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System Impedance and High Speed Transient Behavior
of the Alcator-C Magnet Power Supply System

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Abstract

The commutation inductance is one of the parameters which determines the voltage regulation, ac bus notch depth, inversion margin angle and converter conduction mode for the TF power supply. It was felt that measuring the actual commutation inductance would provide valuable information on this parameter and a chance to become familiar with the details of the Alcator power supplies. Although initial work indicated that the commutation inductance varied during an Alcator experimental run, the measurements reported here show the inductance to be almost constant. Its value is reasonably close to the predicted value used in the initial system studies.

While measuring the commutation inductance, two seemingly unrelated phenomena were observed; lightly damped ringing in the commutation notches and growing oscillations of the alternator voltage envelope. The commutation notch ringing does not present any serious problems but the oscillation of the voltage envelope suggested the possibility of a destructive overvoltage on the alternator at higher power levels. Further study of these two phenomena revealed that they are both the result of a resonance created by adding protection capacitors to the system. Theoretical models and simulations have been developed to explain the ringing and envelope oscillations. Two possible methods of damping the resonance (and thus eliminating the ringing and envelope oscillation) are proposed and the relative merits of each solution have been outlined.

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I Commutation Inductance Measurement

A. System Modelling

The schematic of a conventional 6-pulse converter is shown in figure 1. The commutation inductance is modelled by L1, L2 and L3. Normally, the converter is fed from a low impedance utility connection. In the Alcator system, the commutating inductance is higher than would normally be encountered in utility connected operation because of the contribution of the machine reactances.

When the converter is driving an inductive load with a time constant that is much longer than one ac cycle, the dc output current is

$$I_{dc} = \frac{V_{p11}}{2\omega L_c} [\cos(\alpha) - \cos(\alpha+\mu)] \quad (1)$$

where

V_{p11} is the peak line-to-line voltage

α is the firing angle

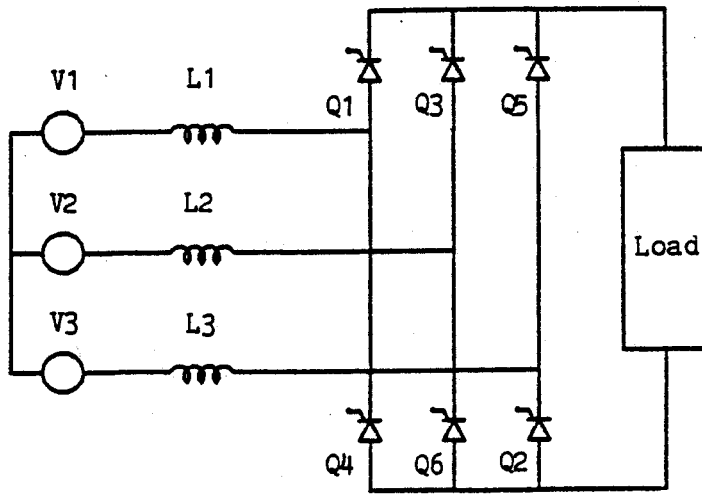
μ is the commutation overlap angle

L_c is the commutation inductance

Equation (1) can be rearranged to solve for L_c as a function of the peak line-to-line voltage, frequency, dc current, firing angle and commutation overlap angle.

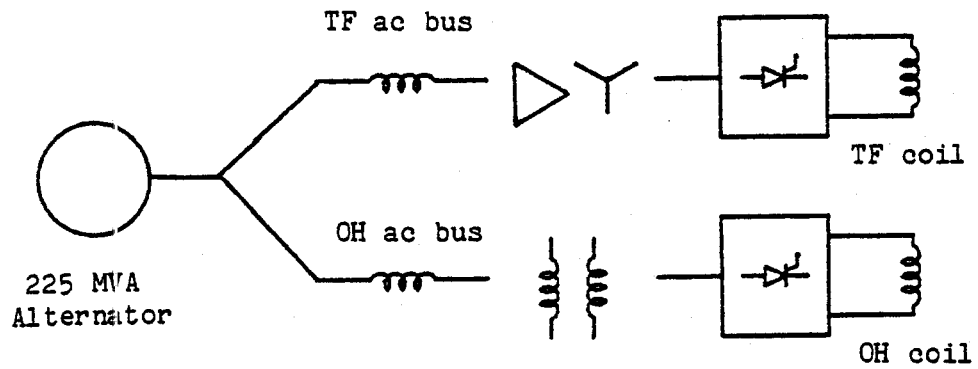
$$L_c = \frac{V_{p11}}{2\omega I_{dc}} [\cos(\alpha) - \cos(\alpha+\mu)] \quad (2)$$

Figure 2 is a one-line diagram for the part of the system under study. The alternator, ac bus and step-down transformer contribute to the commutation inductance.



6 Pulse Rectifier with Commutation Reactance

Figure 1



One-Line Diagram for the Alcator Power System

Figure 2

The delta-*W*ye connection of the step-down transformers requires that careful bookkeeping be done in order to analyze the system. The TF transformers are connected using the American standard for terminal markings. The high side line-to-neutral voltage leads the low side line-to-neutral voltage by 30 degrees, as illustrated in figure 3. The equations relating the voltages and currents on the primary and secondary sides of the transformer are

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \frac{R}{\sqrt{3}} M \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = \frac{-1}{\sqrt{3} R} M \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \frac{1}{\sqrt{3} R} M^T \begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \frac{R}{\sqrt{3}} M^T \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \quad (6)$$

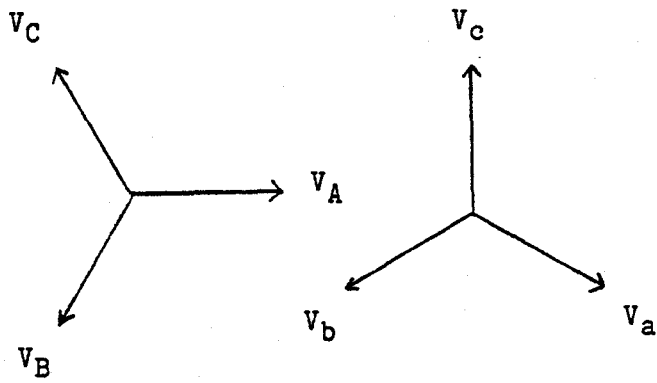
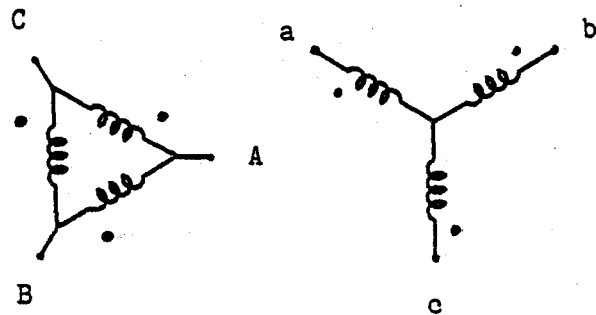
where

$$M = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \quad (7)$$

$$R = \frac{\text{High side line-to-line voltage}}{\text{Low side line-to-line voltage}} \quad (8)$$

These matrix equations imply that the line-to-neutral quantities on one side of the transformer are proportional to the line-to-line quantities on the other side. In order to simplify the analysis, a Thevenin equivalent of the alternator, ac bus and transformer can be constructed if certain approximations are made.

The alternator is a nonlinear time-varying system. It will be



Delta-Wye Transformer Phase Relations

Figure 3

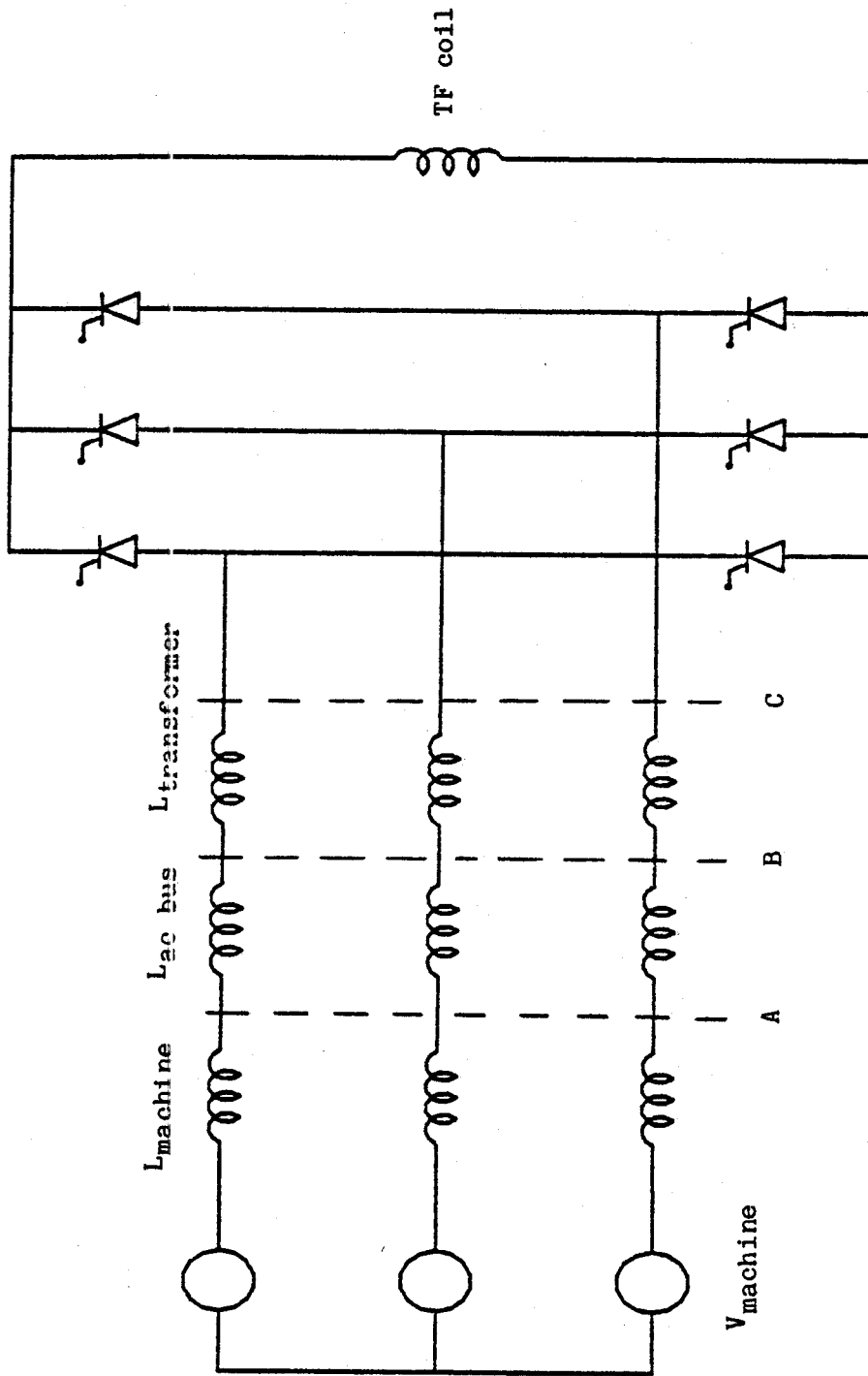
modelled by a three-phase voltage source behind a single reactance. This model is valid if the positive and negative-sequence reactances are equal for the time period of interest and no zero-sequence currents are present. The equality of the positive and negative-sequence reactances is equivalent to assuming that the flux associated with the very fast commutation transients does not penetrate the machine rotor.

