To the Graduate Council:

I am submitting herewith a thesis written by John A. White entitled "Computer Simulated Design Study of A High Voltage, High Current, DC Circuit Breaker for Fusion Research." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.

J. M. Bailey, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:

Vice Chancellor
Graduate Studies and Research

COMPUTER SIMULATED DESIGN STUDY OF A HIGH VOLTAGE, HIGH CURRENT, DC CIRCUIT BREAKER FOR FUSION RESEARCH

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

John A. White

June 1983

1182837

ACKNOWLEDGMENTS

The author would like to express his appreciation to J. M. Bailey for information and suggestions provided in the course of this study.

This research was sponsored by the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26 with the Union Carbide Corporation.

ABSTRACT

The purpose of this thesis is to develop a proposal for a circuit breaker meeting specific requirements to be used on a fusion research experiment. A vacuum circuit breaker with forced commutation is chosen due to energy and time considerations.

The various circuit breaker models are simulated using the computer program SUPER*SCEPTRE. Plots and tables of the current profiles during interruption are studied and used to determine component values that will permit the circuit breaker to meet previously established operational criteria.

TABLE OF CONTENTS

SECTION		PAGE
I.	INTRODUCTION	1
II.	VACUUM CONTACTOR LIMITATIONS	12
	A. Previous Study Results	12
	B. RFIC	12
	C. Approximate Circuit During Interruption	13
	D. RRRV	16
III.	SINGLE VACUUM CONTACTOR DESIGN	17
	A. Constant Inductance Simulation	17
	B. Saturable Reactor Simulation	19
IV.	SIX VACUUM CONTACTOR DESIGN	25
	A. Constant Inductance Simulation	25
	B.. Saturable Reactor Simulation	27
	C. Proposed Vacuum Circuit Breaker	33
V.	CONCLUSIONS	43
LIST OF REFERENCES		44
VITA		46

LIST OF FIGURES

FIGURE		PAGE
1.	Schematic of a Tokamak	2
2.	Cross Section of Tokamak, Showing Ohmic Heating Coils	4
3.	Ohmic Heating System Schematic	5
4.	Circuit Breaker with Six Vacuum Contactors	8
5.	Circuit Breaker with Ionization Resistor Divided	9
6.	Circuit Breaker with Commutation Circuit	10
7.	Approximation of Circuit Breaker Prior to Current Zero	14
8.	Single Vacuum Contactor Circuit Breaker with Constant Inductance	18
9.	Current Profile with One Vacuum Contactor, Constant Inductance Reactor	20
10.	Current Profile with One Vacuum Contactor, Saturable Reactor	23
11.	Circuit Breaker with Six Vacuum Contactors and Constant Inductance Reactors	26
12.	Current Profile with Six Vacuum Contactors, Constant Inductance	28
13.	Circuit Breaker with Six Vacuum Contactors and Saturable Reactors	32
14.	Current Profile with Six Vacuum Contactors, Saturable Reactors	34
15.	Ohmic Heating Circuits as Proposed for ISX-C	40

I. INTRODUCTION

Fusion is one alternative to current methods of producing usable energy, such as the burning of coal and oil and the use of nuclear fission. Research is being conducted in several laboratories in the United States and around the world in an effort to obtain the energy released from the fusion of deuterium and tritium isotopes of hydrogen.

One of the difficulties in producing fusion energy has been the development of a device that can heat the deuterium-tritium fuel to a sufficiently high temperature and then confine it for a long enough time so that more energy is released through the fusion reaction than is used for heating. Due to the high temperatures required ($\sim$100 million degrees Celsius), magnetic fields are considered the most feasible method of containing the deuterium-tritium fuel, which ionizes at these high temperatures and forms a plasma. Many different magnetic confinement schemes have been studied, but the one that has received the greatest attention in the U.S. magnetic fusion energy program is the tokamak concept.

The tokamak is a toroidal device that has a hollow, doughnut-shaped vessel through which magnetic fields twist, confining the plasma. These magnetic fields are produced by electric currents passing through wires and the plasma itself. A toroidal magnetic field is generated by electric currents flowing in rings around the torus. A poloidal magnetic field is generated by a current flowing through the plasma. A schematic representation of these magnetic fields is shown in Fig. 1.

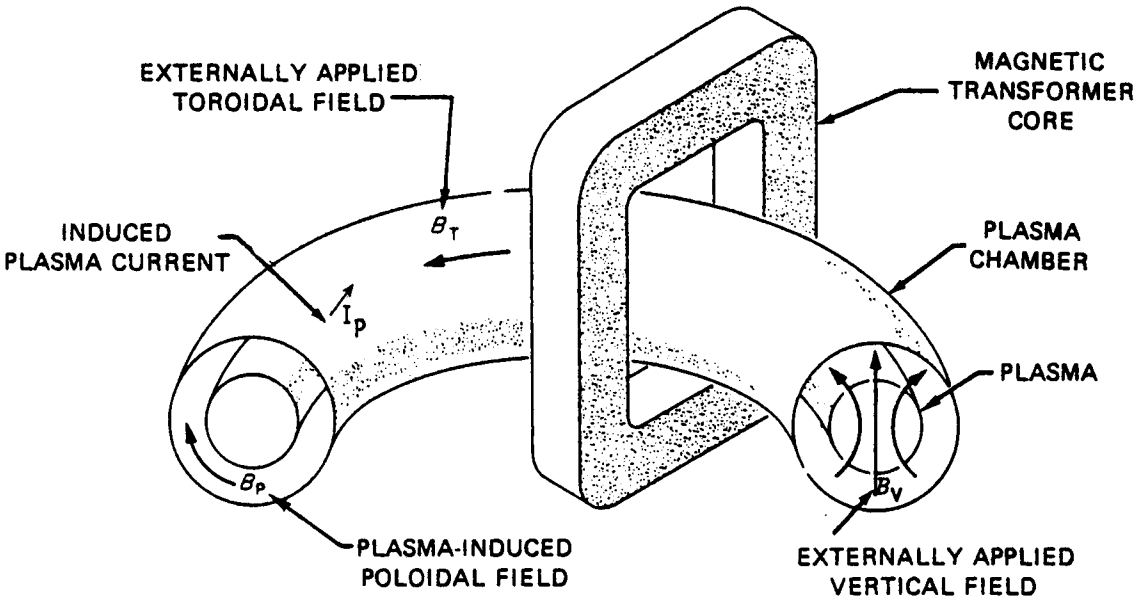


Figure 1. Schematic of a tokamak.

Since the plasma is an electrical conductor, it is possible to heat the plasma by passing a current through it; in fact, the current that generates the poloidal field (β_p) also heats the plasma. This method is called ohmic heating because the heat generated is due to current flowing through the resistance of the plasma (as seen in Fig. 2). As the plasma temperature increases, however, its resistance decreases, thus diminishing the heating effectiveness. To obtain the still higher temperatures required for fusion, various auxiliary heating techniques are employed, such as neutral-beam heating injection, radio frequency heating, and electron-cyclotron heating.

One of the major fusion research centers in the United States is at the Oak Ridge National Laboratory (ORNL) in Oak Ridge, Tennessee. A conceptual design was proposed in 1980 to upgrade the existing ISX-B (Impurities Study Experiment – B) tokamak to a larger machine (ISX-C) capable of 30-s pulses, as compared to current designs of less than 5 s.

The basic components of the ISX-C ohmic heating (OH) system are the ohmic heating solenoid (located in the center of the tokamak), a bipolar 3-kV, 20-kA, dc power supply with inversion capability, a resistor in series with the ohmic heating solenoid, and a circuit breaker in parallel with the resistor. A simplified schematic is shown in Fig. 3.

Initially, the circuit breaker is closed while the power supply is charging the ohmic heating solenoid, which is essentially a larger inductor. As the current reaches 20 kA, the power supply is switched into a mode that allows the current just to circulate and the circuit breaker opens, interrupting the 20 kA and forcing it through the resistor. This results in a potential of 30 kV across the resistor

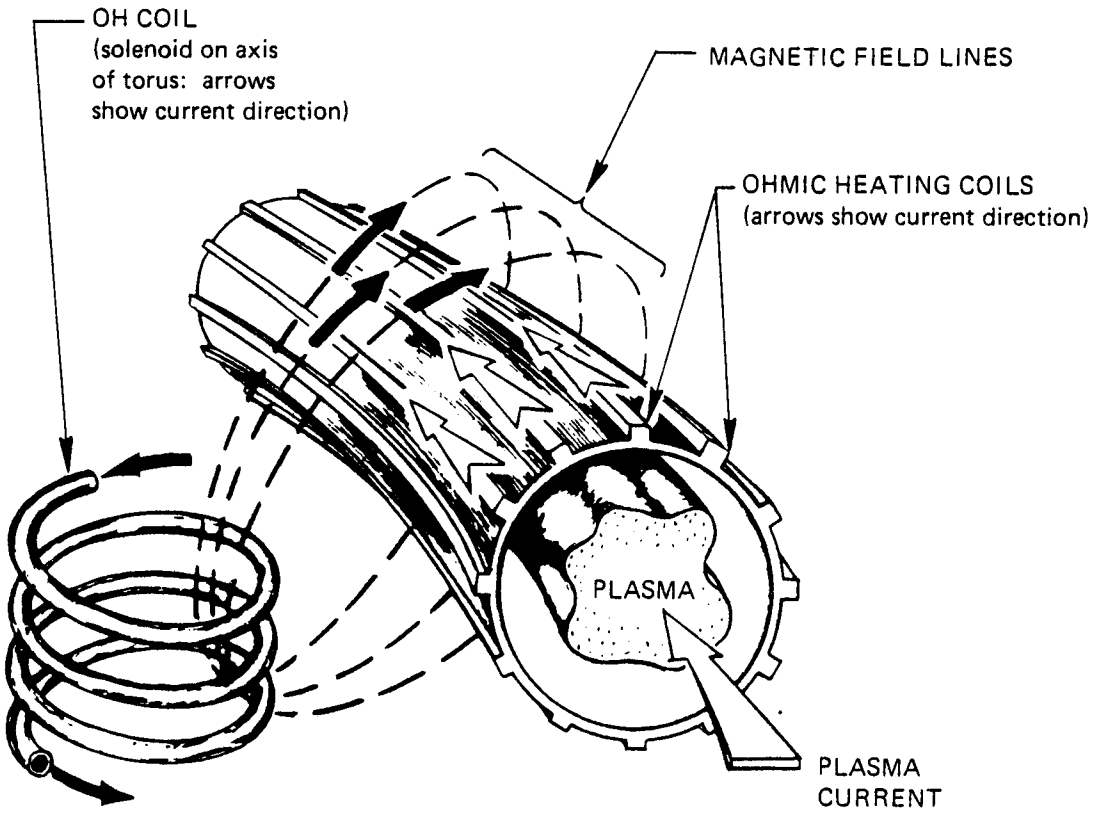


Figure 2. Cross section of tokamak, showing ohmic heating coils.

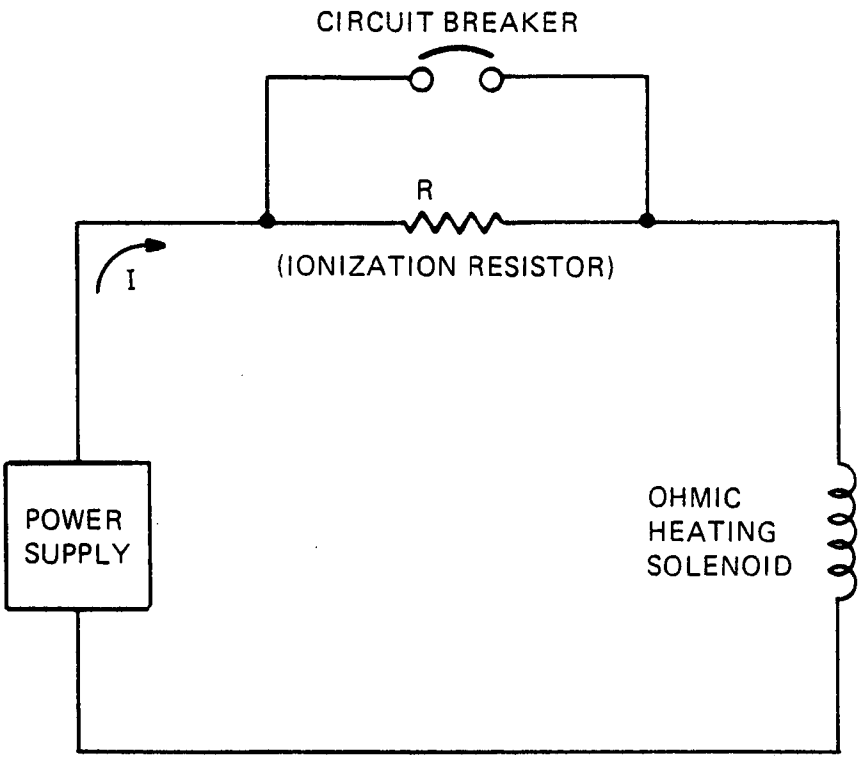


Figure 3. Ohmic heating system schematic.

as well as the circuit breaker and a 30-kV potential in the opposite polarity across the ohmic heating solenoid. This rapidly changing electric field ionizes hydrogen gas in the tokamak, forming the plasma, and induces a large current through it.

The interruption of direct currents has always been more of a problem than alternating currents due to the absence of a natural current zero, but switches for relatively low levels of current are commercially available.[1-11] These conventional switches achieve interruption by establishing a high arc voltage that dissipates a considerable amount of energy. This method has been shown to be impractical in other studies of high current interruption.[1]

The method most often being pursued in fusion research today involves the use of vacuum circuit breakers with a commutation circuit to force a current zero. A 1976 proposal for the Oak Ridge Tokamak (ORMAK) Upgrade in Oak Ridge suggested the use of two Ross Engineering units, each consisting of a 4-in. vacuum contactor and actuator assembly, in parallel to interrupt 20 kA and withstand 20 kV of recovery voltage.[2] The Alcator tokamak program at MIT utilizes three Ross Engineering units, each with a 7-in. vacuum contactor, in parallel to interrupt 25 kA with a recovery voltage of 20 kV.[6] The success of the Alcator circuit breaker indicates a very reliable method of current interruption compatible with ISX-C requirements. However, the recovery voltage of 30 kV in the case of ISX-C is above the safe rating of any vacuum contactor commercially available today. Because of this voltage consideration, the circuit breaker proposed for ISX-C will consist of three 7-in. vacuum contactors paralleled in series with a second set of three 7-in.

vacuum contactors in parallel. As in Alcator, resistors will be placed in series with each vacuum contactor and a mechanical switch will short across the entire vacuum circuit breaker assembly, as seen in Fig. 4. The series resistors will ensure that the bulk of the 20 kA will be conducted through the mechanical switch, except during current interruption when the mechanical switch will be opened just prior to the vacuum contactors opening. This arrangement will increase the lifetime of the expensive vacuum contactors.

