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74011

THE HYDRO-ELECTRIC POWER COMMISSION OF ONTARIO
RESEARCH DIVISION REPORT

To Mr. J.H. Waghorne
Director of Research

PERFORMANCE OF NEUTRALIZING TRANSFORMERS

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Analysis of the operation of neutralizing transformers indicates that the neutralizing transformers presently purchased by the Commission may functionally fail in service due to saturation of the core under transient system fault conditions. Air gapped, or biased core construction are suggested as means for reducing remanence and pre-magnetization in the neutralizing transformer core. Also, increased voltage ratings for the transformers are necessary if they are not to saturate during transient ground rise voltage conditions.

The purpose of this report is to calculate the performance of neutralizing transformers under transient system fault conditions. The transient component of fault current gives rise to a transient component of ground rise voltage which may saturate the core of a neutralizing transformer and cause a functional failure. The frequency of occurrence, the amplitude and the time constants of transient components of fault currents on the Ontario Hydro system are beyond the scope of this report.

INTRODUCTION

During system fault conditions, when fault currents flow through the ground resistance of a station, the voltage of the station ground rises with respect to a remote ground. This station ground rise may be several thousand volts in magnitude and will contain any transient components that are present in the fault current. In the worst case, the transient component will have an amplitude equal to the crest value of the alternating voltage component, and a time constant equal to the L/R ratio of the power system at the point of fault.

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The station ground rise voltage will appear between any remotely grounded, metallic, communications circuits and the station ground. The appearance of this voltage is dangerous to personnel, may damage communications terminal equipment, or may cause faulty operation of any protection or control equipment connected to the communications circuits.

One way of overcoming the above mentioned problems is to use a neutralizing transformer in the communications circuits. The function of the transformer is to induce a voltage in the communications circuit that is equal in magnitude to the ground rise voltage but of opposite polarity. In this manner, the voltage between the communications circuits and the station ground is reduced to a negligible value, or neutralized.

THE NEUTRALIZING TRANSFORMER

The neutralizing transformer is a two-winding transformer exhibiting very close coupling between the primary and secondary windings and having a 1-to-1 ratio between them. The primary, consisting of a single conductor, is connected between the station ground and a remote ground. The secondary may consist of any number of balanced communications pairs, and is connected in series with the communications circuits entering the station.

For proper operation, the remote ground must be sufficiently remote to span the entire station ground rise voltage, and the transformer must not saturate under the application of this voltage. Saturation must be avoided because it causes the transformer to draw a large exciting current, which in turn causes large voltage drops in the primary circuit of the transformer. These voltage drops are not induced in the secondary winding and appear, therefore, as a residual or an unneutralized voltage on the communication circuits. When the neutralizing transformer is saturated, most of the station ground rise voltage may appear as the residual voltage.

Neutralizing Transformer Flux Requirements

Formulas for the flux requirement to cope with different waveforms are developed in Appendix II. They show that to cope with a sinusoidal voltage waveform (no transient component), the transformer must have a flux swing of 2 per unit (1 per unit flux swing is obtained in the core when 1 per unit voltage is applied to the winding at the rated frequency). To cope with a voltage with a transient component of maximum amplitude, a flux swing of $(1 + \frac{X}{R})$ per unit must be available.

For Ontario Hydro's 230-kV system, the X/R ratio varies from about 5 at the end of long lines to about 30 near large generating stations. The X/R ratio will be steadily increasing with the expansion of the 230-kV and 500-kV grids and the addition of generating capacity to the system.

It would follow then, that to cope with station ground rise voltages containing a transient component, without saturation, a flux swing of between 6 and 31 per unit must be available in the neutralizing transformer. This means that the voltage rating of the neutralizing transformer must be between 6 and 31 times the maximum calculated station ground rise voltage (RMS). The exact value would depend on the X/R ratio of the power system at the particular point (station) of interest.