The delta-wye transformer prevents zero-sequence currents from flowing anywhere in the system. Therefore, the zero-sequence networks are irrelevant in analyzing the system and the series reactances are assumed equal to the positive-sequence subtransient reactance.

The model for the system is shown in figure 4. The voltages and currents at point C in figure 4 are the voltages and currents at the secondary terminals of the transformer. The quantities calculated at points A and B are the alternator and transformer primary voltages and currents referred to the transformer secondary. These quantities can be converted to their actual values by using equations (3) and (4). For example, the actual alternator line-to-neutral voltages are equal to the line-to-line voltages calculated at point A of the model times a constant, $R/\sqrt{3}$.

B. Instrumentation for Commutation Inductance Measurements

Potential and current transformers were built into the system at the primary terminals of the step-down transformers for metering and diagnostic purposes. This is the most convenient place to measure the supply performance (point B in figure 4). The line-to-neutral voltage at this point should have 6 notches per cycle. Two of the notches will have a larger amplitude than the other four. The angle from the sine wave



Alcator Power System Model

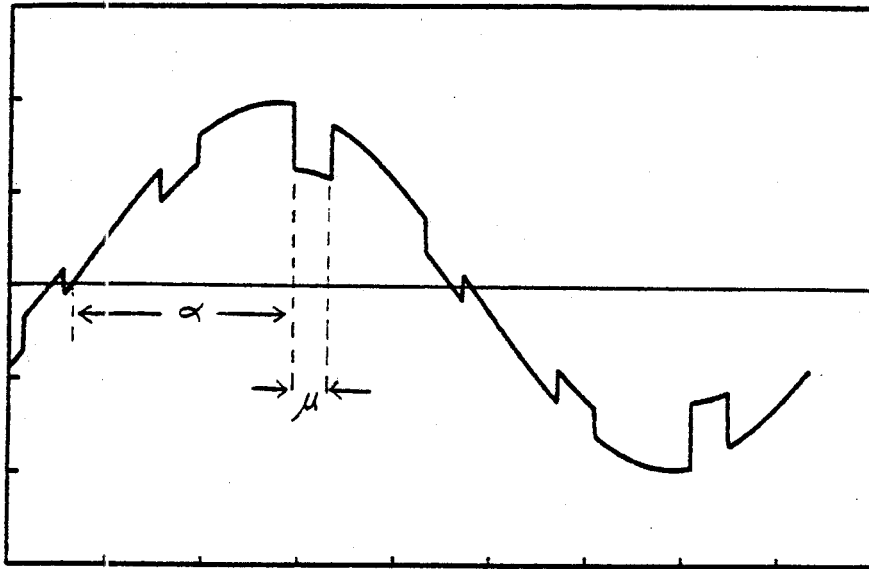
Figure 4

zero crossing; to the beginning of the larger notch is the converter firing angle, α . The angular duration of the notch is the commutation overlap angle, μ . Figure 5 illustrates how the firing and commutation overlap angles can be determined from the notch positions.

Another parameter needed to determine the commutation inductance is the peak line-to-line voltage. Except during the commutation period, all of the currents in the system can be approximated as dc due to the very long time constant of the toroidal field coil. Thus, there will be no voltage drop across the inductances and the machine voltage behind the reactances can be measured directly during non-commutation times. Calculations show that the resistance of the alternator and ac bus combined is 0.018 ohms. This resistance would produce a voltage drop of approximately 130 V, at 200 kA output, which is negligible compared the 13.8 kV system voltage.

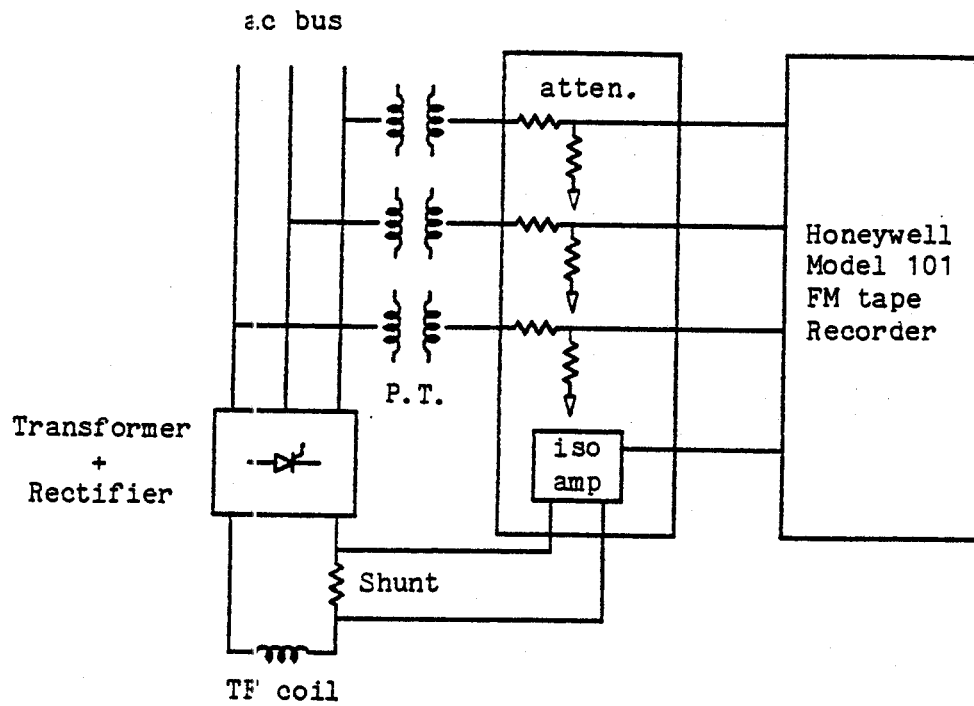
The actual instrumentation setup is shown in figure 6. All of the necessary signals were available in the Robicon control cabinet. A wye-connected resistive divider was used to reduce the potential transformer voltages to a level compatible with the FM tape recorder. The cables from the Alcator control room introduced a great deal of high frequency noise into the current measurement. Burr Brown model 506 isolation amplifiers set for a gain of 1 were necessary to isolate the instrumentation from the Alcator control room cabling and reduce the noise to an acceptable level. The Honeywell FM tape recorder allowed the transient measurements to be recorded at high speed and bandwidth (120 ips, 80 kHz) and expanded in time by a factor of 16 (7.5 ips) for later analysis.

Line-to-Neutral AC Bus Voltage



Firing Angle and Commutation Overlap Angle Measurement

Figure 5



Instrumentation for Measuring the Commutating Inductance

Figure 6

C. Experimental Results

Figure 7 shows a typical expanded voltage trace during the flat-top portion of the experiment. The top trace is the dc current. The measured commutation inductance of 3 consecutive experimental runs is plotted in figure 8. Figure 9 presents straight line fits to the data. The plots indicate that the commutation inductance of the alternator rises slightly during an experimental run. The specifications for the alternator show that the saturated and unsaturated negative-sequence reactances differ significantly. The slight rise in the commutation inductance of the machine might be due to the reduced saturation of the machine at the end of the experiment. The ringing during and after commutation make it difficult to determine the commutation overlap angle and peak line-to-line voltage, which causes the inductance to appear noisy.

A comparison of the average of the measured inductances to the the values derived from data sheets and calculations is presented in table 1.

	Specified Inductance	Average Measured Inductance	Difference
Alternator	0.293 mH		
ac bus	0.085 mH		
Total	0.378 mH	0.422 mH	-10.4%
Transformer	0.537 mH	0.553 mH	-2.9%

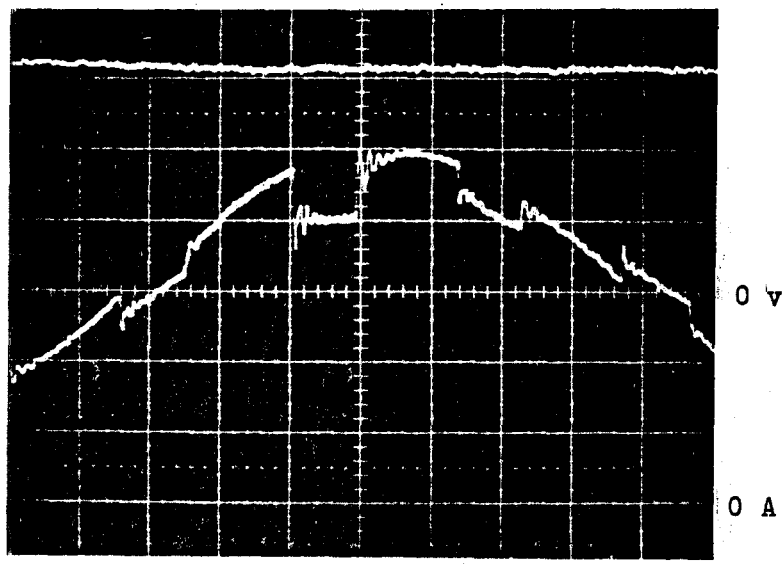
Comparison of measured and specified values
for the commutation inductance

Table 1

The average measured inductance was calculated by taking the

Line-to-Neutral Voltage (4.75 kV/div)

TF Current (22.6 kA/div)

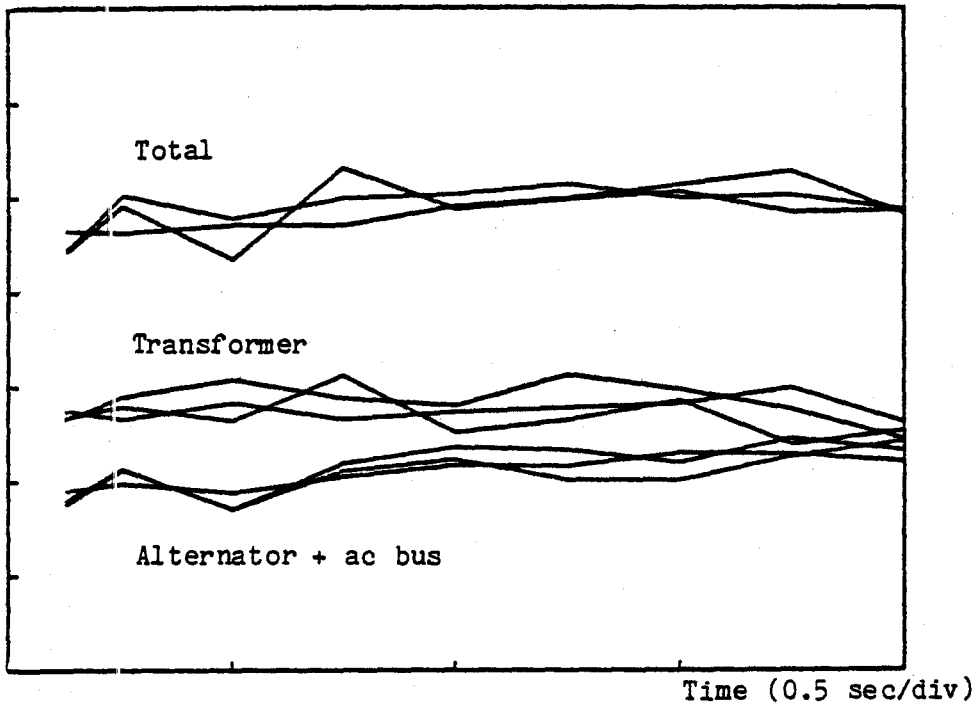


time (1.25 msec/div)