Inadequate synchronization during the opening of the paralleled vacuum contactors could result in premature failure of contactors that carried greater than their share of current. This problem has been shown to be of negligible importance on Alcator since the synchronizing of the Ross Engineering contactor units can be adjusted electronically rather than mechanically.[6]

Another synchronization problem could result in overstressing contactors with voltage if all of one set of three parallel contactors opened before the second set of three parallel contactors. This problem can be eliminated by dividing the ionization resistor into two parts, each paralleled by one set of three parallel contactors as shown in Fig. 5. This will result in a worst-case voltage stress of 15 kV across any one contactor. Again, the electronic adjustment of each individual vacuum interrupter should allow for very accurate synchronized operation.

After the interrupters have opened enough to withstand the recovery voltage, the arc will be extinguished by forcing a current zero through the use of a precharged commutation capacitor bank (Fig. 6). An

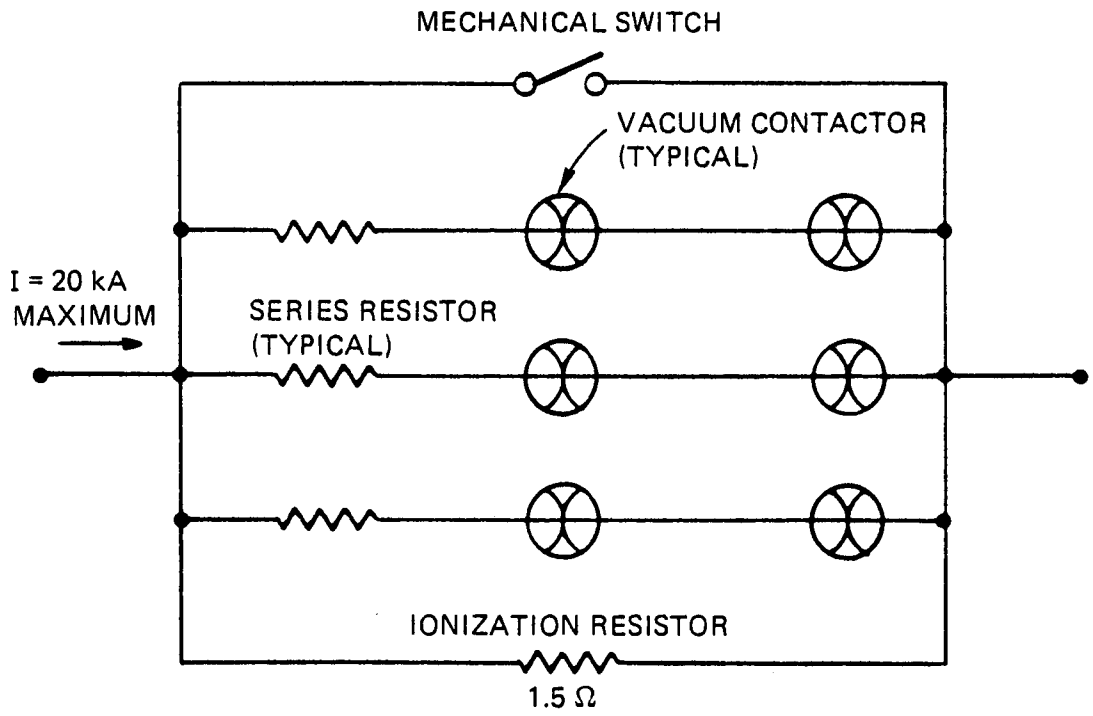


Figure 4. Circuit breaker with six vacuum contactors.

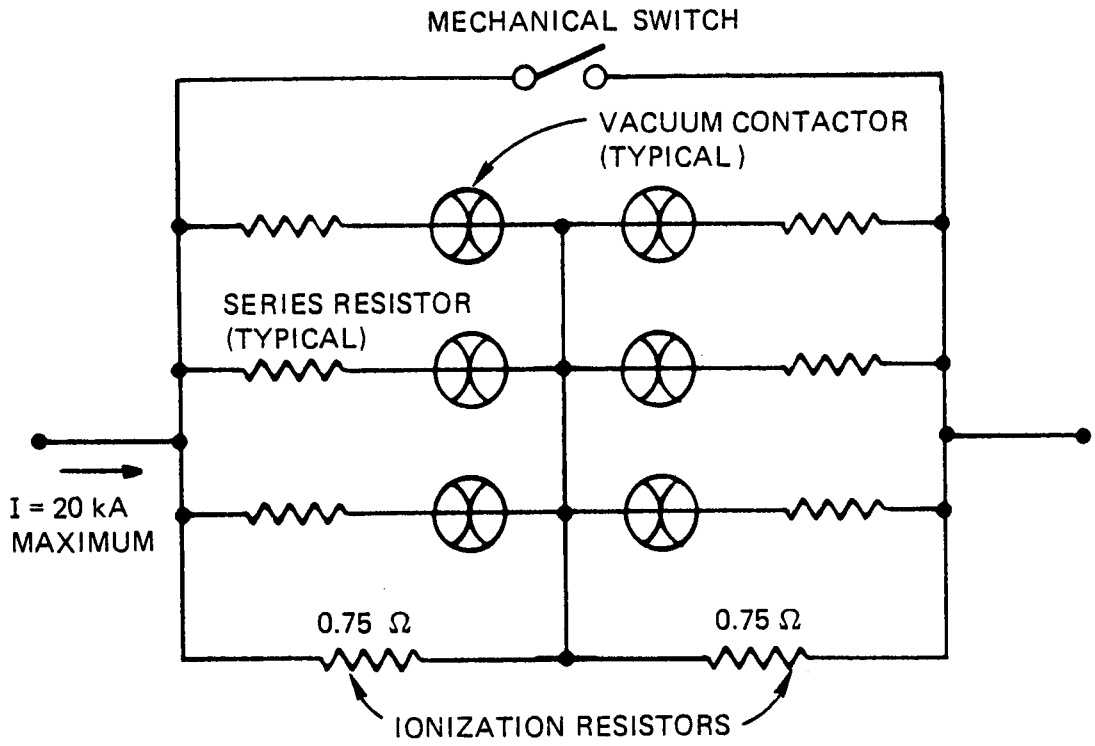


Figure 5. Circuit breaker with ionization resistor divided.

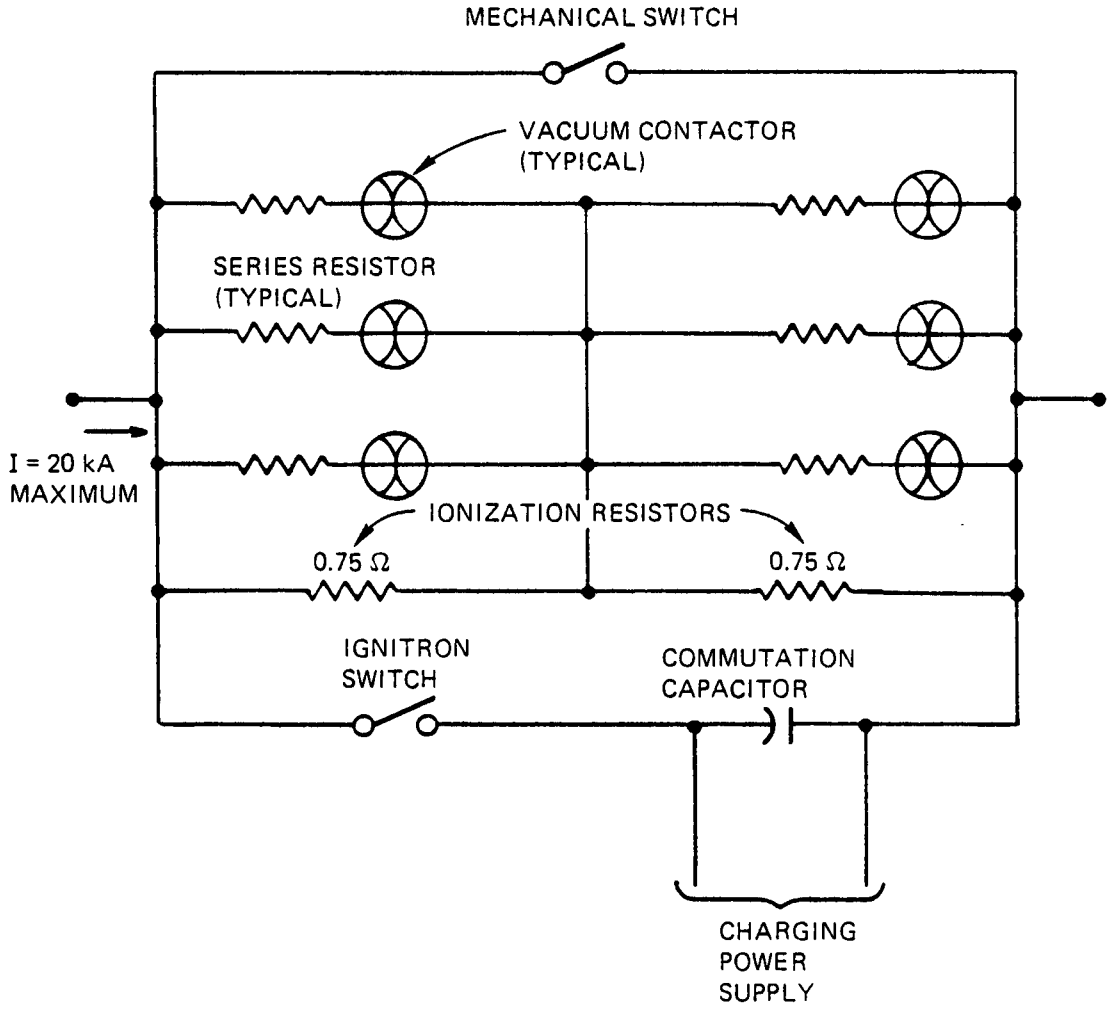


Figure 6. Circuit breaker with commutation circuit.

ignitron is switched on to discharge the capacitor, which is in a polarity, to force a current through the contactors in opposition to the main circuit current. When the sum of the currents in the vacuum contactor reaches zero, the arc extinguishes and the main current flow is interrupted.

This thesis is a computer simulated design study of the proposed circuit breaker for the ISX-C tokamak.

II. VACUUM CONTACTOR LIMITATIONS

A. Previous Study Results

For the ORMAK Upgrade Proposal in 1976, a team of Westinghouse Electric Corporation engineers was contracted to do a preliminary design for an ohmic heating system switch. Two very important design parameters were established during this study based on the specifications for a Westinghouse WX-32722 vacuum contactor. The rate of fall of interrupting current (RFIC) should be limited to no more than 40 A/μs and the rate of rise of recovery voltage (RRRV) should be confined to 700 V/μs or less.

B. RFIC

The RFIC is essentially the dI/dt of the current just prior to reaching zero. Generally speaking, the likelihood of a successful interruption increases as the RFIC decreases. A high current along with a high RFIC makes interruption difficult because there is an abundance of plasma in the contact gap after interruption and during the recovery voltage buildup phase. This plasma is a conducting path that could allow the arc to restrike.

A method of achieving an acceptable current profile just prior to current zero is to add a saturable reactor in series with the vacuum contactor. Under normal load conditions, the reactor is saturated and has a low inductance. During commutation, the current through this reactor begins a rapid decline toward zero. At the current level where the reactor becomes unsaturated, the inductance becomes much higher.

This higher inductance substantially increases the L/R time constant for the circuit and, thus, reduces the rate of current decay.

C. Approximate Circuit During Interruption

The circuit shown in Fig. 7 approximates the condition prior to the current zero, including the period of contact arcing. The effects of the remainder of the ohmic heating circuit can be ignored because of its long time constant as compared with that of the switch elements. This circuit can be described by a set of differential equations, assuming constant inductance:

$$L \frac{di_2}{dt} = -V_c \tag{1}$$

$$\frac{dV_c}{dt} = - \frac{i_{OH}}{C} + \frac{i_2}{C} \tag{2}$$

$$V_c\Big|_{t=0} = V_o \; ; \quad i_2\Big|_{t=0} = 20 \text{ kA} \tag{3}$$

where

i_2 = current through the inductance and vacuum contactor,

L = inductance of the saturated reactor,

C = commutation capacitance value,

V_c = voltage across the commutation capacitor,

i_{OH} = current through the ohmic heating coil — considered constant during current interruption.

