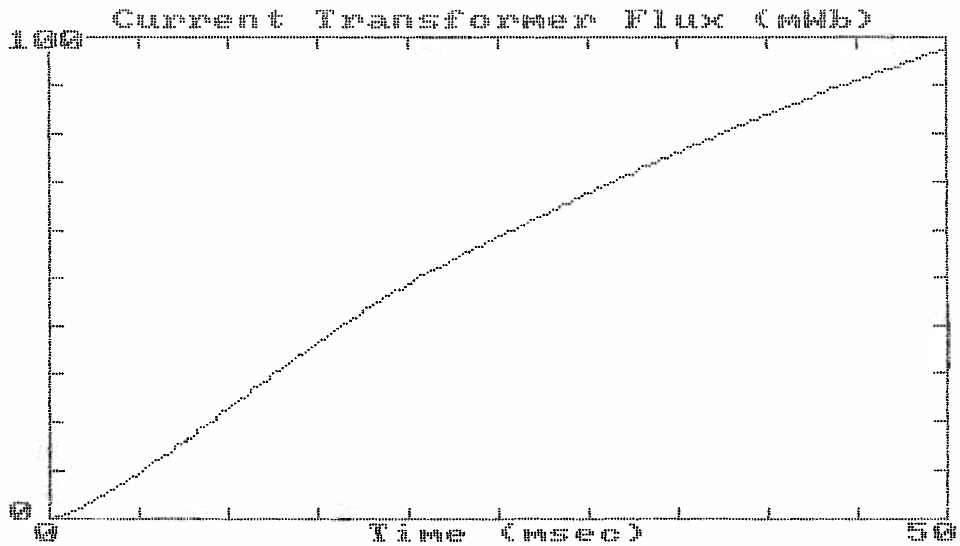


Figure 4(i)

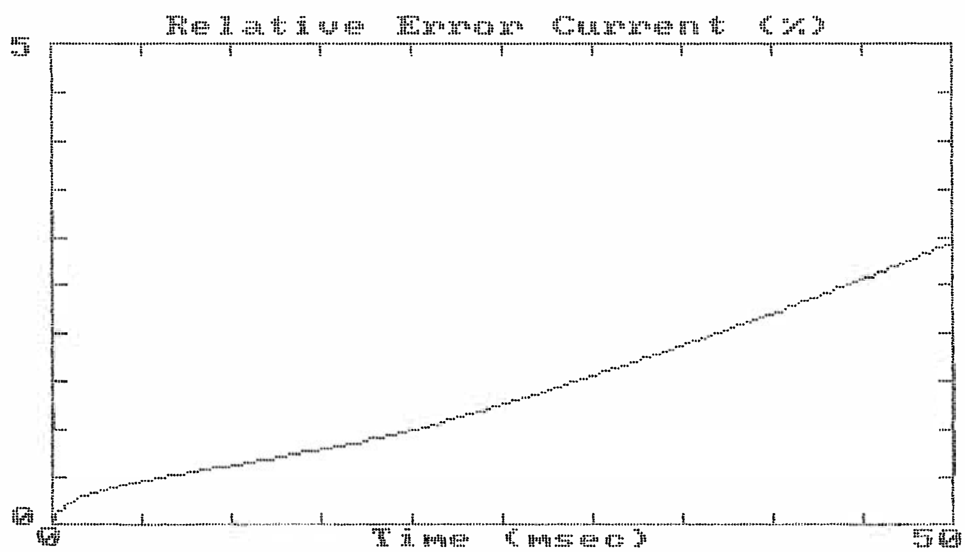


Figure 4(j)