Expanded Voltage Trace from the Alcator System

Figure 7

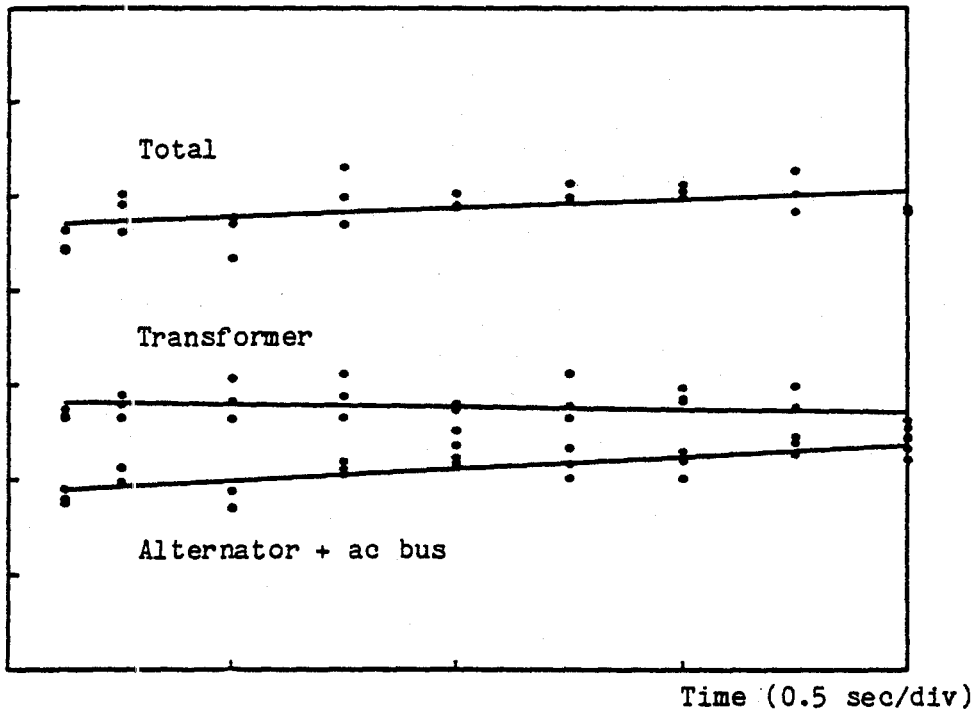
Commutating Inductance (0.2 mH/div)



Commutating Inductance of 3 Experimental Runs

Figure 8

Commutating Inductance (0.2 mH/div)



Least Squares Fit to the Commutation Inductance Data

Figure 9

average of all of the points that make up the curves in figure 8. The alternator inductance specification was taken from the specified value for the saturated negative-sequence reactance. The ac bus inductance was calculated from its physical dimensions. The agreement with the specified values is fair, if the saturated values of the alternator parameters are used.

D. Converter Firing Angle During Inversion

The firing angle during inversion has been chosen very conservatively. The maximum observed firing angle during inversion was approximately 98 degrees. Based on the commutation inductance measurements, if the dc current is 200 kA and the machine voltage decays to 70% of its original value, the commutation overlap angle would be 47.0 degrees. This would leave a margin angle of 35.0 degrees. The SCR specifications claim a reverse recovery time of 150 microseconds, which is equivalent to only 3.2 degrees at 60 Hz. Some added margin is certainly prudent, but there is ample room to increase the firing angle. The amount of inversion time saved by increasing the inversion firing angle depends strongly on the inductance and resistance of the TF coil. The data taken to date indicates that the the coil resistance is above the generally accepted value of 1.5 mohms and the inductance is well below the 4.5 mH value often quoted. The data indicate 2.0 mohms and 3.2 mH for the coil. Using these numbers, even a modest increase in the firing angle from 98 to 108 degrees would decrease the inversion time for a 140 kA pulse from 1.6 sec to 1.1 sec.

More study will have to be done to determine accurate values for the TF coil resistance and inductance.

II Commutation Induced Transients

A. Commutation Notch Waveform

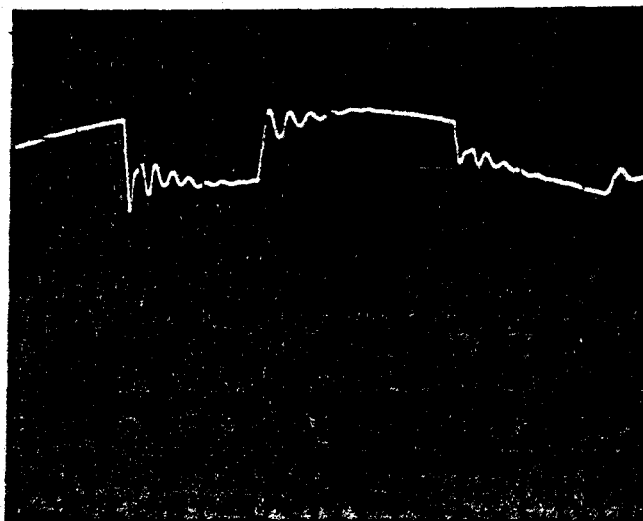
The ringing on the voltage waveform during and after commutation makes the measurement of the commutation overlap angle difficult if the angle is small. An experiment was performed to determine if the ringing was actually in the power system or if it was caused by instrumentation problems. A 40 kV oscilloscope probe was connected directly to the high side of one of the potential transformers. The probe was calibrated, using a low voltage squarewave source, to have a risetime under 30 nanoseconds with no overshoot or ringing.

Figure 10 shows a single commutation notch measured with the high voltage probe. The ringing is still present, indicating that there is a resonance in the power system. On closer inspection, it can be seen that during commutation the ring frequency is 7.67 kHz. When the commutation is complete, the ring frequency drops to 6.19 kHz.

Inspection of the power supplies revealed that each of the four TF transformer cabinets contains 0.25 μ F surge capacitors connected from each phase to ground. These capacitors were originally installed to suppress line transients and to create a path for the transformer current in the event of an energized disconnect.

The ac bus cable was measured to have 94 pF of capacitance per foot per conductor. The capacitance was measured from the conductor to the shield which is normally grounded. There are a total of 6 conductors per phase with a run of 500 feet, giving a cable capacitance of 0.28 μ F and a total capacitance of 1.28 μ F from line-to-ground.

Line-to-Neutral Voltage (4.0 kV/div)



time (1.0 msec/div)

Commutation Notch Measured with the Calibrated High Voltage Probe

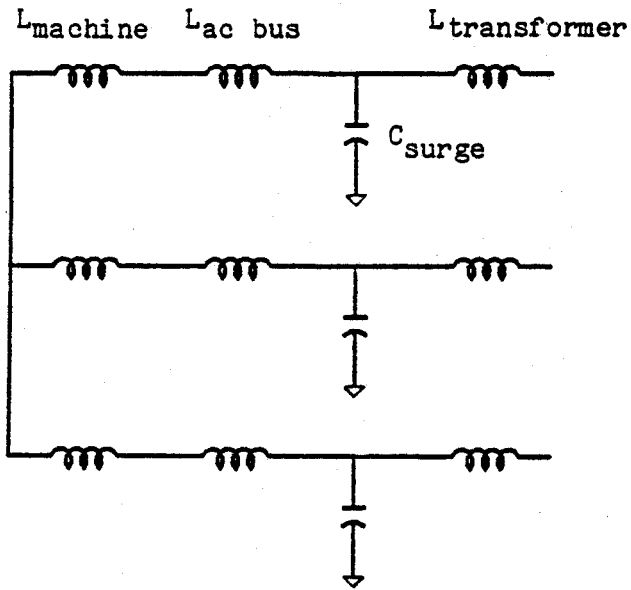
Figure 10

The two different ring frequencies can be partially explained by an incremental analysis of the system during and after commutation. When commutation is complete, all of the currents in the system are essentially dc. The very long time constant of the TF coil allows it to be replaced by an open circuit at the frequencies of interest. The incremental circuit after commutation is given in figure 11. This simple network has 3 identical natural frequencies. Using the measured values of the inductance and capacitance gives a calculated natural frequency of 6.85 kHz. This is 10.5% away from the observed ring frequency of 6.19 kHz.

During commutation, the incremental circuit is very different as shown in figure 12. The ideal transformer is necessary to model the effects of the line-to-line short-circuit on the low side of the delta-wye transformer. The natural frequencies of this network are 9.09 kHz and 6.85 kHz. Neither of these frequencies match the observed ring frequency very closely for reasons that will be explained later.

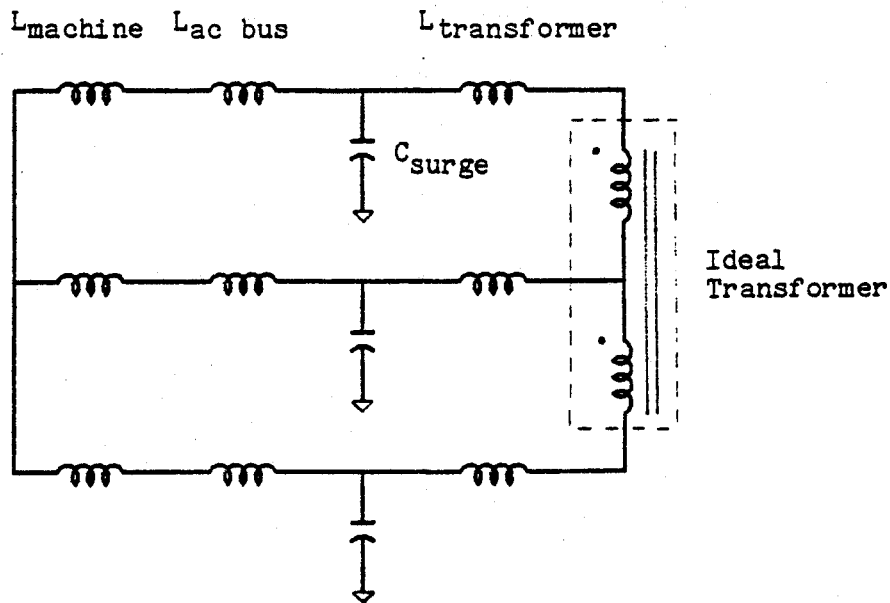
B. Frequency Response Measurements

Further investigation into the nature and origin of the system resonances causing the commutation induced ringing was undertaken. A plot of the line-to-line impedance of the system versus frequency was made to allow comparison of inductance and capacitance values with previous measurements. The impedance was determined from the magnitude and relative phases of a voltage and current that were injected into the system line-to-line. The alternator was connected to the system but it was rotating at only 2 rpm on its turning gear. The instrumentation setup is shown in figure 13.