The time response of the current through the vacuum contactor becomes

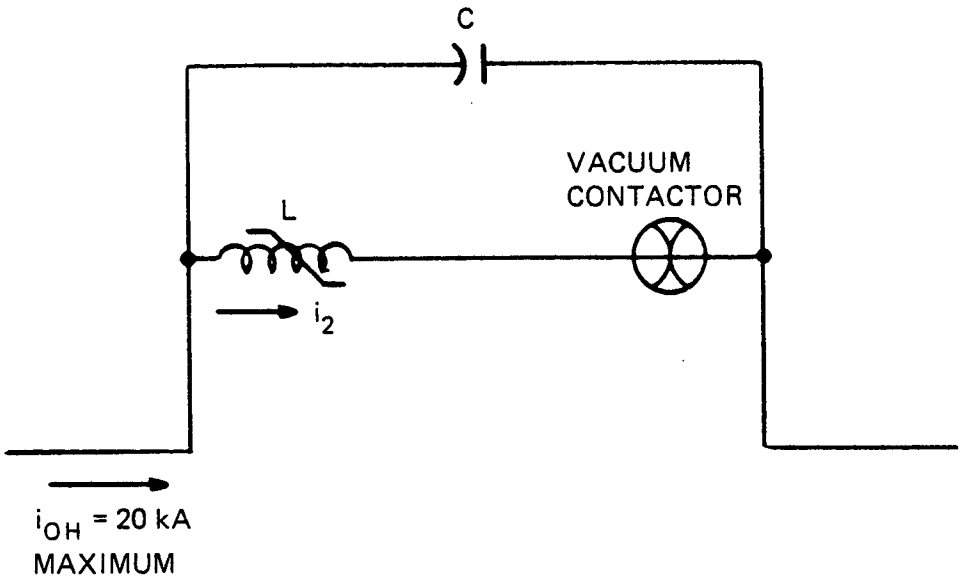


Figure 7. Approximation of circuit breaker prior to current zero.

$$i_2(t) = 2 \times 10^4 - \sqrt{C/L}\, V_o \sin(t/\sqrt{LC})$$

The times of the current zero and the RFIC are, respectively,

$$t_{co} = \sqrt{LC}\, \sin^{-1} \frac{2 \times 10^4}{\sqrt{C/L}\, V_o} \tag{4}$$

$$RFIC = \sqrt{C/L}\, \frac{V_o}{\sqrt{LC}\, \cos[t_{co}/\sqrt{LC}]} \tag{5}$$

Based on information from experimental physicists at ORNL, an interruption time in the range of 25 to 50 μs is desired. A 50 μs interruption time results in a typical set of circuit parameters with values

$C = 200\ \mu f$

$L = 10\ \mu H$

$V_c = 6\ kV$ at $t = 0$

Equations (4) and (5) now result in $t_{co} = 37.9\ \mu s$ and RFIC = 397 A/μs. It is obvious that a RFIC $\leq$ 40 A/μs was not achieved. One solution to this problem is to use a saturable reactor that has a low inductance when saturated and a much higher inductance at a low value of current. Equations (4) and (5) do not apply in a variable inductance case; therefore, an acceptable RFIC will be calculated from computer simulations later.

D. RRRV

After arc extinction, the vacuum contactor is subjected to a recovery voltage buildup. Once again, this rate must be limited to prevent the arc from reigniting due to the presence of ionized gases in the gap. The rate of rise of recovery voltage should be limited to ≤700 V/μs, as previously stated.

The current during this phase is low and the saturable reactor has its high value. The differential equations describing the vacuum contactor during this phase now become

$$\frac{dV_c}{dt} = \frac{-i_{OH}}{C} + \frac{i_2}{C}$$

$$L_2 \frac{di_2}{dt} + R_2 i_2 = -V_c$$

$$i_2\Big|_{t=t_{co}} = 0 \; ; \quad \frac{di_2}{dt}\Big|_{t=t_{co}} = \text{RFIC} \; ; \quad V_c\Big|_{t=t_{co}} = V_o$$

The RRRV immediately after interruption is simply the RFIC times the ionization resistor. Even the unacceptable value of RFIC = 397 A/μs calculated in the previous section results in a RRRV = 397 A/μs × 1.5 Ω or 595.5 V/μs, which is still below the limit.

Observation reveals that an acceptable RFIC will automatically result in an acceptable RRRV for the particular circuit under consideration here.

III. SINGLE VACUUM CONTACTOR DESIGN

A. Constant Inductance Simulation

A logical first step in simulating a circuit breaker design would be to start with the simple case of a single vacuum contactor and a constant inductance reactor. The circuit to be simulated is shown in Fig. 8. The computer program utilized to analyze the circuit is a version of SUPER*SCEPTRE developed by the University of South Florida. It is an automatic circuit-analysis program that determines the initial conditions and/or transient response of large nonlinear electrical networks. The system uses a free-format, engineer-oriented language to write and solve circuit equations from simple descriptions of the circuit topology and component values.

The SUPER*SCEPTRE input for the circuit shown in Fig. 8 is as follows:

```
CIRCUIT DESCRIPTION
ELEMENTS
L1,1-2=10.0E-6
C1,1-2=200.0E-6
R1,1-2=1.5
ROH,2-3=60.0E-3
LOH,3-1=62.0E-3
OUTPUTS
VC1,IL1,VR1
INITIAL CONDITIONS
ILOH=20000,VC1=-6000,IL1=20000
RUN CONTROLS
MAXIMUM STEP SIZE=1.0E-6
STARTING STEP SIZE=1.0E-6
TERMINATE IF (IL1 .LE. 0.)
STOP TIME=100.0E-6
END
```

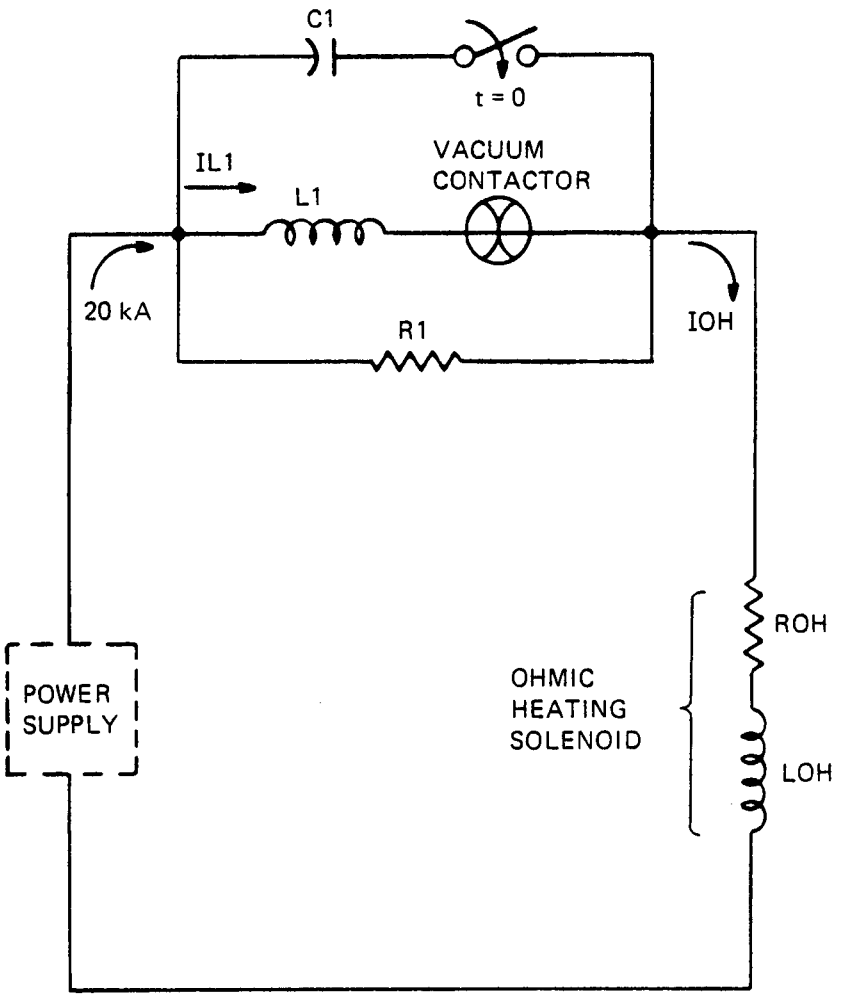


Figure 8. Single vacuum contactor circuit breaker with constant inductance.

The assumption has been made that once the current in the vacuum contactor gap reaches zero an interruption has occurred and no restrikes take place. This assumption is not valid unless the RFIC and RRRV criteria established earlier are satisfied.

From the output data shown in Fig. 9 and Table 1, the RFIC for this example is determined to be 309 A/μs, which is unacceptable. Note, however, that the time until current zero is 42 μs, which is acceptable.

B. Saturable Reactor Simulation

In order to slow the rate of current decay just prior to an interruption attempt, the constant inductance reactor is replaced with a saturable reactor that has the characteristics of 10-μH saturated inductance and 50-μH unsaturated. The saturation point is chosen to occur at 1000 A. The circuit input is as follows:

```
CIRCUIT DESCRIPTION
ELEMENTS
L1,1-2=TABLE 1 (IL1)
C1,1-2=200.0E-6
R1,1-2=1.5
ROH,2-3=60.0E-3
LOH,3-1=62.0E-3
OUTPUTS
VC1,IL1,VR1
INITIAL CONDITIONS
ILOH=20000,VC1=-6000,IL1=20000
FUNCTIONS
TABLE 1
0.0,50.0E-6
1000.,50.0E-6
1000.,10.0E-6
20000.,10.0E-6
RUN CONTROLS
MAXIMUM STEP SIZE=1.0E-6
STARTING STEP SIZE=1.0E-6
TERMINATE IF (IL1 .LE. 0.)
STOP TIME=100.0E-6
END
```

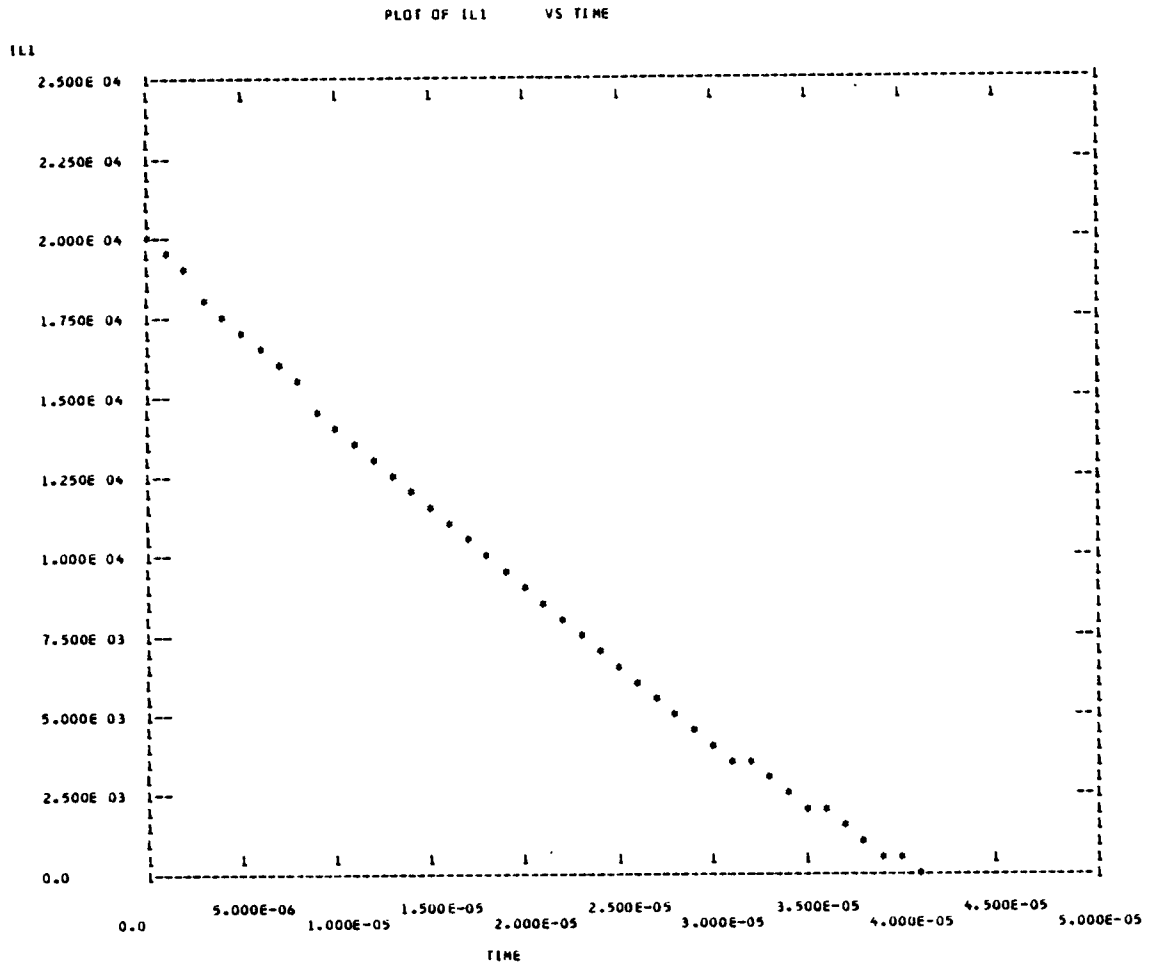


Figure 9. Current profile with one vacuum contactor, constant inductance reactor.

Table 1. Circuit response for one vacuum contactor with constant inductance reactor

TRANSIENT ANALYSIS RESULTS

TIME	0.0	9.99999E-07	2.00000E-06	3.00000E-06	4.00000E-06	5.00000E-06	6.00000E-06
VC1	-6.00000E 03	-5.98000E 03	-5.95561E 03	-5.92832E 03	-5.89817E 03	-5.86518E 03	-5.82936E 03
IL1	2.00000E 04	1.94000E 04	1.88031E 04	1.82089E 04	1.76175E 04	1.70292E 04	1.64444E 04
VR1	-6.00000E 03	-5.98000E 03	-5.95561E 03	-5.92832E 03	-5.89817E 03	-5.86518E 03	-5.82936E 03
TIME	7.00000E-06	8.00000E-06	9.00000E-06	1.00000E-05	1.10000E-05	1.20000E-05	1.30000E-05
VC1	-5.79075E 03	-5.74938E 03	-5.70528E 03	-5.65848E 03	-5.60900E 03	-5.55689E 03	-5.50218E 03
IL1	1.58634E 04	1.52863E 04	1.47135E 04	1.41452E 04	1.35818E 04	1.30234E 04	1.24704E 04
VR1	-5.79075E 03	-5.74938E 03	-5.70528E 03	-5.65848E 03	-5.60900E 03	-5.55689E 03	-5.50218E 03
TIME	1.40000E-05	1.50000E-05	1.60000E-05	1.70000E-05	1.80000E-05	1.90000E-05	2.00000E-05
VC1	-5.44491E 03	-5.38510E 03	-5.32281E 03	-5.25806E 03	-5.19091E 03	-5.12139E 03	-5.04954E 03
IL1	1.19229E 04	1.13814E 04	1.08459E 04	1.03168E 04	9.79425E 03	9.27856E 03	8.76994E 03
VR1	-5.44491E 03	-5.38510E 03	-5.32281E 03	-5.25806E 03	-5.19091E 03	-5.12139E 03	-5.04954E 03
TIME	2.10000E-05	2.20000E-05	2.30000E-05	2.40000E-05	2.50000E-05	2.60000E-05	2.70000E-05
VC1	-4.97541E 03	-4.89904E 03	-4.82048E 03	-4.73978E 03	-4.65697E 03	-4.57212E 03	-4.48527E 03
IL1	8.26861E 03	7.77482E 03	7.28877E 03	6.81068E 03	6.34076E 03	5.87923E 03	5.42629E 03
VR1	-4.97541E 03	-4.89904E 03	-4.82048E 03	-4.73978E 03	-4.65697E 03	-4.57212E 03	-4.48527E 03
TIME	2.80000E-05	2.90000E-05	3.00000E-05	3.10000E-05	3.20000E-05	3.30000E-05	3.40000E-05
VC1	-4.39646E 03	-4.30576E 03	-4.21321E 03	-4.11886E 03	-4.02277E 03	-3.92500E 03	-3.82558E 03
IL1	4.98212E 03	4.54693E 03	4.12091E 03	3.70422E 03	3.29706E 03	2.89959E 03	2.51198E 03
VR1	-4.39646E 03	-4.30576E 03	-4.21321E 03	-4.11886E 03	-4.02277E 03	-3.92500E 03	-3.82558E 03
TIME	3.50000E-05	3.60000E-05	3.70000E-05	3.80000E-05	3.90000E-05	4.00000E-05	4.10000E-05
VC1	-3.72459E 03	-3.62207E 03	-3.51809E 03	-3.41270E 03	-3.30595E 03	-3.19791E 03	-3.08863E 03
IL1	2.13439E 03	1.76697E 03	1.40988E 03	1.06325E 03	7.27231E 02	4.01948E 02	8.75297E 01
VR1	-3.72459E 03	-3.62207E 03	-3.51809E 03	-3.41270E 03	-3.30595E 03	-3.19791E 03	-3.08863E 03
TIME	4.20000E-05						
VC1	-2.97817E 03						
IL1	-2.15904E 02						
VR1	-2.97817E 03						

The results of this simulation, shown in Fig. 10 and Table 2, produce a RFIC = 24.7 A/μs and, therefore, a RRRV = 37 V/μs. These are acceptable values, but the time to interruption was 61 μs, which is longer than desired.