The above values of flux swing are only required if the fault causing the station ground rise is not cleared but persists for a long period of time. To cope with short periods (a few cycles), a smaller value of flux swing will suffice. The per unit flux swing requirement is plotted as a function of time in Figure 1 for a number of different X/R ratios of the system. The figure shows that the large per unit flux swings required to cope with transients of long duration take some time to build up, and therefore smaller values could suffice if fault clearing in a few cycles is expected under all conditions.

REMANENT FLUX

A core with low remanence permits maximum flux swing in the core, irrespective of the polarity of the transient component of station ground rise. This is a desirable characteristic of the transformer.

Remanence in the neutralizing transformer core can be set up by one of two ways. The first is due to the retentivity of the core material after it has been subjected to a high flux density. The second is due to the biasing of the core by the unbalanced direct current flowing in the communications circuits. It is therefore desirable to have core characteristics that exhibit low remanence, that give rise to a relatively small percentage of saturation flux density due to the maximum unbalance direct current, and that have a reasonable small magnetizing current at high flux densities (high applied voltages). Air gaps in the core and a biased core design/1,2/ are two measures that can be considered suitable for reducing remanence.

TESTS AND CALCULATIONS

To determine the performance of neutralizing transformers that are presently supplied to the Commission, the exciting current characteristics of a transformer rated at 6000 volts were measured (nameplate data of tested transformer appears in Appendix I). These characteristics were used in a computer program that calculates the neutralizing transformer's performance under transient station ground rise conditions. The program and brief explanations are shown in Appendix III. (Detailed

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/1/ Remanent Flux in Current Transformers. RDR 70-60.

/2/ Saturation Control of Relaying Current Transformers. RDR 70-98.

explanations of the computer program will be the subject of a subsequent report.) Actual test on a neutralizing transformer could not be carried out because of the lack of suitable equipment and high power test facilities.

The measured exciting characteristics for the transformer are shown in Figure 2, as are the computed characteristics for a transformer of same voltage rating but using air gaps or a biased core design to reduce remanence to a low value.

The neutralizing transformer's remanence was measured to be 40 per cent of saturation flux density, or about 12 volt-seconds (about 3200 volts at 60 Hz). This value was measured after the transformer was saturated with a direct current of 10 amperes. The value of 40 per cent could be compared to the computed remanence of less than 2 per cent (160 volts at 60 Hz) for either the air-gapped or the biased-core designs.

Figures 3 and 4 show the calculated performance of the neutralizing transformer when subjected to voltages containing transient components. Figures 3A, 3B, 4A and 4B reveal that functional failures (ie, residual voltage $\geq$ 300 volts) for a 6000-volt transformer occur within the first half cycle when the transformer is subjected to a voltage of 3000 volts and containing a transient component of large (100%) or medium (54%) amplitude, having a short (0.013 s) or long (0.08 s) time constant. Figure 3C reveals that no failure occurs when the transformer's rating is increased to 18,000 volts for the transient with the short time constant (TC = 0.013 s; X/R = 5). The value of 18,000 comes about from the 3000-volt applied voltage multiplied by a flux requirement of 6, as obtained from Figure 1, for X/R = 5. Similarly, Figure 4C reveals no failure when the transformer's rating is increased to 90,000 volts for the transient with the long time constant (TC = 0.08; X/R = 30). Figures 3D and 4D reveal that failure of the oversized transformers is still possible if remanence is not controlled.

DISCUSSION

Figures 3 and 4 indicate that neutralizing transformers may fail to function in service when they are subjected to voltages containing transient components. To cope with transient components the voltage rating of the transformer must be increased by a factor which is proportional to the X/R ratio of the system at the point of interest. This factor could be as large as 30 or more for some locations on Hydro's system, resulting in a prohibitively large and very costly transformer.

It is unfortunate that during severe fault conditions, the neutralizing transformer is most likely to saturate and result in a functional failure. It is during these times that the communication circuits must not be interrupted so that accurate signaling can take place. Neutralizing transformers of higher voltage ratings, and using air gaps for reducing remanence will help greatly in reducing the number and the severity of functional failures. The size of the neutralizing transformers, that could guarantee no functional failure, would be very large and their cost would be very high.