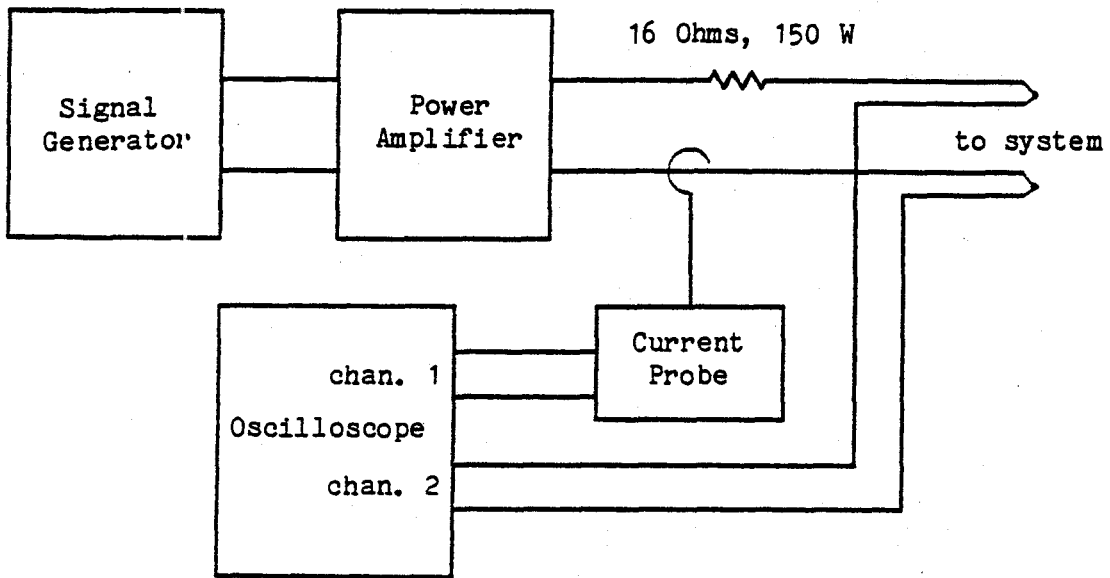
Incremental Circuit after Commutation

Figure 11



Incremental Circuit During Commutation

Figure 12



Instrumentation for Measuring the Line-to-Line Impedance

Figure 13

The first set of data was taken with both the TF and OH1 supplies online. Figure 14 is a plot of the measured magnitude and phase of the impedance. There is a sharp peak (parallel resonance) at 6.19 kHz. and a notch (series resonance) at 9.52 kHz. The parallel resonance occurs at a frequency that matches the ring frequency after commutation.

In order to simulate the conditions during commutation, two of the low side transformer phases were short circuited and the measurement was repeated. The frequency of the parallel resonance increased to 7.58 kHz. The series resonance moved up very slightly to 9.67 kHz.(see figure 15). Again, the parallel resonant frequency is very close to the observed ring frequency after commutation.

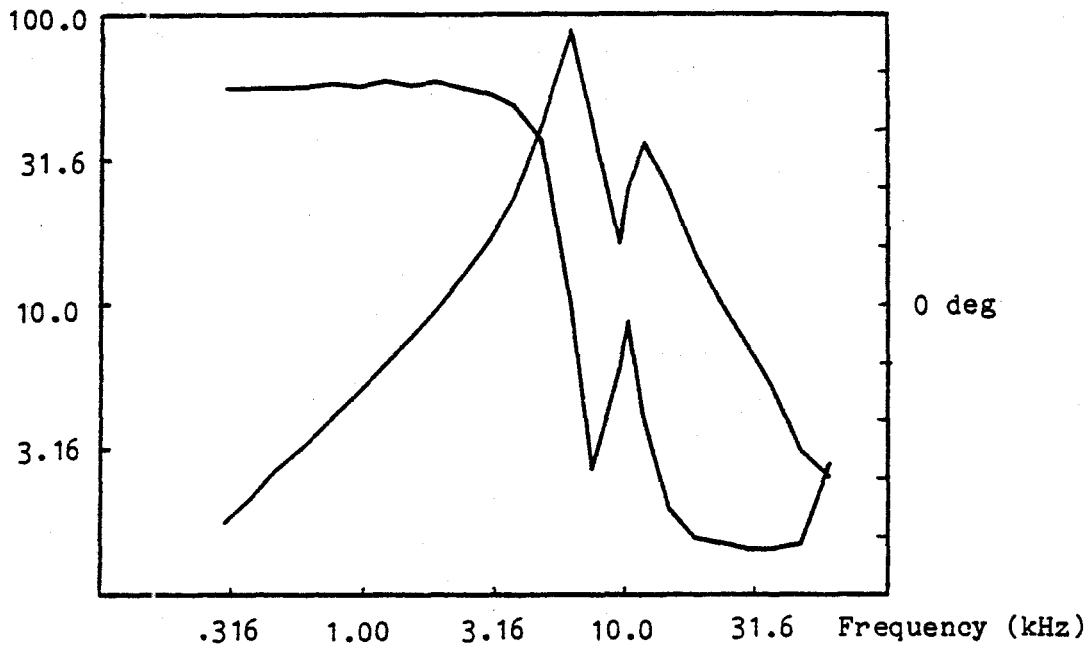
The series resonance was only slightly affected by shorting the low voltage phases of the TF supply transformer, which indicates that the resonance is either in the OH1 supply or the alternator. The data were taken again with OH1 disconnected, this time the series resonance was missing as shown in figure 16 and the parallel resonance moved up to 9.52 kHz. This parallel resonance corresponds to the higher natural frequency calculated earlier using the model in figure 12. This is not an observed ring frequency because it is masked by the series resonance in OH1.

C. Resonant System Model

Inspection of the OH1 schematics and switchgear revealed that air-core current limiting reactors followed by surge capacitors to ground were installed for system protection. The reactors were measured to be 0.831 mH and the capacitors were 0.266 uF. The effective ac bus inductance between the impedance measurement point and the reactors is 0.151

Impedance (ohms)

Phase (20 deg/div)

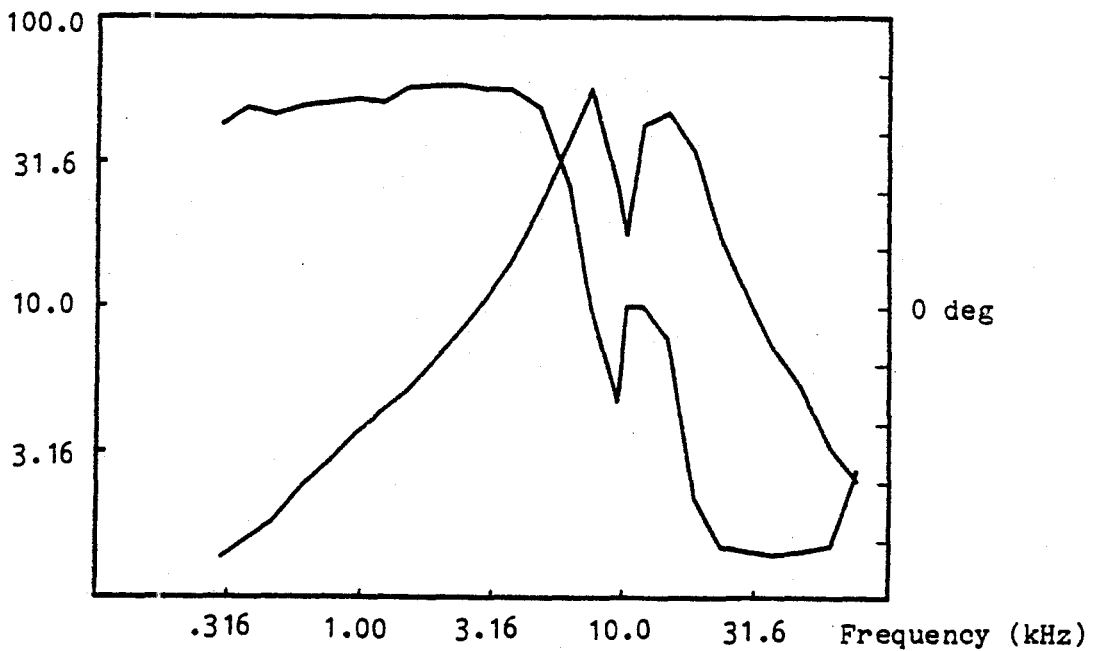


Impedance Measured with the Transformer Secondary Open-Circuited

Figure 14

Impedance (ohms)

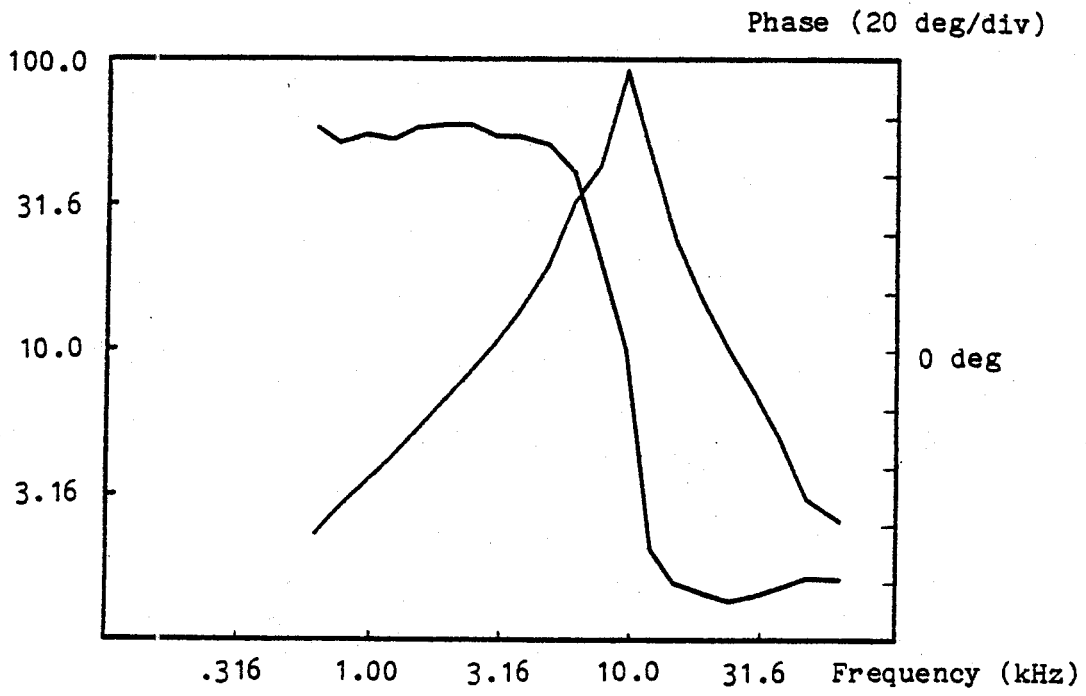
Phase (20 deg/div)



Impedance Measured with a Line-to-line
Short-Circuit on the Secondary

Figure 15

Impedance (ohms)



Impedance Measured with OH1 Removed

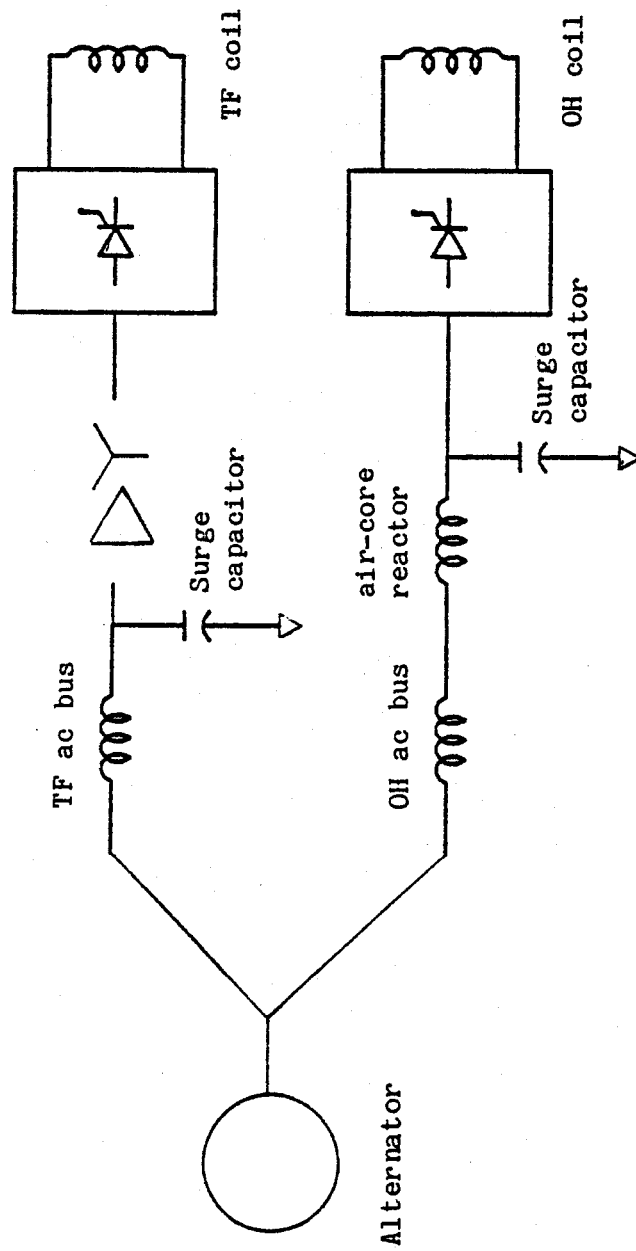
Figure 16

mH. These values lead to a calculated series tuned resonance of 9.85 kHz, which compares favorably to the observed value of 9.62 kHz. A one-line diagram of the resonant system is given in figure 17.