The usefulness of a saturable reactor to lower the RFIC was demonstrated in this simulation, but a problem of recovery voltage still exists. The RRRV is well below its limit, but the magnitude of the recovery voltage exceeds the safe limit of the vacuum contactor. The ionization resistor in this study is 1.5 Ω, which results in a recovery voltage of 30 kV. Earlier studies at MIT indicated that a single vacuum contactor can safely interrupt 12 kA with a recovery voltage of 17 kV. This leads to the conclusion that several vacuum contactors will be required to achieve the desired results.

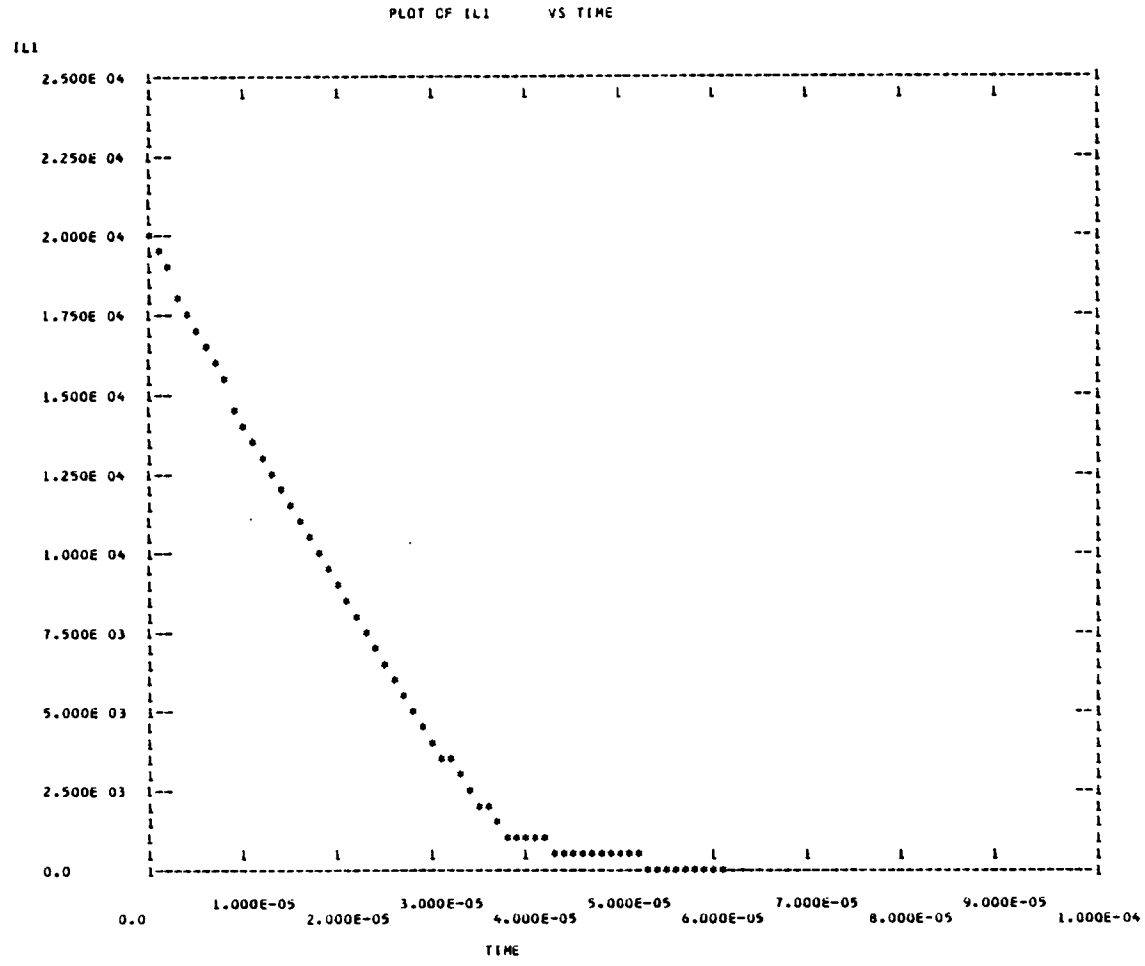


Figure 10. Current profile with one vacuum contactor, saturable reactor.

Table 2. Circuit response for one vacuum contactor with saturable reactor

TRANSIENT ANALYSIS RESULTS

TIME	0.0	2.00000E-06	4.00000E-06	6.00000E-06	8.00000E-06	1.00000E-05	1.20000E-05
VC1	-6.00000E 03	-5.95561E 03	-5.89817E 03	-5.82936E 03	-5.74938E 03	-5.65848E 03	-5.55689E 03
IL1	2.00000E 04	1.88031E 04	1.76175E 04	1.64444E 04	1.52863E 04	1.41452E 04	1.30234E 04
VR1	-6.00000E 03	-5.95561E 03	-5.89817E 03	-5.82936E 03	-5.74938E 03	-5.65848E 03	-5.55689E 03
TIME	1.40000E-05	1.60000E-05	1.80000E-05	2.00000E-05	2.20000E-05	2.40000E-05	2.60000E-05
VC1	-5.44491E 03	-5.32281E 03	-5.19091E 03	-5.04954E 03	-4.89904E 03	-4.73978E 03	-4.57212E 03
IL1	1.19229E 04	1.08459E 04	9.79425E 03	8.76994E 03	7.77482E 03	6.81068E 03	5.87923E 03
VR1	-5.44491E 03	-5.32281E 03	-5.19091E 03	-5.04954E 03	-4.89904E 03	-4.73978E 03	-4.57212E 03
TIME	2.80000E-05	3.00000E-05	3.20000E-05	3.40000E-05	3.60000E-05	3.80000E-05	3.81562E-05
VC1	-4.39646E 03	-4.21321E 03	-4.02277E 03	-3.82558E 03	-3.62207E 03	-3.41270E 03	-3.39611E 03
IL1	4.98212E 03	4.12091E 03	3.29706E 03	2.51198E 03	1.76697E 03	1.06325E 03	1.01006E 03
VR1	-4.39646E 03	-4.21321E 03	-4.02277E 03	-3.82558E 03	-3.62207E 03	-3.41270E 03	-3.39611E 03
TIME	3.81875E-05	3.82187E-05	3.82500E-05	3.82969E-05	3.83594E-05	3.84219E-05	3.84844E-05
VC1	-3.39279E 03	-3.38946E 03	-3.38614E 03	-3.38116E 03	-3.37451E 03	-3.36787E 03	-3.36122E 03
IL1	9.99450E 02	9.97331E 02	9.95213E 02	9.92041E 02	9.87819E 02	9.83605E 02	9.79399E 02
VR1	-3.39279E 03	-3.38946E 03	-3.38614E 03	-3.38116E 03	-3.37451E 03	-3.36787E 03	-3.36122E 03
TIME	3.86094E-05	3.87344E-05	3.88594E-05	3.90469E-05	3.92969E-05	3.95469E-05	3.97969E-05
VC1	-3.34793E 03	-3.33464E 03	-3.32135E 03	-3.30142E 03	-3.27484E 03	-3.24827E 03	-3.22170E 03
IL1	9.71013E 02	9.62660E 02	9.54340E 02	9.41922E 02	9.25481E 02	9.09173E 02	8.92998E 02
VR1	-3.34793E 03	-3.33464E 03	-3.32135E 03	-3.30142E 03	-3.27484E 03	-3.24827E 03	-3.22170E 03
TIME	4.02969E-05	4.07969E-05	4.12969E-05	4.20469E-05	4.30469E-05	4.40469E-05	4.50469E-05
VC1	-3.16856E 03	-3.11543E 03	-3.06231E 03	-2.98265E 03	-2.87650E 03	-2.77040E 03	-2.66439E 03
IL1	8.61047E 02	8.29626E 02	7.98737E 02	7.53398E 02	6.94804E 02	6.38332E 02	5.83981E 02
VR1	-3.16856E 03	-3.11543E 03	-3.06231E 03	-2.98265E 03	-2.87650E 03	-2.77040E 03	-2.66439E 03
TIME	4.60469E-05	4.70469E-05	4.80469E-05	4.90469E-05	5.00469E-05	5.10469E-05	5.20469E-05
VC1	-2.55846E 03	-2.45263E 03	-2.34690E 03	-2.24129E 03	-2.13581E 03	-2.03047E 03	-1.92528E 03
IL1	5.31749E 02	4.81635E 02	4.33636E 02	3.87750E 02	3.43975E 02	3.02309E 02	2.62747E 02
VR1	-2.55846E 03	-2.45263E 03	-2.34690E 03	-2.24129E 03	-2.13581E 03	-2.03047E 03	-1.92528E 03
TIME	5.30469E-05	5.40469E-05	5.50469E-05	5.60469E-05	5.70469E-05	5.80469E-05	5.90469E-05
VC1	-1.82024E 03	-1.71537E 03	-1.61068E 03	-1.50617E 03	-1.40187E 03	-1.29777E 03	-1.19388E 03
IL1	2.25287E 02	1.89927E 02	1.56661E 02	1.25488E 02	9.64016E 01	6.93993E 01	4.44763E 01
VR1	-1.82024E 03	-1.71537E 03	-1.61068E 03	-1.50617E 03	-1.40187E 03	-1.29777E 03	-1.19388E 03
TIME	6.00469E-05	6.07969E-05	6.12969E-05				
VC1	-1.09023E 03	-1.01264E 03	-9.60991E 02				
IL1	2.16282E 01	5.85238E 00	-4.01681E 00				
VR1	-1.09023E 03	-1.01264E 03	-9.60991E 02				

IV. SIX VACUUM CONTACTOR DESIGN

A. Constant Inductance Simulation

Due to the voltage and current limitations discussed in Sect. III(B), a series-parallel combination of six vacuum contactors seems to be a possible solution. Three in parallel will safely interrupt the 20 kA, and two in series should provide a safe margin for the 30-kV recovery voltage. As seen in Fig. 11, the center points of the three sets of vacuum contactors and the ionization resistor are connected together. This will prevent any voltage overstress due to unsynchronized operation by allowing only 15 kV across any one vacuum contactor.

The computer input for simulating a circuit with six vacuum contactors with the constant inductance reactors divided accordingly is as follows:

```
CIRCUIT DESCRIPTION
ELEMENTS
L1,1-2=10.0E-6
L3,1-2=10.0E-6
L5,1-2=10.0E-6
L2,2-3=10.0E-6
L4,2-3=10.0E-6
L6,2-3=10.0E-6
C1,1-3=200.0E-6
R1,1-2=.75
R2,2-3=.75
ROH,3-4=60.0E-3
LOH,4-1=62.0E-3
OUTPUTS
VC1,IL1,IL5,IL4,IR1,IR2,IC1
INITIAL CONDITIONS
ILOH=20000,VC1=-6000,IL1=6667.,IL2=6667.,IL3=6667.,IL4=6667,
IL5=6667.,IL6=6667.
FUNCTIONS
```