Figures 3 and 4 were computed for a 30 ohm resistance in the primary circuit, which is close to the 35 ohm rating for the neutralizing transformer. A reduction in resistance by a factor of 10, down to 3 ohms, would result in only a marginal improvement in the neutralizing transformer's performance.

CONCLUSIONS

The voltage ratings of neutralizing transformers must be increased if their functional failures are to be reduced under transient station ground rise conditions. The factor by which their rating must be increased is approximately proportional to the system X/R ratio at the particular location of interest. Since the system X/R ratio may be very high in certain locations, it may be economically unjustifiable to provide a transformer that will not fail under the worst conditions.

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APPENDIX I

NAMEPLATE DATA

Neutralizing Transformer

Type 190-017-B Serial No 70-169

Primary Volts 6000 Cycles 60

Number of Secondary Pairs 16 Gauge 22

Maximum Remanent Volts 150 at 35 ohms External Z

Manufactured by

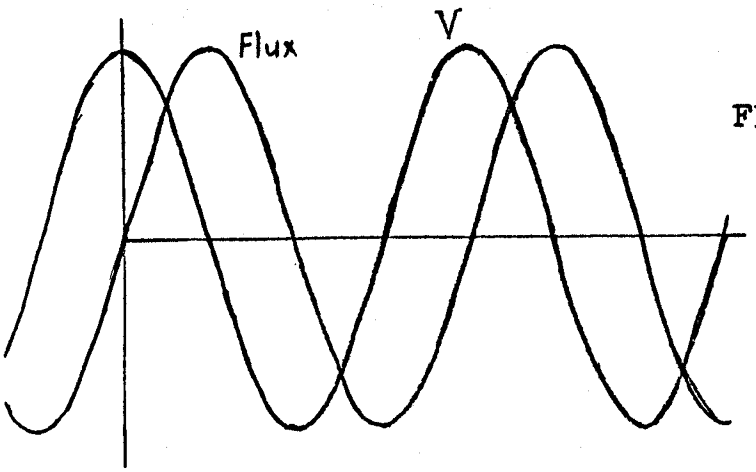
Osborne Electric Co Limited

Toronto, Canada

APPENDIX II

NEUTRALIZING TRANSFORMER FLUX REQUIREMENTS

A. Steady State Conditions



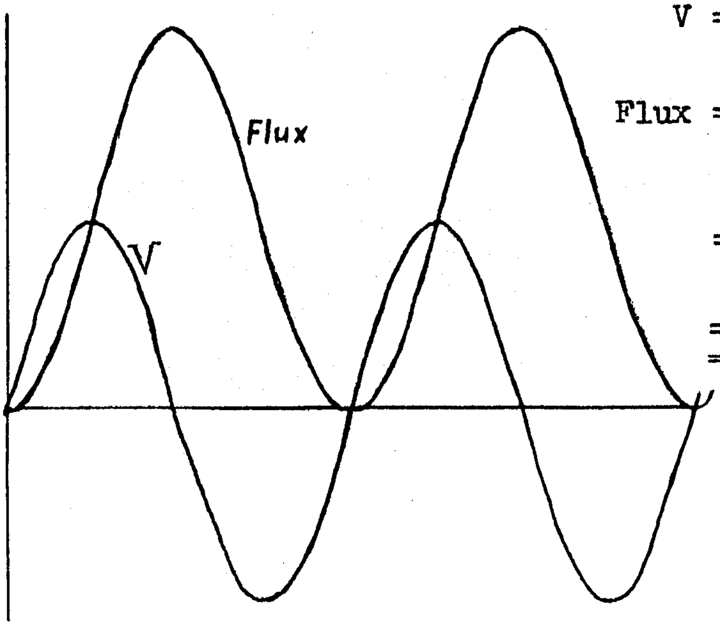
$$V = V_o \cos(\omega t)$$

$$\text{Flux} = \int_0^{\pi/2} (V_o \cos(\omega t))dt$$

$$= \frac{V_o}{\omega}$$

$$= 1 \text{ per unit}$$

B. Fault Initiation - No Transient



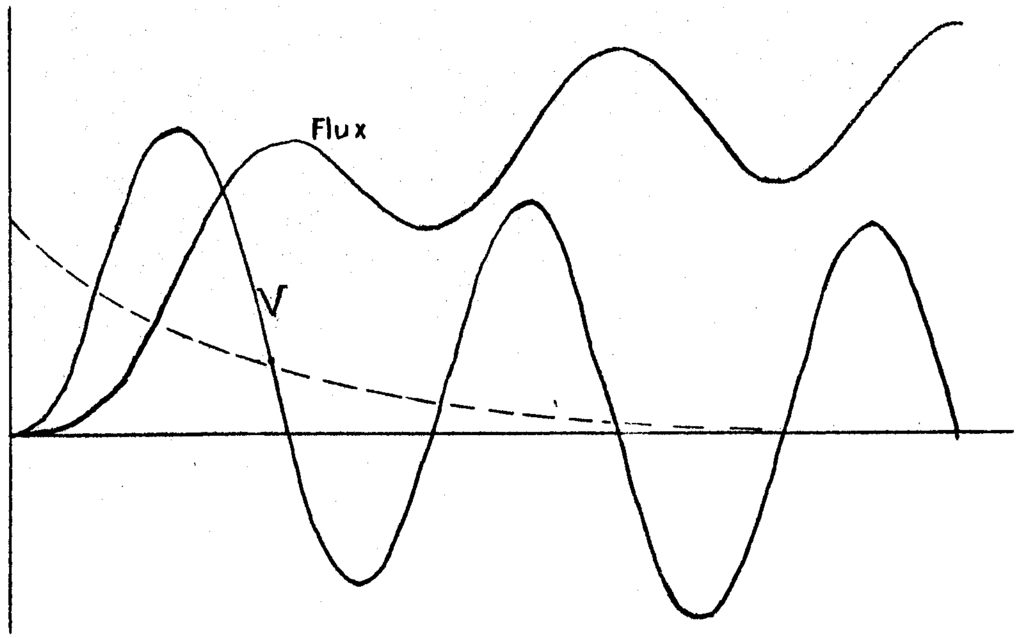
$$V = V_o \sin(\omega t)$$

$$\text{Flux} = \int_0^{\pi} (V_o \sin(\omega t))dt$$

$$= 2\frac{V_o}{\omega}$$

$$= 2 \text{ per unit}$$

C. Fault Initiation - Maximum Transient



$V = V_o(-\cos(\omega t) + e^{-t/T})$

Flux due to ac component $= \int_o^{\pi/2} (V_o \cos(\omega t))dt = \frac{V_o}{\omega}$

Flux due to transient component $= \int_o^{\infty} (V_o\, e^{-t/T})dt = V_oT$

By definition $T = X/R\omega$ where T = system time constant
X = system reactance
R = system resistance
ω = system frequency

Flux (total) $= \frac{V_o}{\omega} + \frac{V_oX}{R\omega} = \frac{V_o}{\omega}(1 + \frac{X}{R})$