The impedance of the system cannot be totally attributed to lumped element models. In all of the measurements, the slope of the magnitude vs. frequency plot on log/log coordinates is less than 0.91 from 300 Hz to 1.5 kHz. This slope should be 1.0 except in the vicinity of a pole. The phase also hovers around +70 degrees where it should be very close to +90 degrees. These effects indicate that some frequency dependent phenomena are taking place in the system, possibly due to skin effect or core lamination losses.

D. Comparison of Time and Frequency Domain Measured Inductances

In order to compare the inductances from the frequency response measurements with the values derived from the commutation notch widths, the loss mechanism must be classified as either parallel, series or a combination of the two. Series resistor-inductor and parallel resistor-inductor models will be considered. Table 2 presents a comparison of the frequency domain and time domain inductance referred to the point where the frequency response measurements were made.



One-Line Diagram of the Resonant System

Figure 17

Condition	Frequency Domain		Time Domain
	Series Model	Parallel Model	
Transformer secondary short-circuited	0.552 mH	0.594 mH	0.570 mH
Transformer secondary open	0.841 mH	0.898 mH	0.844 mH

Comparison of Frequency and Time Domain
Inductance Measurements

Table 2

The agreement between the time and frequency domain measurements is good considering the very different conditions under which they were made. The time domain measurements were made under actual operating conditions and the frequency domain measurements were made at very low voltages and currents with the machine practically at a standstill. This demonstrates that the flux associated with commutation does not depend strongly on the rotor speed or machine voltage.

III Alternator Voltage Envelope Dynamics

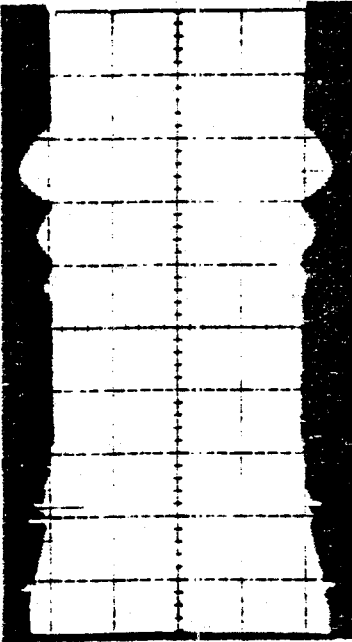
A. Voltage Envelope Oscillations

The top trace in figure 18 shows what appear to be 3 cycles of a growing oscillation on the alternator voltage envelope. These oscillations have been noticed in a number of studies using a variety of instrumentation. If one cycle of the oscillation is expanded, it can be seen that very short commutation spikes which grow and decay in amplitude are responsible for the effect (bottom trace in figure 18).

The growth and decay of the spikes can be explained using a voltage source to approximate the short-circuiting of the transformer phases during commutation as shown in figure 19. It is very important that the capacitors causing the parallel-tuned resonance be included in the model. The effect of the OH1 series-tuned resonance will initially be ignored. The voltage source should have a pulse shape that starts at the pre-commutation voltage, goes to zero for the commutation overlap period, and then returns to the pre-commutation level. Since the system is linear and time invariant, the response can be calculated by decomposing the input into two steps and adding the responses. The width of the input pulse compared to the ring frequency is very important in determining if the two responses add constructively or destructively as shown in figure 20.

During the TF coil ramp down period, the commutation pulse width is continuously decreasing until it reaches zero. The decay of the step responses causes the reinforcement to be larger for narrow pulses than wide ones. This explains why the voltage envelope oscillations grow as the current and commutation notch width decrease.

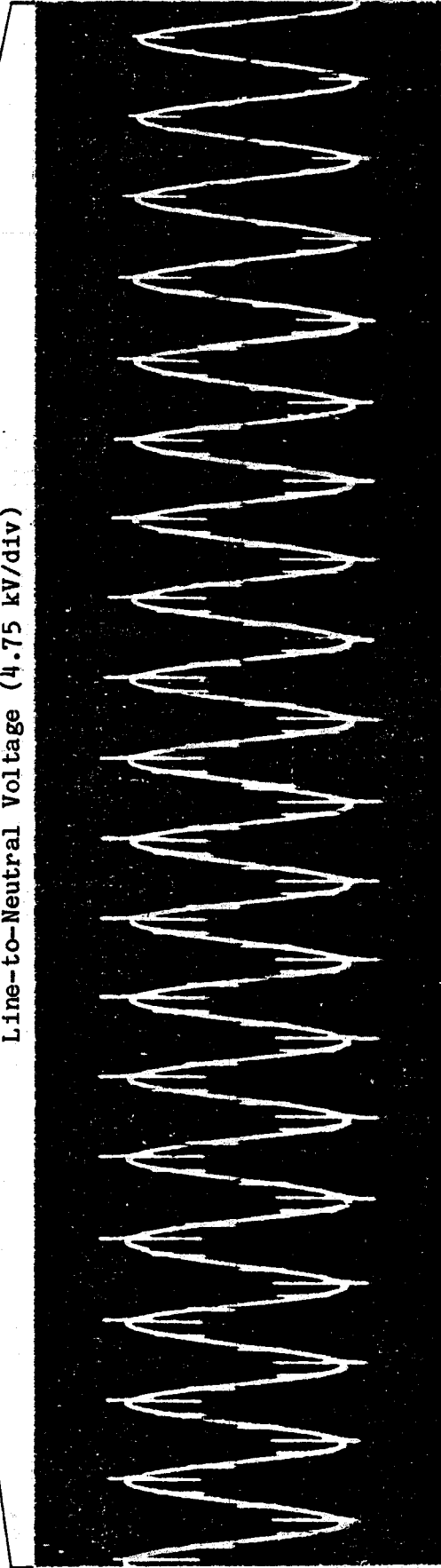
Line-to-Neutral Voltage (4.75 kV/div)



(a) Alternator Voltage Envelope

time (0.312 sec/div)

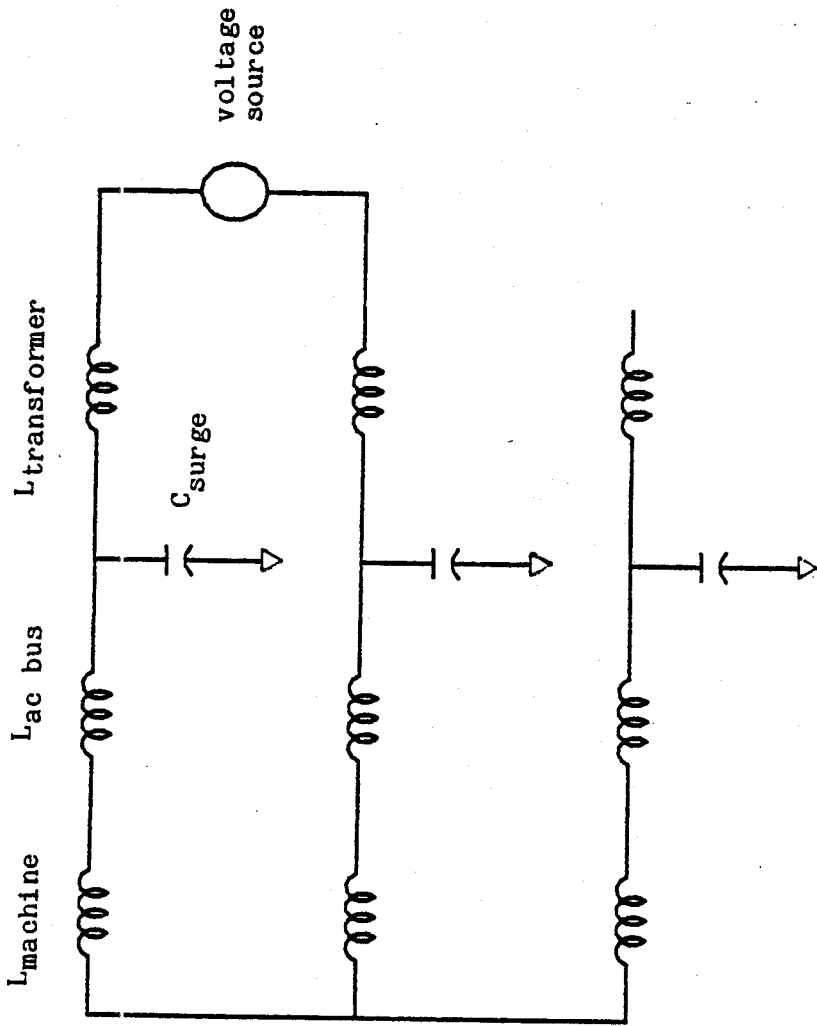
Line-to-Neutral Voltage (4.75 kV/div)