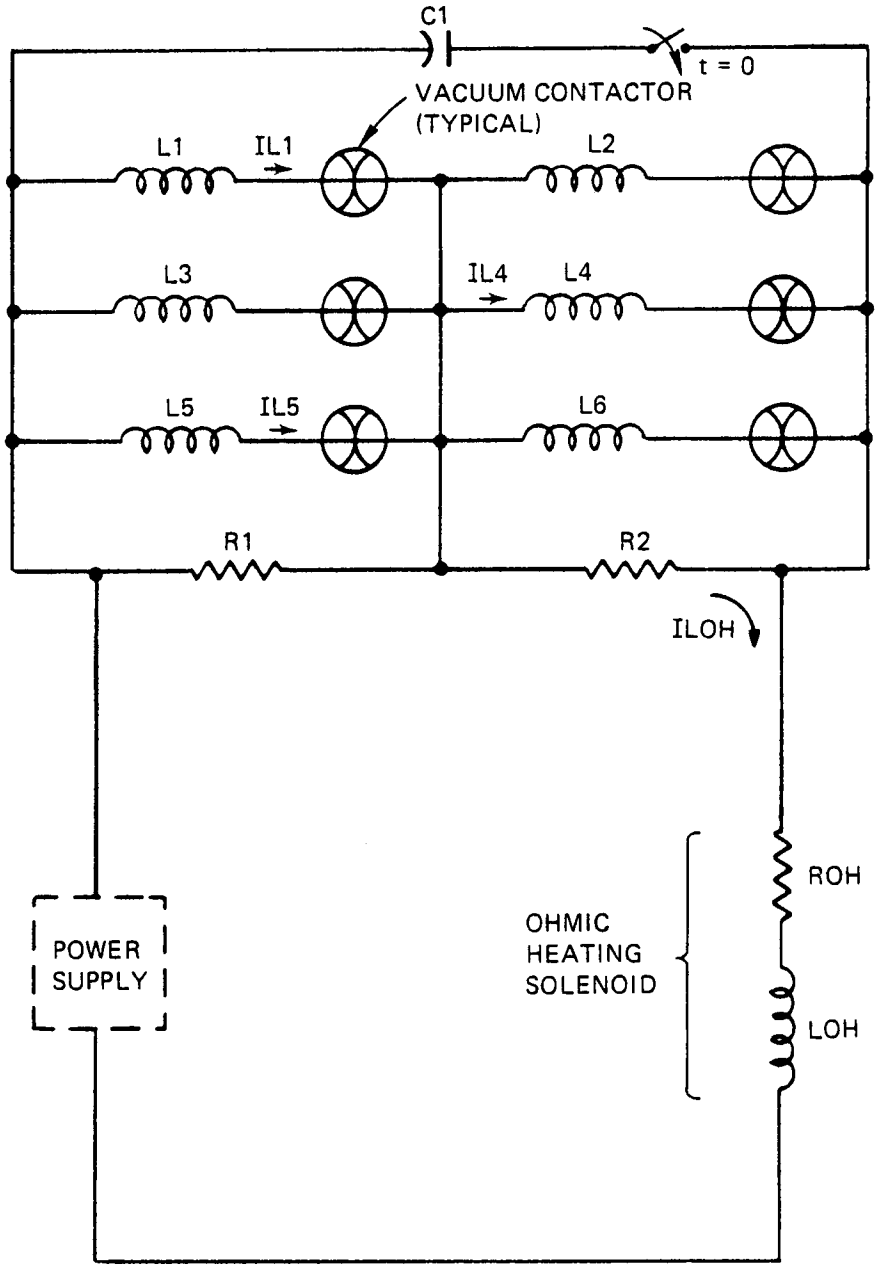


Figure 11. Circuit breaker with six vacuum contactors and constant inductance reactors.

```
TABLE L
0.,50.0E-6,500.,50.0E-6,500.,10.0E-6,20000.,10.0E-6
RUN CONTROLS
MAXIMUM STEP SIZE=1.0E-6
STARTING STEP SIZE=1.0E-6
TERMINATE IF (IL1 .LE. 0.)
STOP TIME=100.0E-6

END
```

Figure 12 and Table 3 show the results from this simulation. Three individual current plots are included to demonstrate that the current division is symmetrical in this example. The real circuit components could not be manufactured with such precision and would result in adjustments being necessary to approach symmetry conditions.

From Table 3, the figures of merit for this curcuit are RFIC = 212 A/μs, RRRV = 318 V/μs, and a time to interruption of approximately 25 μs. With a constant inductance of 10 μH, the RFIC once again is above the specified limit.

B. Saturable Reactor Simulation

The circuit from the previous section is simulated again with the 10-μH reactors replaced by saturable reactors with a 10-μH saturated inductance, 50-μH unsaturated inductance, and a saturation point of 500 A. A lower saturation point was chosen for this case as compared to the earlier simulation of a single vacuum contactor because the initial current in each vacuum contactor has been reduced due to the parallel paths through the vacuum circuit breaker. Figure 13 describes the circuit as simulated. Once again the simulation depicts circuit components with identical values and thus equal current flow at all times through the six vacuum contactors. The computer input is as follows:

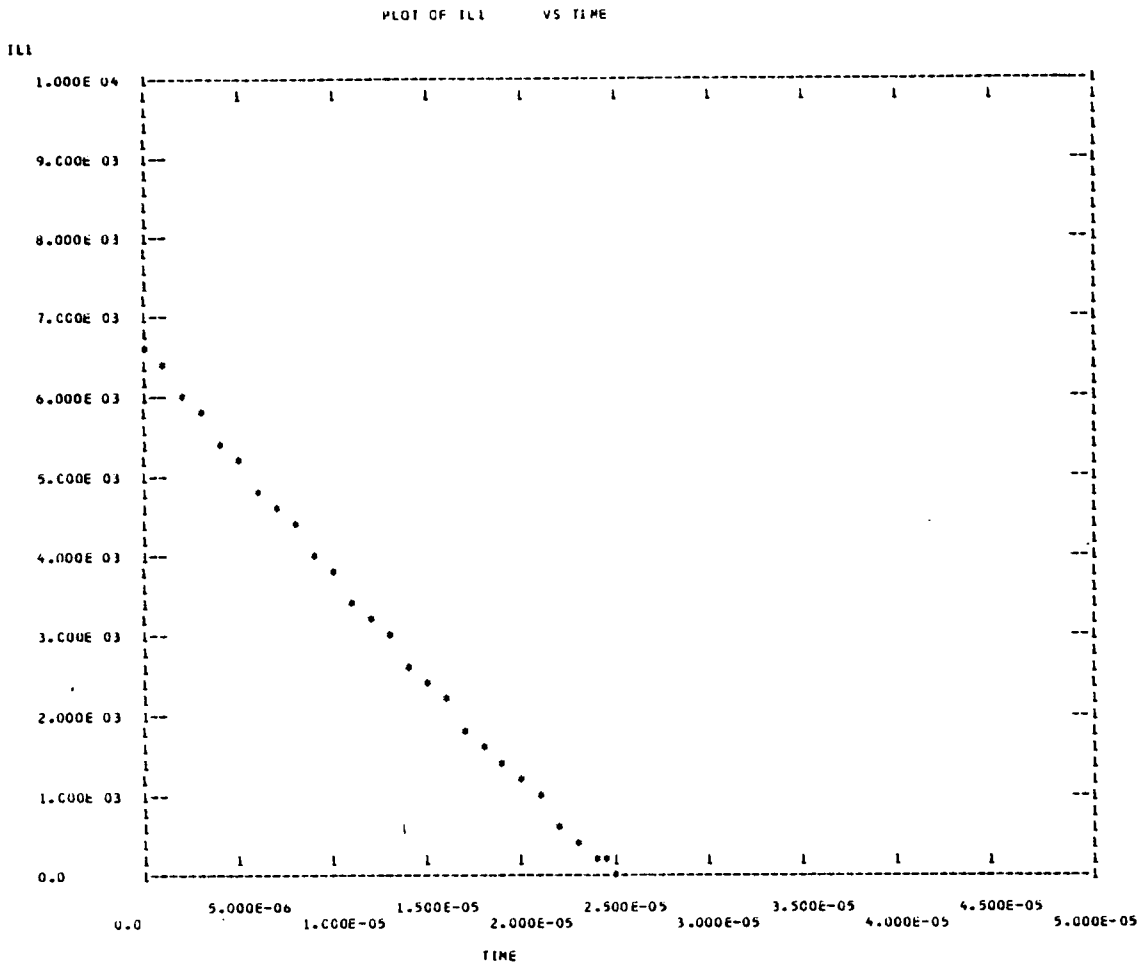


Figure 12. Current profile with six vacuum contactors, constant inductance.

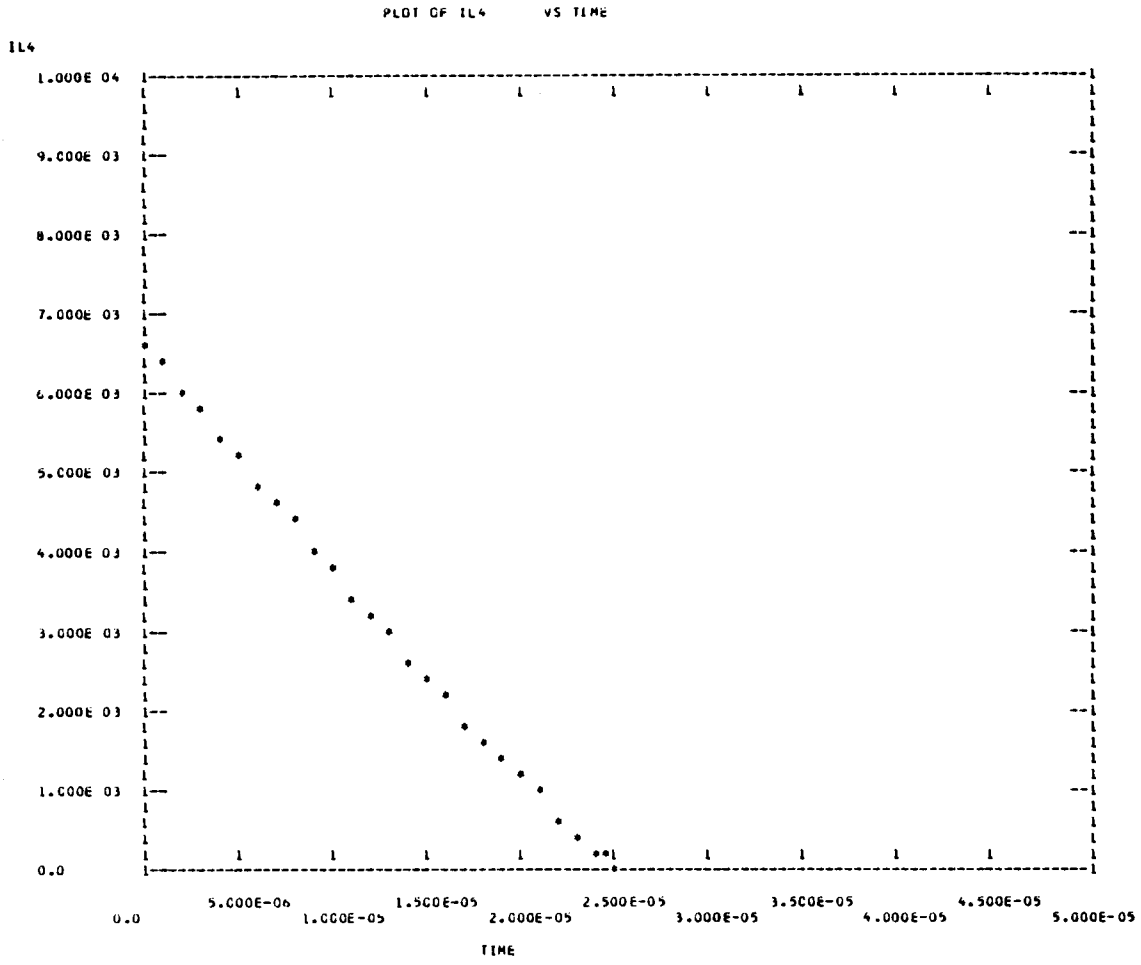


Figure 12 (continued)

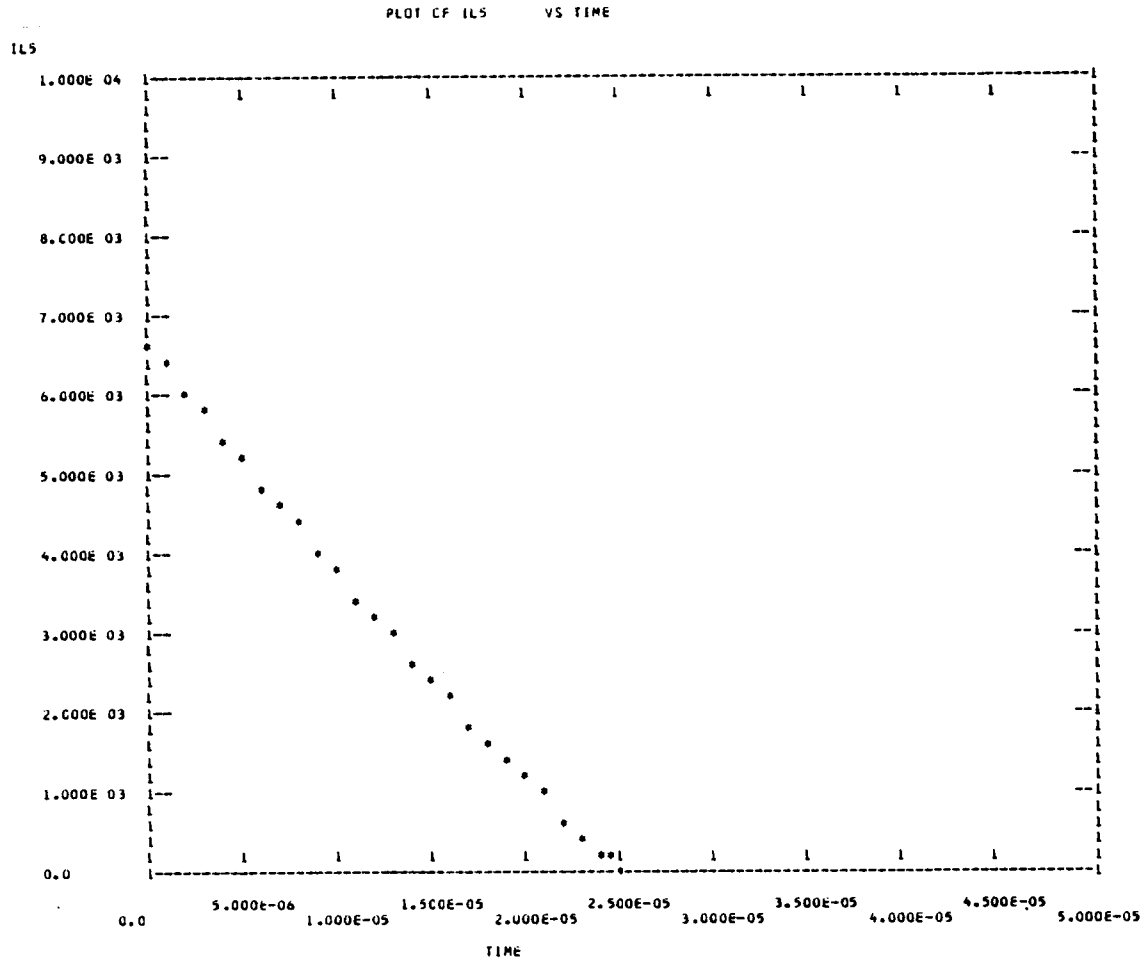


Figure 12 (continued)

Table 3. Circuit response for six vacuum contactors with constant inductance reactors