(b) Expanded Section of Voltage Trace

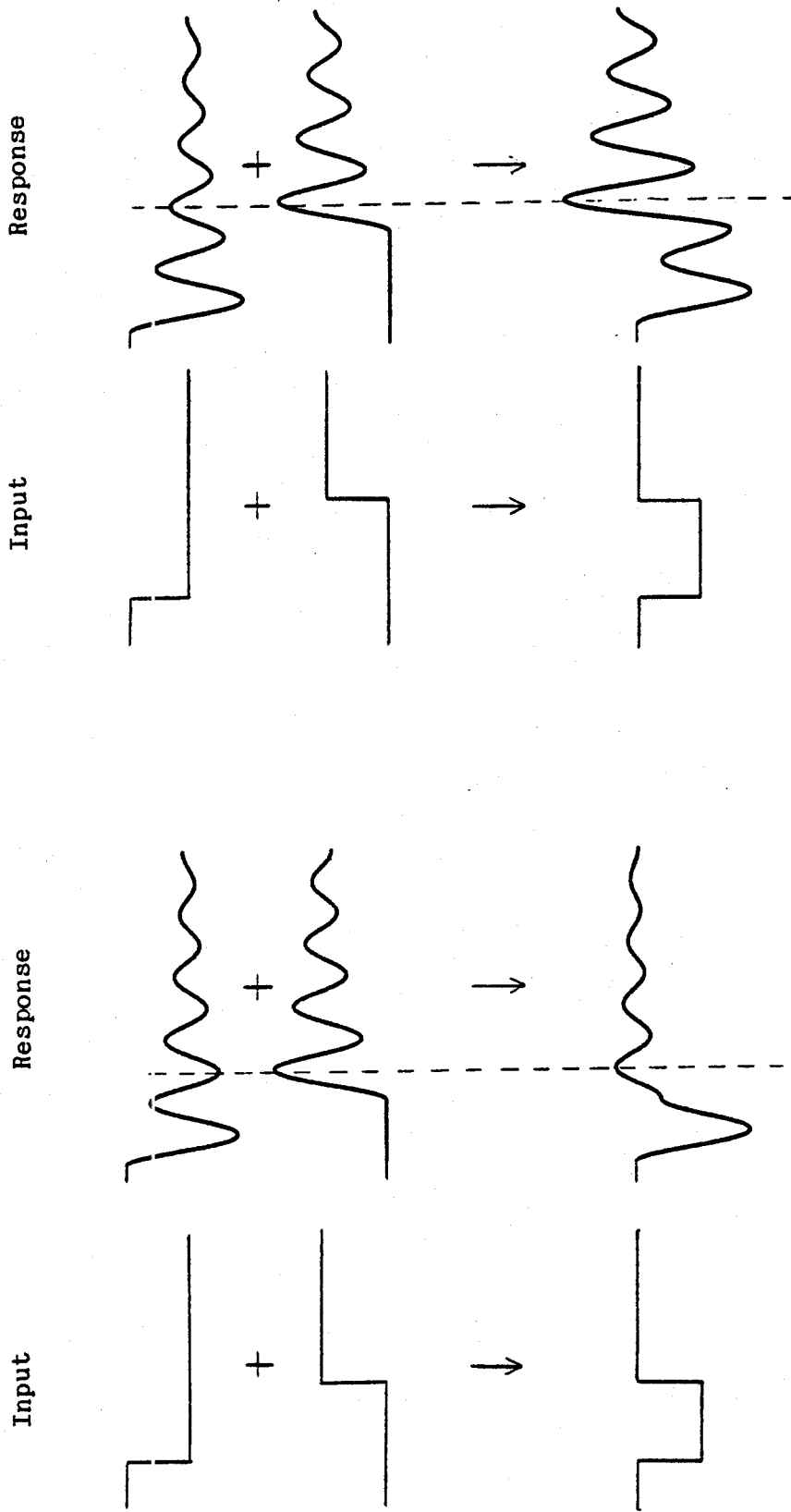
time (12.5 msec/div)

Figure 18



Circuit to Approximate Commutation Spike Oscillation

Figure 19



Destructive and Constructive Pulse Addition

Figure 20

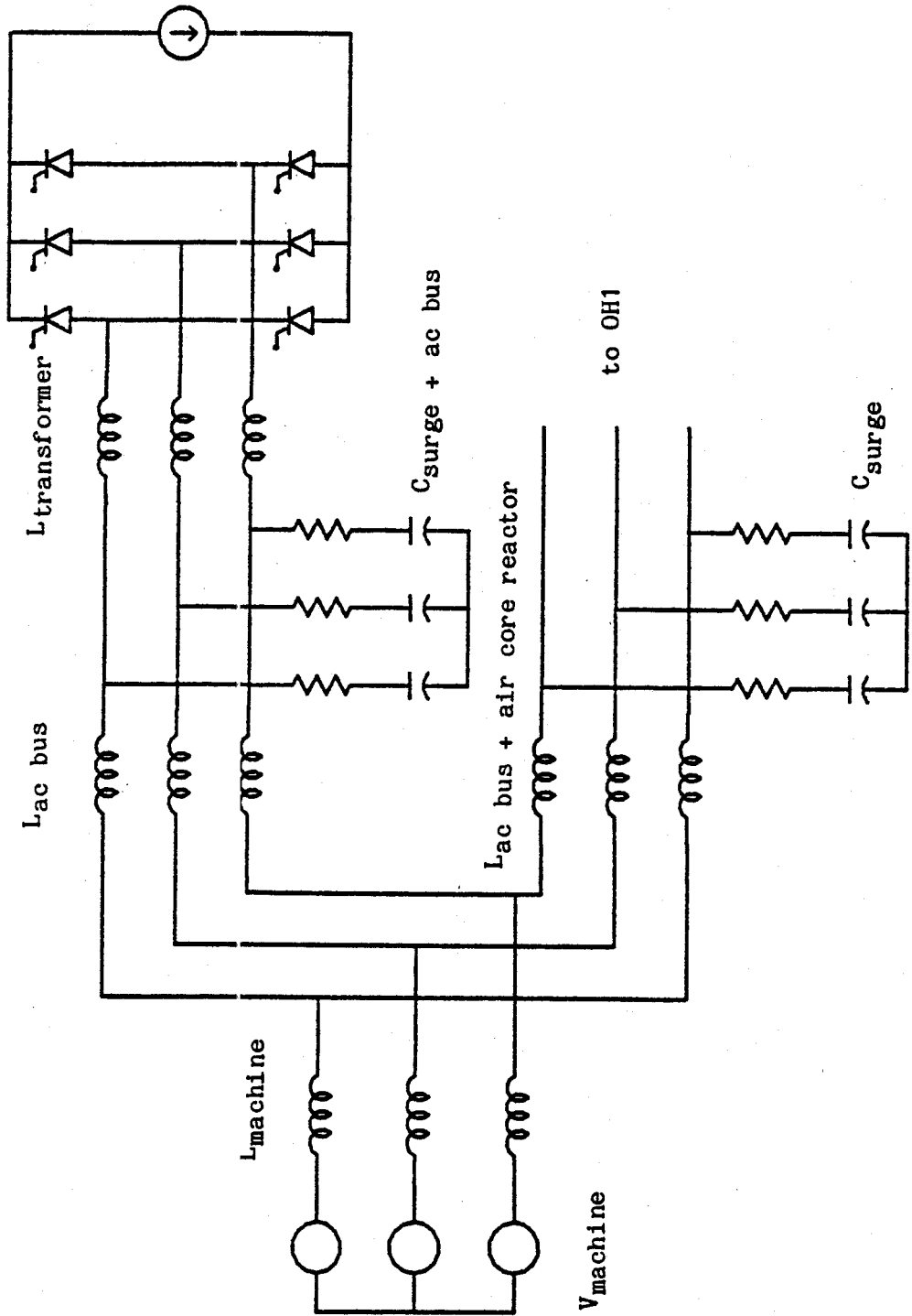
B. Simulation Studies

The voltage source in figure 19 does not provide an exact model for an SCR because it does not model a perfect open-circuit during the post-commutation ringing. This, in turn, does not provide for different ringing frequencies during and after commutation. A more realistic model is possible using the Parity Simulator. The circuit used to simulate the system is given in figure 21. The line-to-line voltage at point A should have the same waveshape as the line-to-neutral voltage on the primary side of the transformer. An expanded view of a commutation notch is shown in figure 22. The ring frequency during commutation is 6.14 kHz and after commutation it is 7.67 kHz, both frequencies agree well with the observed values on the real system.

Figure 23 is a parity simulator plot of the maximum of the line-to-neutral voltage as a function of the dc output current. The plot exhibits the same behavior as predicted using the linear time-invariant model. The largest swing takes place at the lowest current and the oscillations become smaller as the current is increased.

C. Resonance Damping Networks

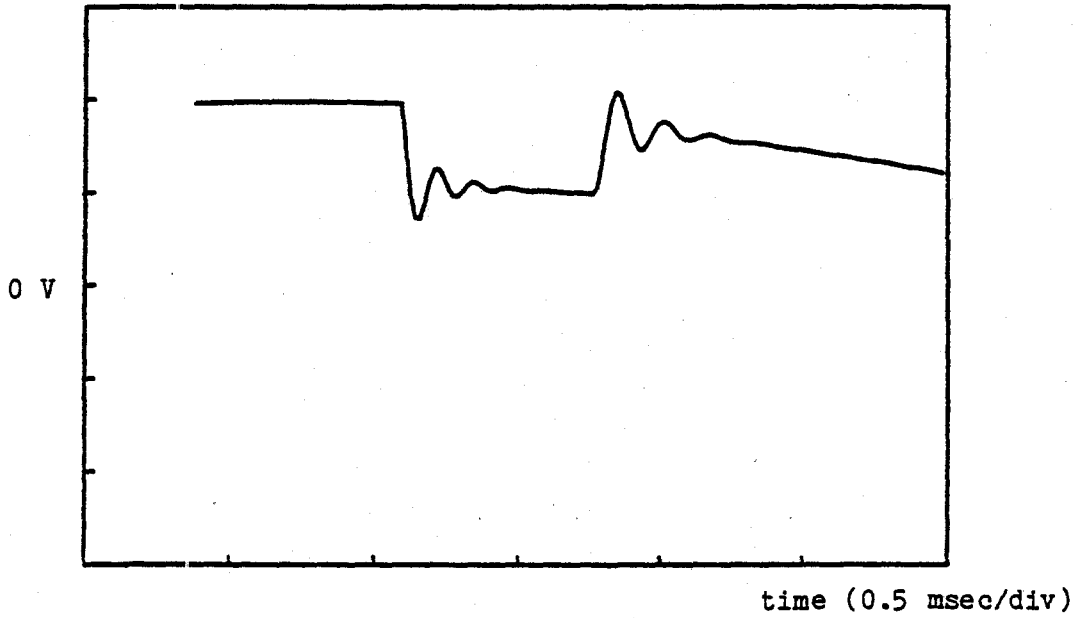
The oscillations in the voltage envelope have not been a serious problem up to this point because the alternator voltage decays so much that the oscillations do not exceed the initial machine voltage. The problem will not get worse at higher power levels, in fact, the problem is worst at low power levels which do not cause much decay in the alternator voltage. The most serious over-voltages are probably caused by the very short TF magnet test pulses done at the beginning of each



Parity Simulator Model for the Resonant System

Figure 21

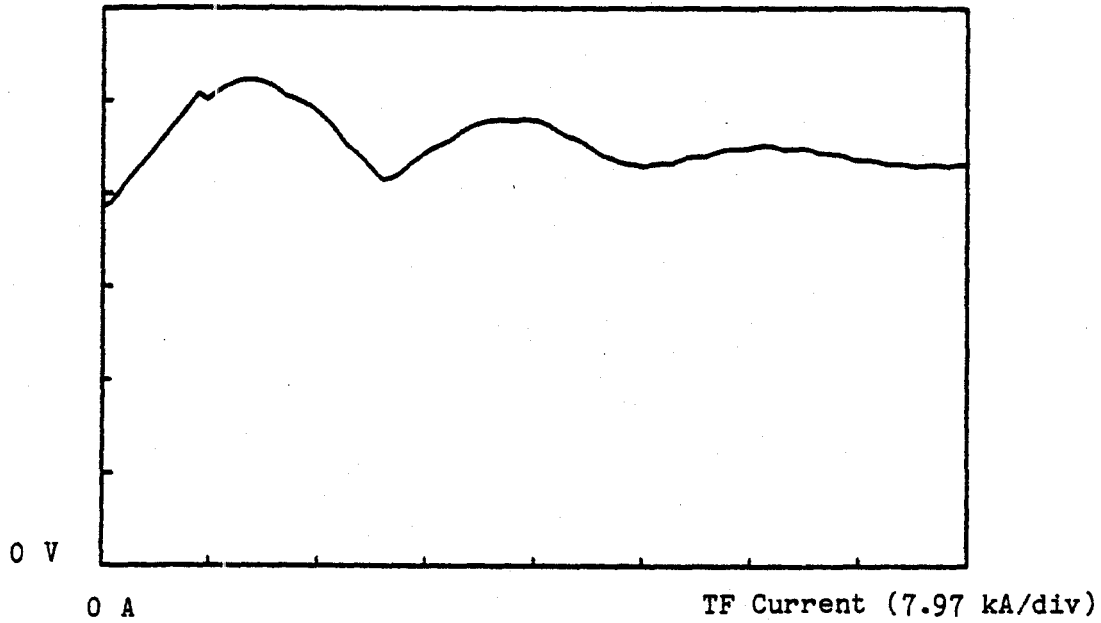
Line-to-Neutral Voltage (5.77 kV/div)



Expanded View of a Commutation Notch on the Parity Simulator

Figure 22

Peak Line-to-Neutral Voltage (2.89 kV/div)



Voltage Envelope on the Parity Simulator
for Increasing Load Current

Figure 23

run.