TRANSIENT ANALYSIS RESULTS

TIME	0.0	9.99999E-07	2.00000E-06	3.00000E-06	4.00000E-06	5.00000E-06	6.00000E-06
VC1	-6.CCCCCE 03	-5.98C00E 03	-5.95337E 03	-5.92237E 03	-5.88704E 03	-5.84741E 03	-5.80354E 03
IL1	6.66700E 03	6.36700E 03	6.06861E 03	5.77166E 03	5.47637E 03	5.18295E 03	4.89162E 03
IL5	6.66700E 03	6.36700E 03	6.06861E 03	5.77166E 03	5.47637E 03	5.18295E 03	4.89162E 03
IL4	6.667CCE 03	6.36700E 03	6.06861E 03	5.77166E 03	5.47637E 03	5.18295E 03	4.89162E 03
IR1	-4.00000E 03	-3.98667E 03	-3.96852E 03	-3.94825E 03	-3.92469E 03	-3.89828E 03	-3.86903E 03
IR2	-4.CC000E 03	-3.98667E 03	-3.96852E 03	-3.94825E 03	-3.92469E 03	-3.89828E 03	-3.86903E 03
IC1	3.5990CE 03	4.88575E 03	5.76324E 03	6.63350E 03	7.49589E 03	8.34980E 03	9.19462E 03
TIME	7.00000E-06	8.00000E-06	9.00000E-06	1.00000E-05	1.10000E-05	1.20000E-05	1.30000E-05
VC1	-5.75547E 03	-5.70325E 03	-5.64692E 03	-5.58656E 03	-5.52221E 03	-5.45395E 03	-5.38182E 03
IL1	4.60259E 03	4.31607E 03	4.03226E 03	3.75137E 03	3.47359E 03	3.19913E 03	2.92818E 03
IL5	4.60259E 03	4.31607E 03	4.03226E 03	3.75137E 03	3.47359E 03	3.19913E 03	2.92818E 03
IL4	4.60259E 03	4.31607E 03	4.03226E 03	3.75137E 03	3.47359E 03	3.19913E 03	2.92818E 03
IR1	-3.83698E 03	-3.80216E 03	-3.76462E 03	-3.72437E 03	-3.68148E 03	-3.63596E 03	-3.58788E 03
IR2	-3.83698E 03	-3.80216E 03	-3.76462E 03	-3.72437E 03	-3.68148E 03	-3.63596E 03	-3.58788E 03
IC1	1.00297E 04	1.08546E 04	1.16685E 04	1.24710E 04	1.32615E 04	1.40395E 04	1.48043E 04
TIME	1.4CCCCE-C5	1.50000E-05	1.60000E-05	1.70000E-05	1.80000E-05	1.90000E-05	2.00000E-05
VC1	-5.30590E 03	-5.22627E 03	-5.14298E 03	-5.05612E 03	-4.96576E 03	-4.87198E 03	-4.77486E 03
IL1	2.66093E 03	2.39757E 03	2.13828E 03	1.88325E 03	1.63265E 03	1.38665E 03	1.14542E 03
IL5	2.66093E 03	2.39757E 03	2.13828E 03	1.88325E 03	1.63265E 03	1.38665E 03	1.14542E 03
IL4	2.66093E 03	2.39757E 03	2.13828E 03	1.88325E 03	1.63265E 03	1.38665E 03	1.14542E 03
IR1	-3.53727E 03	-3.48418E 03	-3.42865E 03	-3.37075E 03	-3.31051E 03	-3.24799E 03	-3.18324E 03
IR2	-3.53727E 03	-3.48418E 03	-3.42865E 03	-3.37075E 03	-3.31051E 03	-3.24799E 03	-3.18324E 03
IC1	1.55555E 04	1.62925E 04	1.70149E 04	1.77222E 04	1.84138E 04	1.90894E 04	1.97484E 04
TIME	2.1CCCCE-C5	2.20000E-05	2.30000E-05	2.40000E-05	2.45000E-05	2.50000E-05	2.55000E-05
VC1	-4.67455E 03	-4.57096E 03	-4.46435E 03	-4.35474E 03	-4.29886E 03	-4.24225E 03	-4.18495E 03
IL1	9.09126E 02	6.77932E 02	4.51991E 02	2.31454E 02	1.23277E 02	1.65055E 01	-8.88422E 01
IL5	9.C9126E 02	6.77932E 02	4.51991E 02	2.31454E 02	1.23277E 02	1.65055E 01	-8.88422E 01
IL4	9.C9126E 02	6.77932E 02	4.51991E 02	2.31454E 02	1.23277E 02	1.65055E 01	-8.88422E 01
IR1	-3.11633E 03	-3.04731E 03	-2.97623E 03	-2.90316E 03	-2.86591E 03	-2.82817E 03	-2.78997E 03
IR2	-3.11633E 03	-3.04731E 03	-2.97623E 03	-2.90316E 03	-2.86591E 03	-2.82817E 03	-2.78997E 03
IC1	2.C3904E 04	2.10150E 04	2.16218E 04	2.22104E 04	2.24977E 04	2.27803E 04	2.30582E 04

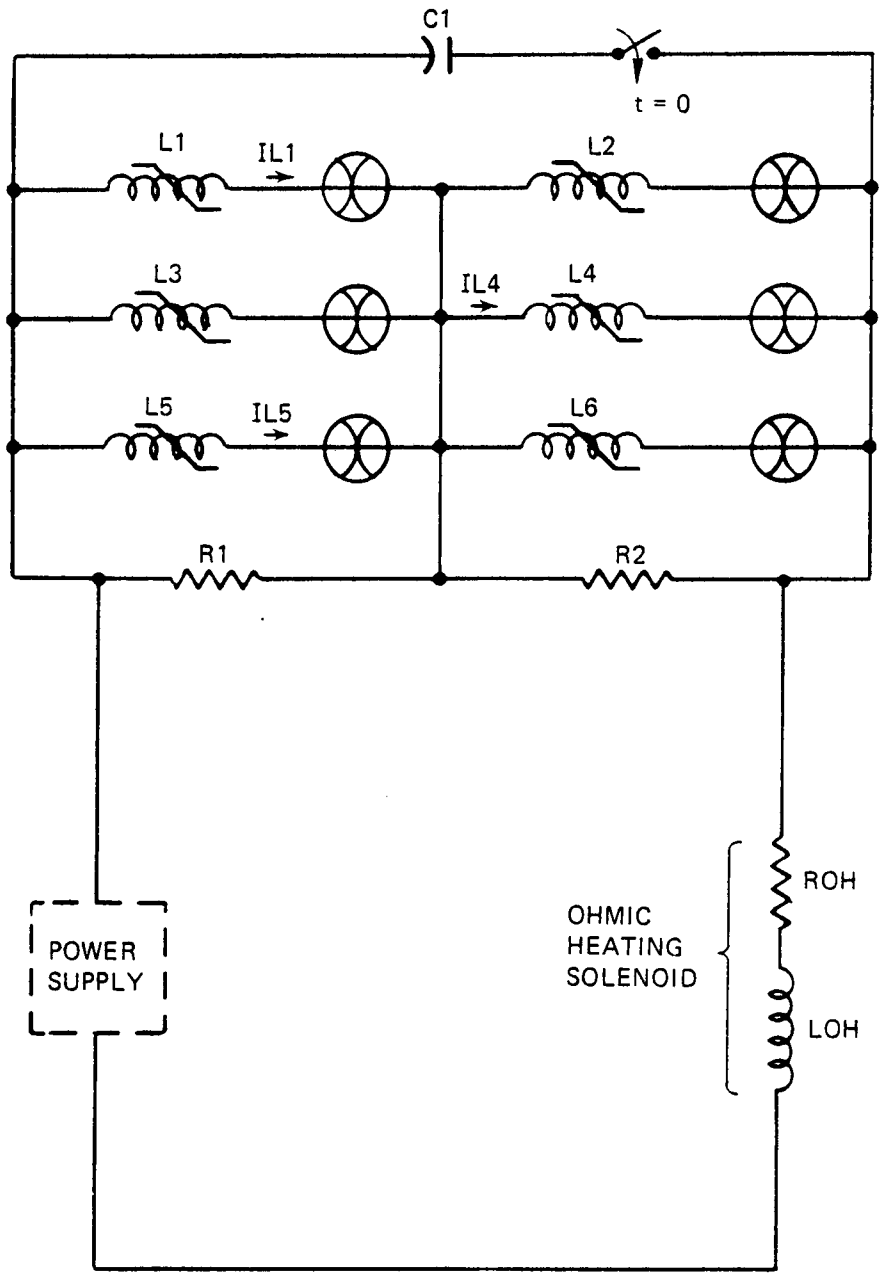


Figure 13. Circuit breaker with six vacuum contactors and saturable reactors.

```
CIRCUIT DESCRIPTION
ELEMENTS
L1,1-2=TABLE L (IL1)
L3,1-2=TABLE L (IL1)
L5,1-2=TABLE L (IL1)
L2,2-3=TABLE L (IL1)
L4,2-3=TABLE L (IL1)
L6,2-3=TABLE L (IL1)
C1,1-3=200.0E-6
R1,1-2=.75
R2,2-3=.75
ROH,3-4=60.0E-3
LOH,4-1=62.0E-3
OUTPUTS
VC1,IL1,IL5,IL4,IR1,IR2,IC1
INITIAL CONDITIONS
ILOH=20000,VC1=-6000,IL1=6667.,IL2=6667.,IL3=6667.,IL4=6667,
IL5=6667.,IL6=6667.
FUNCTIONS
TABLE L
0.,50.0E-6,500.,50.0E-6,500.,10.0E-6,20000.,10.0E-6
RUN CONTROLS
MAXIMUM STEP SIZE=1.0E-6
STARTING STEP SIZE=1.0E-6
TERMINATE IF (IL1 .LE. 0.)
STOP TIME=100.0E-6

END
```

Figure 14 and Table 4 were derived from this simulation and result in a RFIC $\approx$ 30.7 A/μs, RRRV $\approx$ 46 V/μs, and $t_{co} \approx$ 36 μs. All of these values fall within the desired ranges.

C. Proposed Vacuum Circuit Breaker

Based on the computer simulation studies that have been presented, the proposed vacuum circuit breaker for the ISX-C tokamak experiment is shown in schematic form in Fig. 15. Each of the six vacuum contactors has a separate electronically controlled driver circuit that operates the actuating solenoid, causing the vacuum contacts to open. This separate control will permit individual adjustments to triggering signals, which

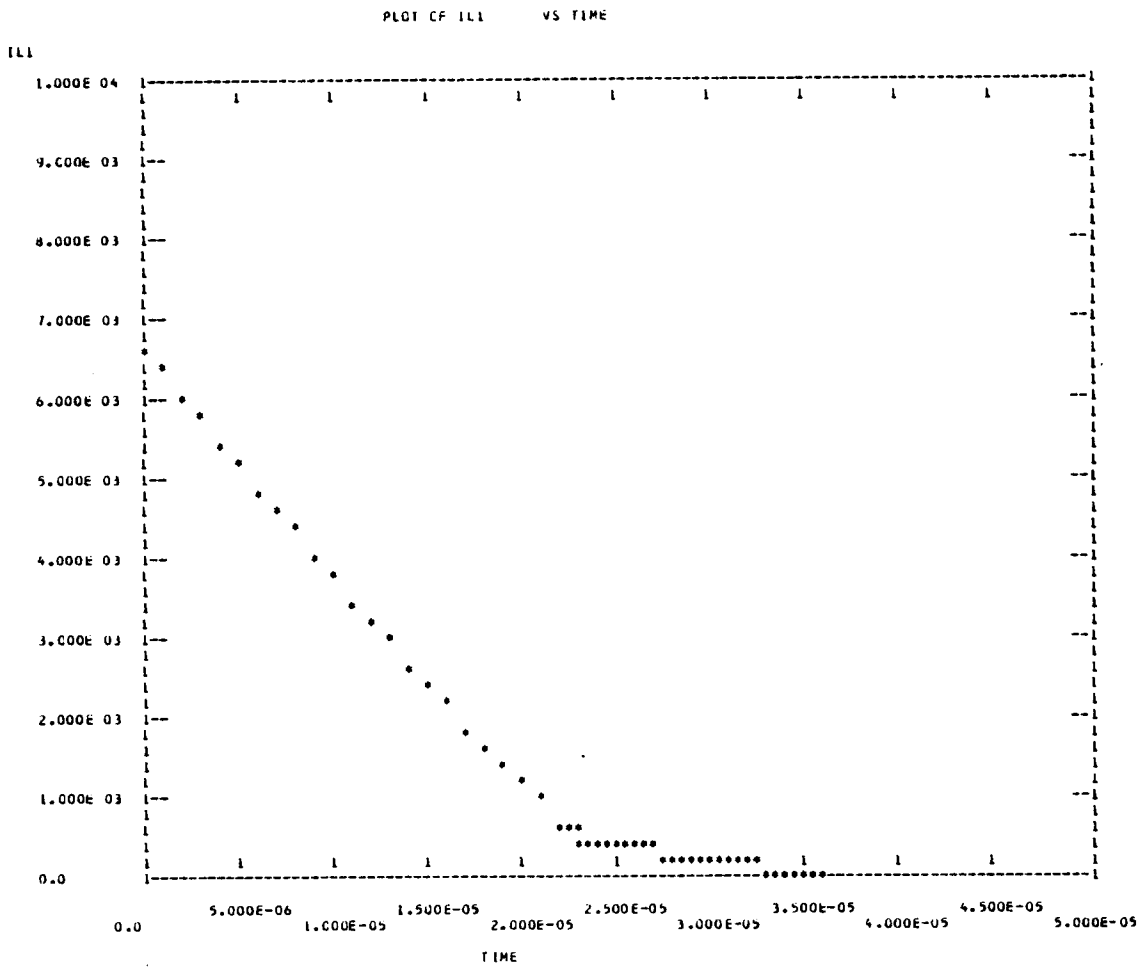


Figure 14. Current profile with six vacuum contactors, saturable reactors.