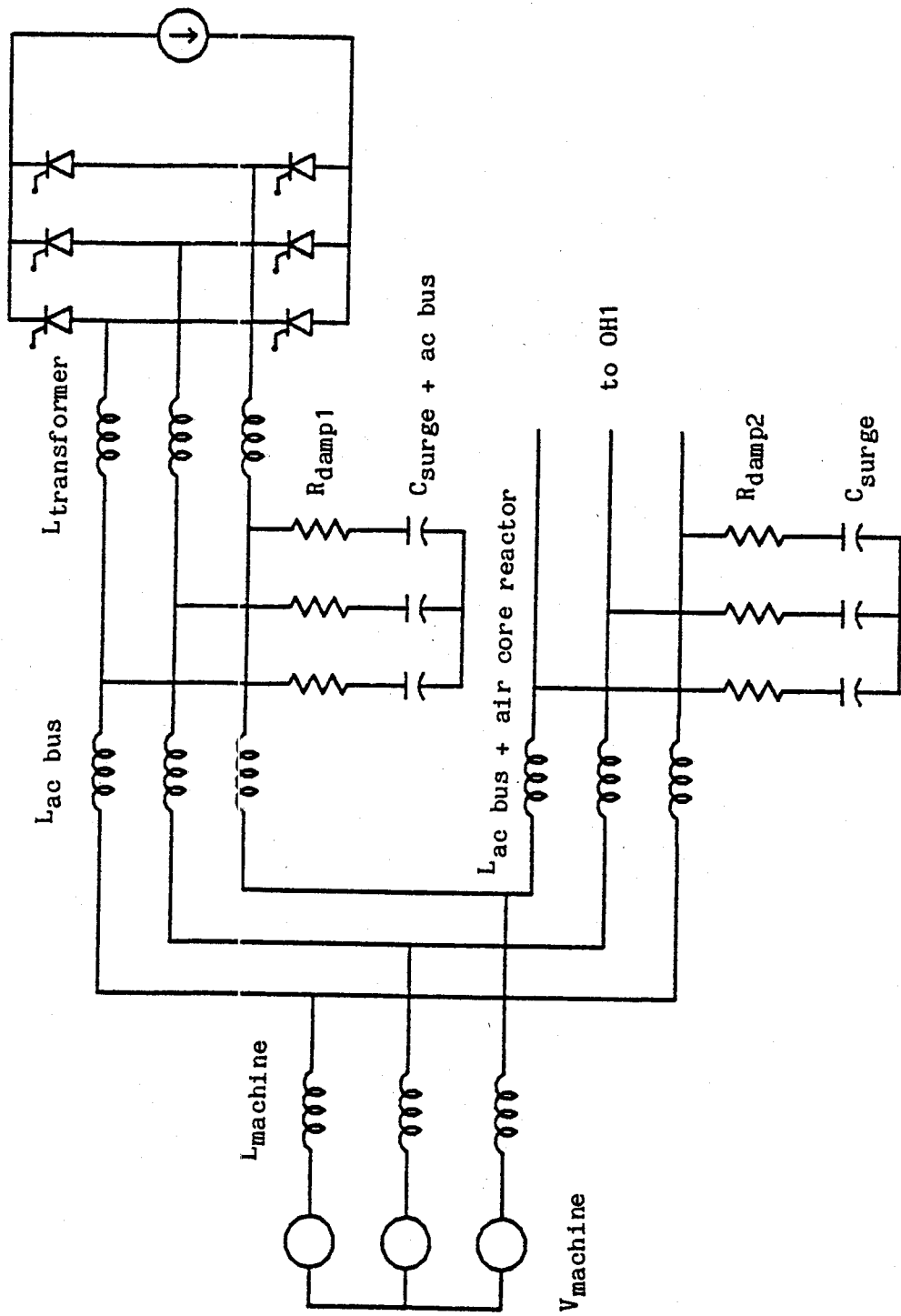
The largest voltage excursion that has been observed is approximately 25% above the normal sinusoidal peak voltage. This would represent a serious overvoltage on the system if methods for eliminating the alternator voltage droop are implemented.

There are 2 ways to damp the resonant circuit; by adding series resistance or by adding parallel resistance.

The best place to add series damping resistors is in the leads to the surge capacitors. This produces the smallest 60 Hz power loss. To damp the resonances in the TF and OH1 supplies, resistors will have to be installed in both. The resistor locations are shown in figure 24. Figure 25 shows a commutation notch with the damping resistors installed. The resistor values and power dissipation were determined on the Parity Simulator. Two values are given for the power dissipation, the continuous rating is the power dissipated during the intervals before and after the experiment when the ac bus is fully energized. The peak power is the power dissipated during the experiment.

A parallel damper resistor network could be connected to the system at a single point. A simple resistor in parallel with the supply would draw a great deal of 60 Hz power. The 60 Hz power can be greatly reduced by capacitively coupling the damper to the power system and choosing the time constant so that the damper is essentially resistive over the frequencies where the ringing occurs. Figure 26 shows the connection of the parallel damper to the system. Figure 27 gives a comparison for 3 different values of the parallel damping components and the results obtained.

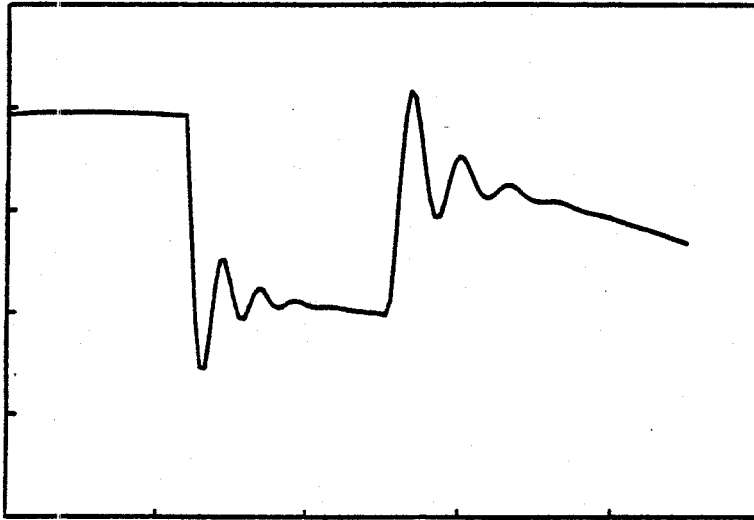
The choice between a parallel damper network or series damping



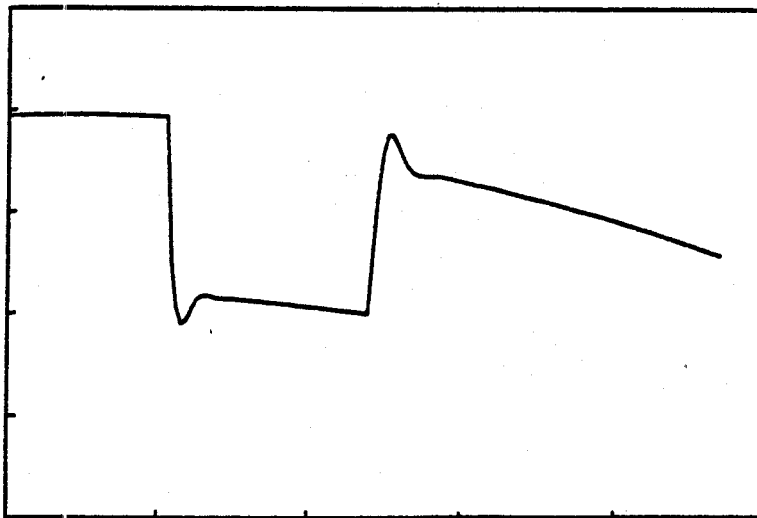
Location of Added Series Damping Resistors

Figure 24

Line-to-Neutral Voltage (2.89 kV/div)



Undamped Response



Damped Response time (0.5 msec/div)