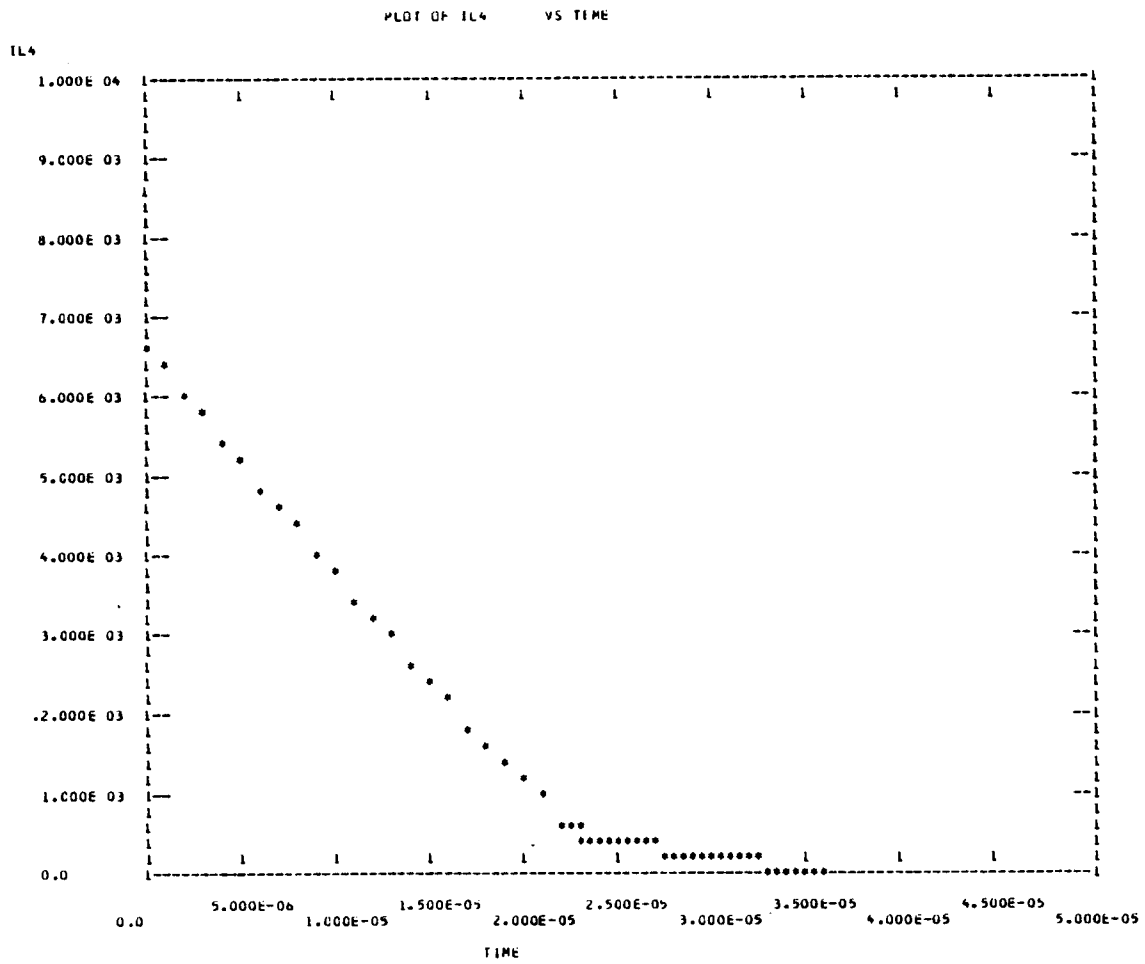


Figure 14 (continued)

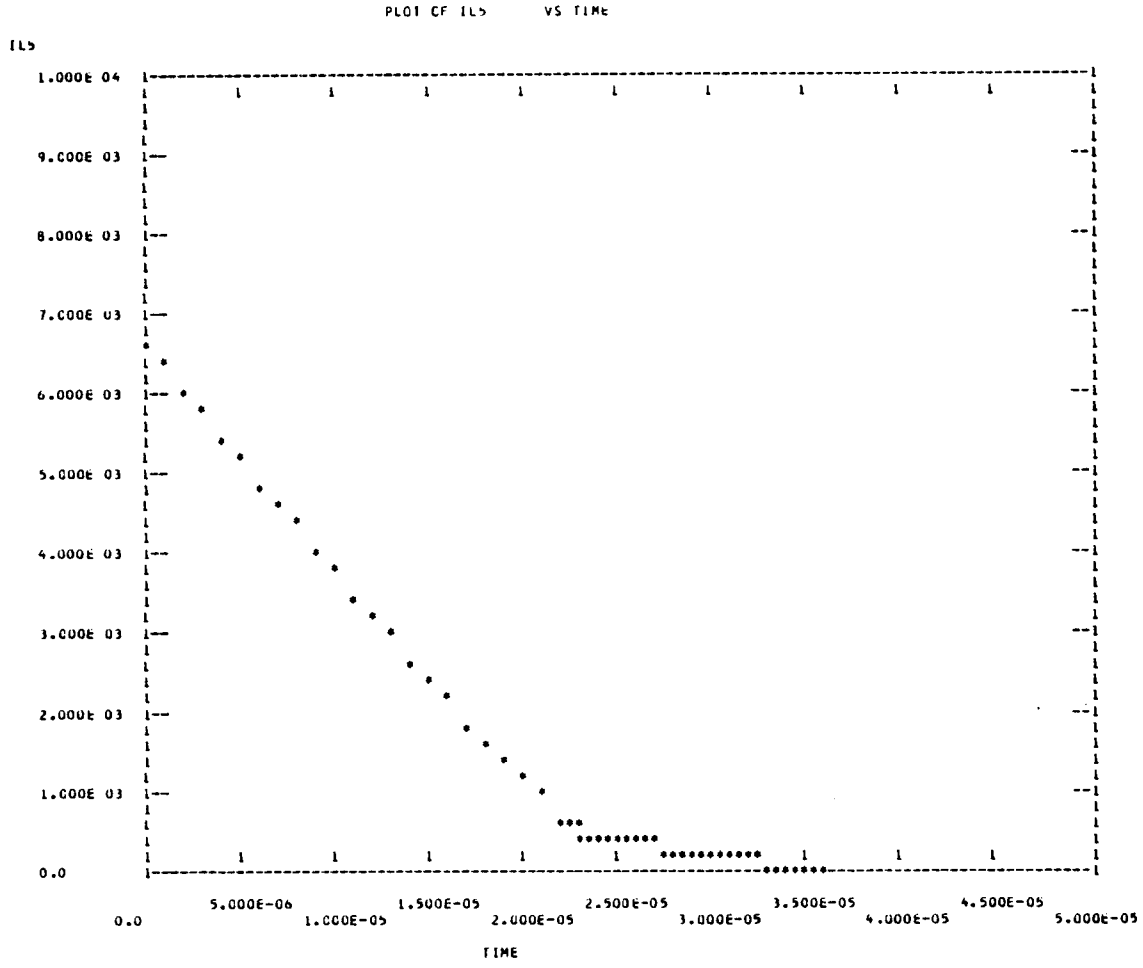


Figure 14 (continued)

Table 4. Circuit response for six vacuum contactors with saturable reactors

TRANSIENT ANALYSIS RESULTS

TIME	0.0	9.99999E-07	2.00000E-06	3.00000E-06	4.00000E-06	5.00000E-06	6.00000E-06
VC1	-6.00000E 03	-5.98000E 03	-5.95337E 03	-5.92237E 03	-5.88704E 03	-5.84741E 03	-5.80354E 03
IL1	6.66700E 03	6.36700E 03	6.06861E 03	5.77166E 03	5.47637E 03	5.18295E 03	4.89162E 03
IL5	6.66700E 03	6.36700E 03	6.06861E 03	5.77166E 03	5.47637E 03	5.18295E 03	4.89162E 03
IL4	6.66700E 03	6.36700E 03	6.06861E 03	5.77166E 03	5.47637E 03	5.18295E 03	4.89162E 03
IR1	-4.00000E 03	-3.98667E 03	-3.96892E 03	-3.94825E 03	-3.92469E 03	-3.89828E 03	-3.86903E 03
IR2	-4.00000E 03	-3.98667E 03	-3.96892E 03	-3.94825E 03	-3.92469E 03	-3.89828E 03	-3.86903E 03
IC1	3.99900E 03	4.88575E 03	5.76324E 03	6.63350E 03	7.49589E 03	8.34980E 03	9.19462E 03

TIME	7.00000E-06	8.00000E-06	9.00000E-06	1.00000E-05	1.10000E-05	1.20000E-05	1.30000E-05
VC1	-5.75547E 03	-5.70325E 03	-5.64692E 03	-5.58656E 03	-5.52221E 03	-5.45395E 03	-5.38182E 03
IL1	4.60259E 03	4.31607E 03	4.03226E 03	3.75137E 03	3.47359E 03	3.19913E 03	2.92818E 03
IL5	4.60259E 03	4.31607E 03	4.03226E 03	3.75137E 03	3.47359E 03	3.19913E 03	2.92818E 03
IL4	4.60259E 03	4.31607E 03	4.03226E 03	3.75137E 03	3.47359E 03	3.19913E 03	2.92818E 03
IR1	-3.83698E 03	-3.80216E 03	-3.76462E 03	-3.72437E 03	-3.68148E 03	-3.63596E 03	-3.58788E 03
IR2	-3.83698E 03	-3.80216E 03	-3.76462E 03	-3.72437E 03	-3.68148E 03	-3.63596E 03	-3.58788E 03
IC1	1.00297E 04	1.08546E 04	1.16685E 04	1.24710E 04	1.32615E 04	1.40395E 04	1.48043E 04

TIME	1.40000E-05	1.50000E-05	1.60000E-05	1.70000E-05	1.80000E-05	1.90000E-05	2.00000E-05
VC1	-5.30590E 03	-5.22627E 03	-5.14298E 03	-5.05612E 03	-4.96576E 03	-4.87198E 03	-4.77486E 03
IL1	2.66093E 03	2.39757E 03	2.13828E 03	1.88325E 03	1.63265E 03	1.38665E 03	1.14542E 03
IL5	2.66093E 03	2.39757E 03	2.13828E 03	1.88325E 03	1.63265E 03	1.38665E 03	1.14542E 03
IL4	2.66093E 03	2.39757E 03	2.13828E 03	1.88325E 03	1.63265E 03	1.38665E 03	1.14542E 03
IR1	-3.53727E 03	-3.48418E 03	-3.42865E 03	-3.37075E 03	-3.31051E 03	-3.24799E 03	-3.18324E 03
IR2	-3.53727E 03	-3.48418E 03	-3.42865E 03	-3.37075E 03	-3.31051E 03	-3.24799E 03	-3.18324E 03
IC1	1.55555E 04	1.62925E 04	1.70149E 04	1.77222E 04	1.84138E 04	1.90894E 04	1.97484E 04

TIME	2.10000E-05	2.20000E-05	2.25000E-05	2.27500E-05	2.27812E-05	2.28125E-05	2.28437E-05
VC1	-4.67450E 03	-4.57096E 03	-4.51804E 03	-4.49129E 03	-4.48794E 03	-4.48458E 03	-4.48122E 03
IL1	9.09126E 02	6.77932E 02	5.64312E 02	5.08003E 02	5.00988E 02	4.98886E 02	4.97485E 02
IL5	9.09126E 02	6.77932E 02	5.64312E 02	5.08003E 02	5.00988E 02	4.98886E 02	4.97485E 02
IL4	9.09126E 02	6.77932E 02	5.64312E 02	5.08003E 02	5.00988E 02	4.98886E 02	4.97485E 02
IR1	-3.11633E 03	-3.04731E 03	-3.01203E 03	-2.99420E 03	-2.99196E 03	-2.98972E 03	-2.98748E 03
IR2	-3.11633E 03	-3.04731E 03	-3.01203E 03	-2.99420E 03	-2.99196E 03	-2.98972E 03	-2.98748E 03
IC1	2.03904E 04	2.10150E 04	2.13208E 04	2.14717E 04	2.14905E 04	2.14946E 04	2.14966E 04

Table 4 (cont.)

TRANSIENT ANALYSIS RESULTS

TIME	2.28750E-05	2.29062E-05	2.29375E-05	2.29687E-05	2.30312E-05	2.30937E-05	2.31562E-05
VC1	-4.47786E 03	-4.47450E 03	-4.47114E 03	-4.46778E 03	-4.46106E 03	-4.45434E 03	-4.44761E 03
IL1	4.96085E 02	4.94686E 02	4.93289E 02	4.91892E 02	4.89102E 02	4.86315E 02	4.83534E 02
IL5	4.96085E 02	4.94686E 02	4.93289E 02	4.91892E 02	4.89102E 02	4.86315E 02	4.83534E 02
IL4	4.96085E 02	4.94686E 02	4.93289E 02	4.91892E 02	4.89102E 02	4.86315E 02	4.83534E 02
IR1	-2.98524E 03	-2.98300E 03	-2.98076E 03	-2.97852E 03	-2.97404E 03	-2.96956E 03	-2.96508E 03
IR2	-2.98524E 03	-2.98300E 03	-2.98076E 03	-2.97852E 03	-2.97404E 03	-2.96956E 03	-2.96508E 03
IC1	2.14985E 04	2.15005E 04	2.15024E 04	2.15044E 04	2.15083E 04	2.15122E 04	2.15160E 04

TIME	2.32187E-05	2.32812E-05	2.33437E-05	2.34062E-05	2.35312E-05	2.36562E-05	2.37812E-05
VC1	-4.44089E 03	-4.43416E 03	-4.42744E 03	-4.42071E 03	-4.40725E 03	-4.39379E 03	-4.38032E 03
IL1	4.80756E 02	4.77982E 02	4.75213E 02	4.72448E 02	4.66931E 02	4.61430E 02	4.55946E 02
IL5	4.80756E 02	4.77982E 02	4.75213E 02	4.72448E 02	4.66931E 02	4.61430E 02	4.55946E 02
IL4	4.80756E 02	4.77982E 02	4.75213E 02	4.72448E 02	4.66931E 02	4.61430E 02	4.55946E 02
IR1	-2.96059E 03	-2.95611E 03	-2.95163E 03	-2.94714E 03	-2.93817E 03	-2.92919E 03	-2.92021E 03
IR2	-2.96059E 03	-2.95611E 03	-2.95163E 03	-2.94714E 03	-2.93817E 03	-2.92919E 03	-2.92021E 03
IC1	2.15199E 04	2.15237E 04	2.15276E 04	2.15314E 04	2.15390E 04	2.15465E 04	2.15540E 04

TIME	2.39062E-05	2.40312E-05	2.41562E-05	2.42812E-05	2.45312E-05	2.47812E-05	2.50312E-05
VC1	-4.36684E 03	-4.35337E 03	-4.33988E 03	-4.32639E 03	-4.29941E 03	-4.27240E 03	-4.24538E 03
IL1	4.50479E 02	4.45029E 02	4.39596E 02	4.34179E 02	4.23397E 02	4.12682E 02	4.02035E 02
IL5	4.50479E 02	4.45029E 02	4.39596E 02	4.34179E 02	4.23397E 02	4.12682E 02	4.02035E 02
IL4	4.50479E 02	4.45029E 02	4.39596E 02	4.34179E 02	4.23397E 02	4.12682E 02	4.02035E 02
IR1	-2.91123E 03	-2.90225E 03	-2.89326E 03	-2.88427E 03	-2.86627E 03	-2.84827E 03	-2.83025E 03
IR2	-2.91123E 03	-2.90225E 03	-2.89326E 03	-2.88427E 03	-2.86627E 03	-2.84827E 03	-2.83025E 03
IC1	2.15614E 04	2.15688E 04	2.15761E 04	2.15834E 04	2.15977E 04	2.16119E 04	2.16258E 04

TIME	2.52812E-05	2.55312E-05	2.57812E-05	2.60312E-05	2.65312E-05	2.70312E-05	2.75312E-05
VC1	-4.21834E 03	-4.19128E 03	-4.16420E 03	-4.13711E 03	-4.08288E 03	-4.02859E 03	-3.97424E 03
IL1	3.91455E 02	3.80943E 02	3.70499E 02	3.60122E 02	3.39571E 02	3.19292E 02	2.99284E 02
IL5	3.91455E 02	3.80943E 02	3.70499E 02	3.60122E 02	3.39571E 02	3.19292E 02	2.99284E 02
IL4	3.91455E 02	3.80943E 02	3.70499E 02	3.60122E 02	3.39571E 02	3.19292E 02	2.99284E 02
IR1	-2.81223E 03	-2.79419E 03	-2.77614E 03	-2.75808E 03	-2.72192E 03	-2.68573E 03	-2.64949E 03
IR2	-2.81223E 03	-2.79419E 03	-2.77614E 03	-2.75808E 03	-2.72192E 03	-2.68573E 03	-2.64949E 03
IC1	2.16395E 04	2.16530E 04	2.16663E 04	2.16794E 04	2.17049E 04	2.17296E 04	2.17534E 04

Table 4 (cont.)

TRANSIENT ANALYSIS RESULTS

TIME	2.80312E-05	2.85312E-05	2.90312E-05	2.95312E-05	3.00312E-05	3.05312E-05	3.10312E-05
VC1	-3.91982E 03	-3.86535E 03	-3.81083E 03	-3.75626E 03	-3.70163E 03	-3.64696E 03	-3.59224E 03
IL1	2.79548E 02	2.60085E 02	2.40894E 02	2.21975E 02	2.03330E 02	1.84957E 02	1.66859E 02
IL5	2.79548E 02	2.60085E 02	2.40894E 02	2.21975E 02	2.03330E 02	1.84957E 02	1.66859E 02
IL4	2.79548E 02	2.60085E 02	2.40894E 02	2.21975E 02	2.03330E 02	1.84957E 02	1.66859E 02
IR1	-2.61322E 03	-2.57690E 03	-2.54055E 03	-2.50417E 03	-2.46775E 03	-2.43130E 03	-2.39483E 03
IR2	-2.61322E 03	-2.57690E 03	-2.54055E 03	-2.50417E 03	-2.46775E 03	-2.43130E 03	-2.39483E 03
IC1	2.17764E 04	2.17985E 04	2.18197E 04	2.18401E 04	2.18596E 04	2.18783E 04	2.18962E 04

TIME	3.15312E-05	3.20312E-05	3.25312E-05	3.30312E-05	3.35312E-05	3.40312E-05	3.45312E-05
VC1	-3.53748E 03	-3.48267E 03	-3.42783E 03	-3.37295E 03	-3.31803E 03	-3.26309E 03	-3.20811E 03
IL1	1.49034E 02	1.31483E 02	1.14206E 02	9.72028E 01	8.04746E 01	6.40210E 01	4.78422E 01
IL5	1.49034E 02	1.31483E 02	1.14206E 02	9.72028E 01	8.04746E 01	6.40210E 01	4.78422E 01
IL4	1.49034E 02	1.31483E 02	1.14206E 02	9.72028E 01	8.04746E 01	6.40210E 01	4.78422E 01
IR1	-2.35832E 03	-2.32178E 03	-2.28522E 03	-2.24863E 03	-2.21202E 03	-2.17539E 03	-2.13874E 03
IR2	-2.35832E 03	-2.32178E 03	-2.28522E 03	-2.24863E 03	-2.21202E 03	-2.17539E 03	-2.13874E 03
IC1	2.19132E 04	2.19293E 04	2.19446E 04	2.19590E 04	2.19726E 04	2.19854E 04	2.19973E 04

TIME	3.50312E-05	3.55312E-05	3.60312E-05	3.65312E-05
VC1	-3.15310E 03	-3.09807E 03	-3.04301E 03	-2.98793E 03
IL1	3.19383E 01	1.63096E 01	9.56076E-01	-1.41221E 01
IL5	3.19383E 01	1.63096E 01	9.56076E-01	-1.41221E 01
IL4	3.19383E 01	1.63096E 01	9.56076E-01	-1.41221E 01
IR1	-2.10207E 03	-2.06538E 03	-2.02867E 03	-1.99195E 03
IR2	-2.10207E 03	-2.06538E 03	-2.02867E 03	-1.99195E 03
IC1	2.20083E 04	2.20185E 04	2.20279E 04	2.20364E 04

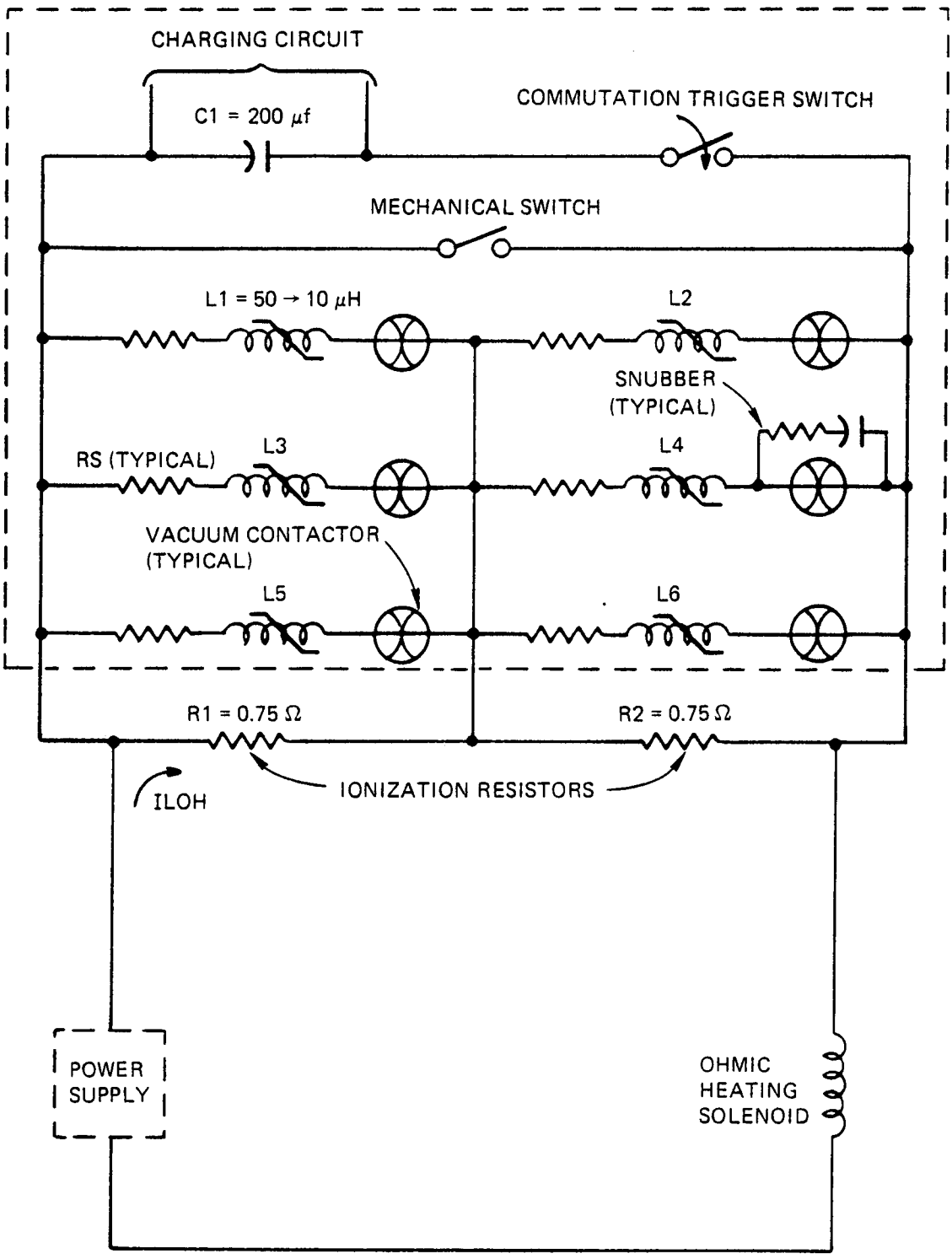


Figure 15. Ohmic heating circuit as proposed for ISX-C.

will result in near synchronous operation of the vacuum contactors. The saturable reactor will be a custom designed device that will require very close manufacturing tolerances to ensure six nearly identical units.

During the ohmic heating solenoid current buildup phase, a mechanical switch in parallel with the vacuum circuit breaker will carry the bulk of the current. Upon reaching the 20-kA level, this switch will open, forcing the 20 kA into the vacuum contactor circuits. The six resistors (RS) are on the order of a few milliohms. Their purpose is to ensure that the mechanical switch will carry the majority of the current during the buildup phase and to assist in forcing load sharing through the vaccum contactors when the mechanical switch is open. The commutation trigger switch, probably an ignition device, will close and discharge the commutation capacitor into the circuit as the six vacuum contactors are triggered to open. As the vacuum contactors are attempting to interrupt the current, the 20 kA being provided by the charged ohmic heating solenoid is actually momentarily diverted through the commutation capacitor. This results in the current being reduced to zero in the vacuum contactors and should remain zero if the RFIC and RRRV requirements for the particular vacuum contactor have been met. As the capacitor continues to discharge, the current flow is transferred into the two 0.75-Ω ionization resistors. This results in approximately 30 kV being imposed across the ohmic heating solenoid, which in turn ionizes the gases in the tokamak to form a plasma. The decay of the current through the ohmic heating solenoid drives a large current through the plasma, creating both heat and stability. The RC snubber

networks across each vacuum contactor will provide addition transient suppression by reducing the rate of rise of recovery voltage.

It should be noted that the circuits in this thesis were simulated many times with various component values and initial voltages on the commutation capacitor. The outputs shown here are examples of the most favorable results obtained in each case studied for this preliminary design.

V. CONCLUSIONS

From the design simulations shown here, it has been demonstrated that the proposed ISX-C ohmic heating circuit breaker theoretically satisfies the restrictions of the rate of fall of interrupting current, the rate of rise of recovery voltage, and the time required to obtain a current interruption. All the components required to construct this vacuum circuit breaker are within the realm of existing technology, although custom designing of some components would be necessary.

The SUPER*SCEPTRE computer program was shown to be a very useful tool in simulating proposed electrical designs. Since the initial studies for this thesis, the program has been utilized at ORNL to simulate several new designs as well as to analyze existing electrical systems.

LIST OF REFERENCES

LIST OF REFERENCES

1. Greenwood, A. N., and Lee, T. H., "Switching Equipment For Inductive Energy Storage Systems In Nuclear Fusion Research," proceedings of a symposium held at Austin, Texas, Nov. 20-22, 1972, pp. 309-321.

2. Bailey, J. M., Broverman, A. Y., Easter, R. B., Harris, J. M., Hill, R. E., Heck, F. M., and Wolf, J. E., "Ohmic Heating System For ORMAK Upgrade," proceedings of IEEE Southeastern Conference, Williamsburg, Va., April 4-6, 1977.

3. Anderson, J. M., and Carroll, J. J., "Applicability of a Vacuum Interrupter as the Basic Switch Element in HVDC Breakers," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, Sept/ Oct 1978, pp. 1893-1899.

4. Greenwood, A. N., and Lee, T. H., "Theory and Application of the Commutation Principle for HVDC Circuit Breakers," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-91, July/Aug 1972, pp. 1570-1574.

5. Greenwood, A. N., Barkan, P., and Kracht, W. C., "HVDC Vacuum Circuit Breakers," IEEE Transactions on Power Apparatus and Systems, Vol. PAS-91, July/Aug 1972, pp. 1575-1588.

6. Fairfax, S., Burke, W., Park, C., and Silva, F., "Development of High Current DC Circuit Breakers for the Alcator Program," Massachusetts Institute of Technology, Cambridge, Mass., unpublished.

7. Warren, R. W., "Experiments with Vacuum Interrupters Used for Large DC-Current Interruption," Los Alamos Scientific Laboratory informal report LA-6909-MS, October 1977.

8. Greenwood, A. N., Electrical Transients in Power Systems, (Wiley-Interscience, 1971), pp. 41-42, 125-151, 356-362.

9. Bowers, J. C., "Super-Sceptre User's Manual, A Program for the Analysis of Electrical, Mechanical, Digital, and Control Systems Revision 1," University of South Florida, May 1975, pp. 1-241.

10. Wolf, J. E., Voshall, R. E., and Frost, L. S., "Fusion Power Systems Technical Note — Preliminary Design of ORMAK Upgrade Ohmic Heating System Switch," Westinghouse Electric Corporation, WFPS-TN-019, August 1976, pp. 1-57.

11. Bailey, J. M., "The Status of Switching Apparatus Technology for Tokamak Operation," unpublished.

VITA

John Audley White was born in Crossville, Tennessee on March 22, 1951. He attended elementary and high school in Dublin, Georgia, and in Seymour, Tennessee, where he graduated from high school in May 1968. He enrolled at The University of Tennessee, Knoxville, in September 1968 and received a Bachelor of Science degree in electrical engineering in June 1974.

After graduation, he began working as an electrical engineer for the Nuclear Division of Union Carbide Corporation in Oak Ridge, Tennessee. In 1975, he began studies that would lead to his obtaining a Master of Science degree in electrical engineering in June, 1983.

He is married to Carolyn Marie (Upchurch) White formerly of Hazard, Kentucky.