$$R_{\text{damp1}} = 25 \text{ ohms}$$

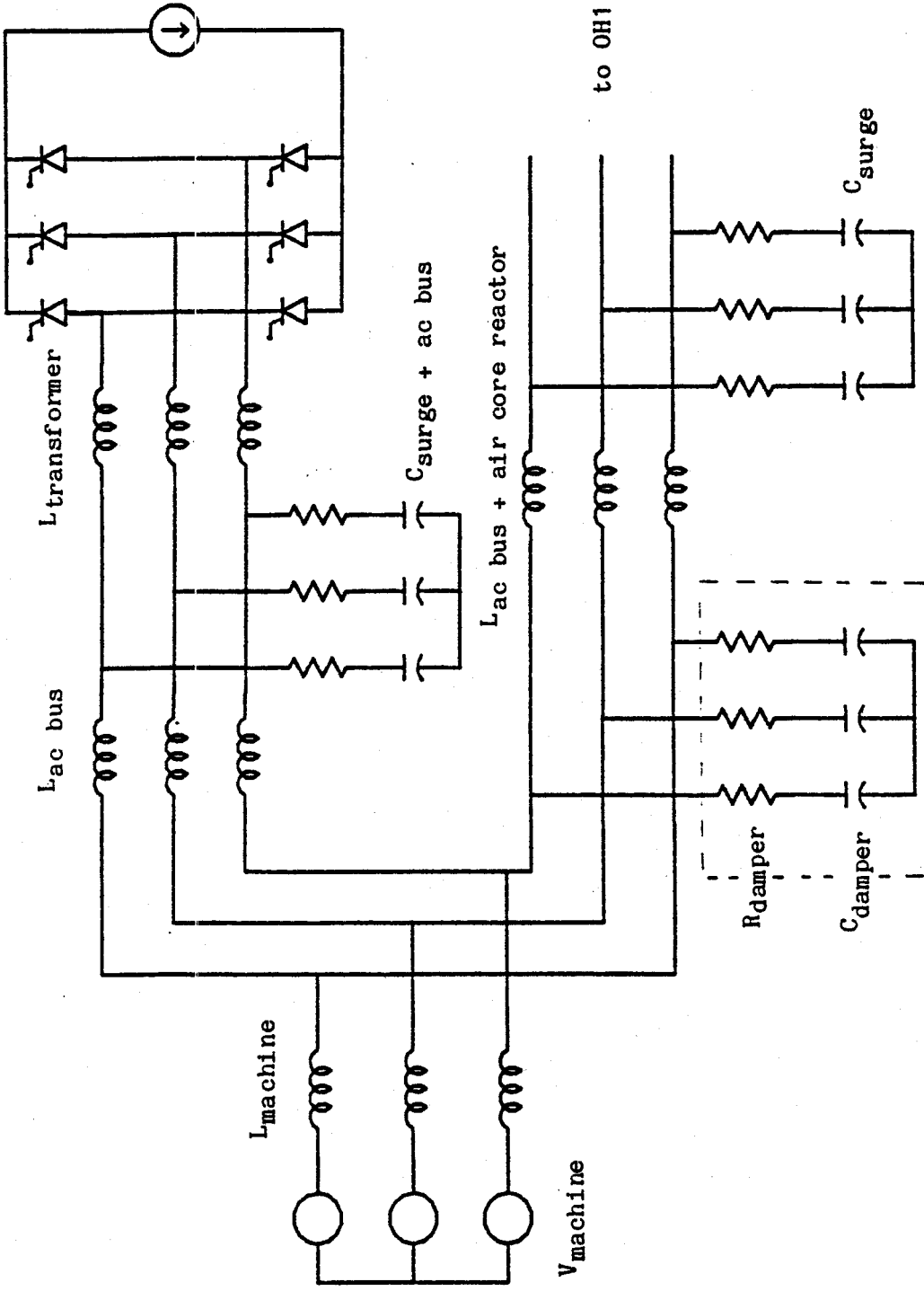
$$R_{\text{damp2}} = 27 \text{ ohms}$$

$$P_{\text{damp1}} = 225 \text{ W continuous, } 616 \text{ W peak}$$

$$P_{\text{damp2}} = 17.2 \text{ W continuous, } 477 \text{ W peak}$$

Commutation Notch with Series Damping Resistors Added.

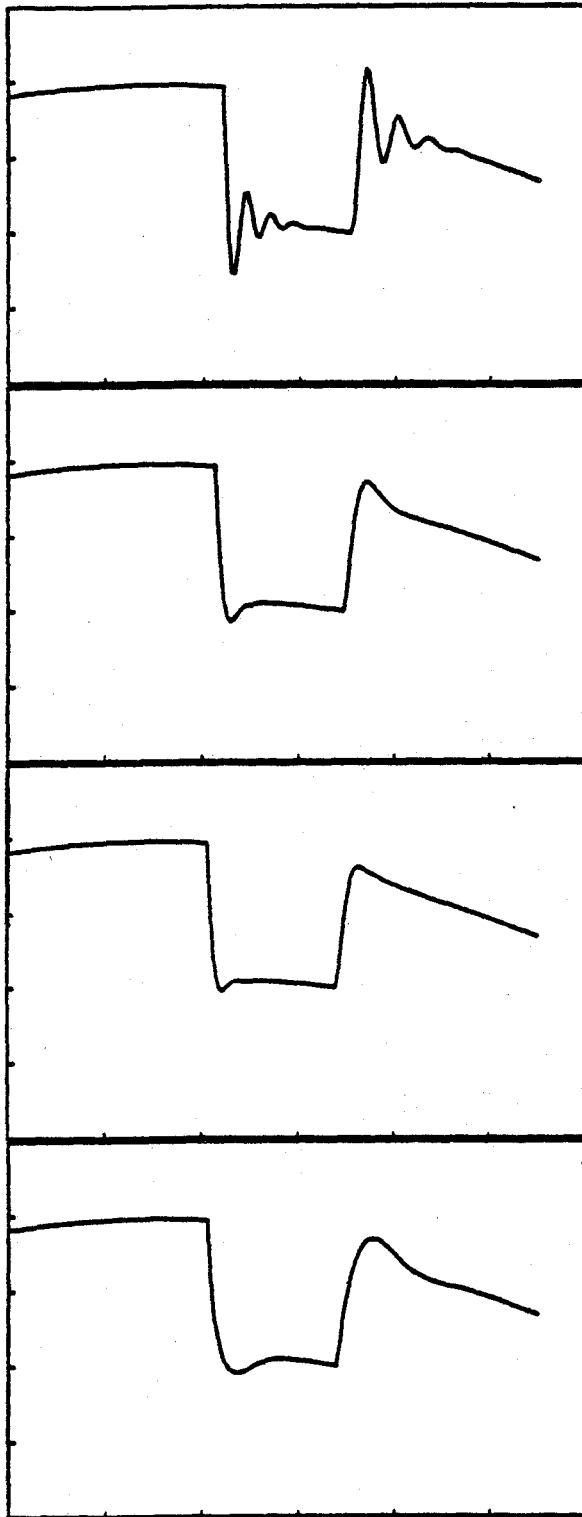
Figure 25



Parity Simulator Model with the Parallel Damper Connected

Figure 26

Line-to-Neutral Voltage (2.89 kV/div)



Undamped

$$R_{\text{damper}} = 10 \text{ ohms}$$

$$C_{\text{damper}} = 10 \text{ uF}$$

$$P_{\text{continuous}} = 9.0 \text{ kW}$$

$$P_{\text{peak}} = 35.4 \text{ kW}$$

$$R_{\text{damper}} = 10 \text{ ohms}$$

$$C_{\text{damper}} = 20 \text{ uF}$$

$$P_{\text{continuous}} = 35.9 \text{ kW}$$

$$P_{\text{peak}} = 80.7 \text{ kW}$$

$$R_{\text{damper}} = 5 \text{ ohms}$$

$$C_{\text{damper}} = 20 \text{ uF}$$

$$P_{\text{continuous}} = 18.2 \text{ kW}$$

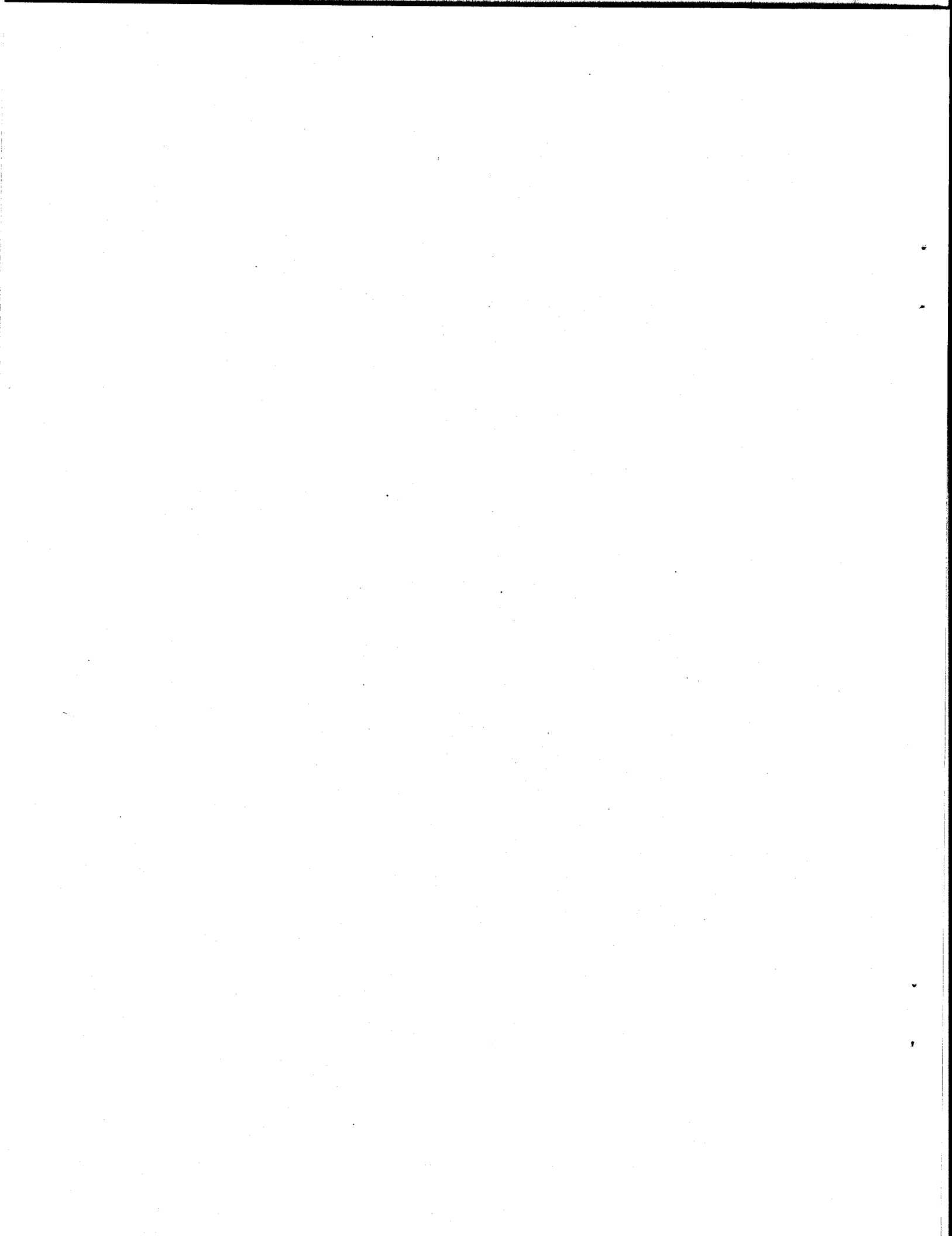
$$P_{\text{peak}} = 66.5 \text{ kW}$$

time (0.5 msec/div)

Comparison of 3 Parallel Damper Designs

Figure 27

resistors depends on electrical and mechanical factors. The addition of series resistors to the surge capacitors will seriously affect their ability to absorb very fast high current surges. Also, the series damping resistors must be installed inside the TF transformer cabinets and the OH1 switchgear, while the location of the parallel damper is flexible. The limited space available inside these enclosures makes the parallel damper attractive despite its much higher power dissipation.



IV Conclusions

The commutating inductance for the Alcator TF power supply has been measured to be 0.975 mH. This inductance can be broken down into two contributions; 0.422 mH from the alternator and ac bus and 0.537 mH from the step-down transformers. These values do not change significantly over the time interval of the experiment and agree fairly well with the values predicted in the initial system studies. Time and frequency-domain methods produced results that were remarkably close considering the different conditions used in making the measurements. The commutating inductance did not depend strongly on the machine saturation level.

The margin angle during inversion is large, leaving room for a significant reduction of the inversion time by increasing the firing angle. In order to accurately predict the possible reduction of the inversion time, more study is needed to determine the inductance and resistance of the TF coil.

Several experiments revealed that the power system contains 2 distinct resonances. Surge capacitors in both the TF and OH1 supplies resonate with the inductance of the system. The resonances are lightly damped and produce two noticeable effects: ringing in the commutation notch waveform and alternator voltage envelope excursions that are 25% above nominal. The voltage envelope excursions will become a serious problem if methods to reduce the alternator voltage droop are implemented.

The resonances and their effects have been accurately modelled on the Parity Simulator. Two possible solutions to the problems created by the resonances have been studied, they involve damping the resonances

with series or parallel resistances. The parallel damper has much greater power dissipation than the series damper, but its physical location in the system is very flexible.