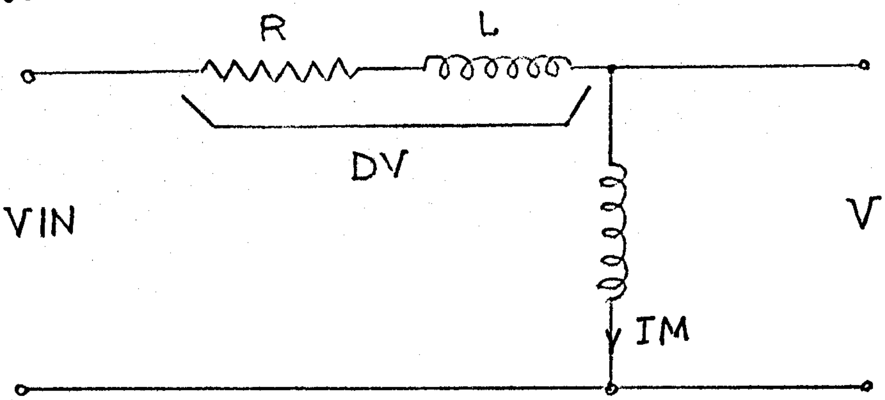
$= (1 + \frac{X}{R})$ per unit

APPENDIX III

COMPUTER PROGRAM

```
      REAL T,VIN,V,DIM,DDV,DFL,OFL,IM,IDV
      INTEGER NO,CNTR,CYC
      PRINT 600
      CYC=10.0
      AMPL=3000.0
      NO=20.0
      DA=1.0
       TC=0.013
      R=30.0
      L=0.002
      A=0.0
      OFL=100.0
      FLUX=0.0
      DV=0.0
      DDV=0.0
      IMO=0.0
      DT=DA/21600.0
      AA=360.0*CYC
      CNTR=0.0
      PRINT 500,A,VIN,V,DV,IM,FLUX
   10 A=A+DA
      CNTR=CNTR+1.0
      T=A/21600.0
      VIN=AMPL*1.414*(-COS(377.0*T)+EXP(-T/TC))
      V=VIN-DV
  100 V=V+DDV
      DFL =4.44*60.0*V*DT
      FLUX=OFL+DFL
      IM=(FLUX*1.5E-7)↑0.42+(FLUX*2.0E-4)↑5.16+(FLUX*1.5E-4)↑11.0
      DIM=IM-IMO
      DV=R*IM+L*DIM/DT
      DDV=VIN-V-DV
      IDV=INT(DDV*100.0)/100.0
      IF(IDV)100,200,100
  200 OFL=FLUX
      IF(CNTR-NO)10,300,300
  300 PRINT 500,A,VIN,V,DV,IM,FLUX
      CNTR=0.0
      IF(A-AA)400,1000,1000
  400 GO TO 10
  500 FORMAT(F6.0,5F8.1)
  600 FORMAT(3X,1HA,5X,3HVIN,6X,1HV,7X,2HDV,6X,2HIM,5X,4HFLUX/)
 1000 STOP
      END
```

The computer calculates the performance of the following circuit:



Explanation of Terms

100	CYC	Number of cycles to be calculated.
110	AMPL	RMS value of applied voltage.
120	NO	Number of calculations between printouts.
130	DA	Interval between calculations (degrees at 60 Hz).
140	TC	System time constant (seconds).
150	R	Resistance of primary circuit (ohms).
160	L	Inductance of primary circuit (Henries).
210	OFL	Remanent flux (volts).
290	VIN	Equation of applied voltage.
295	V	Secondary Voltage (volts).
310	FLUX	Flux (volt seconds x 60 x 4.44).
320	IM	Equation representing transformer characteristics.
340	DV	Voltage drop in primary circuit of the transformer (volts).

Equations

Applied voltage with maximum transient component.

```
290     VIN=AMPLI*1.414*(-COS(377.Ø*T)+EXP(-T/TC))
```

Applied voltage with other than maximum transient component.

```
290     VIN=AMPL*1.414*(-COS(377.Ø*T+1.Ø)+(COS(1-1.Ø)*EXP(-T/TC)))
```

Magnetizing current of 6000-volt transformer.

```
320     IM=(FLUX*1.5E-7)↑Ø.42+(FLUX*2.ØE-4)↑5.16+(FLUX*1.5E-4)↑11.Ø
```

Magnetizing current of 18,000-volt transformer.

```
320     IM=(FLUX*1.5E-7)↑Ø.42+(FLUX*6.66E-5)↑5.12-6+(FLUX*5.ØE-5)↑11.Ø
```

Magnetizing current of 90,000-volt transformer.

```
320     IM=(FLUX*1.5E-7)↑Ø.42+(FLUX*1.33E-5)↑5.16+(FLUX*1.ØE-5)↑11.Ø
```

BRIEF EXPLANATION OF PROGRAM

1. Statements 55 to 255, inclusive, define the starting points for the program and contain such information as the amplitude of the applied voltage, time constant of transient, remanent flux, etc.

2. Calculation is commenced with statement 260, 270, and 280, where the time is advanced an increment DA.

3. The voltage applied to the system is calculated in 290.

4. The voltage applied to the transformer is calculated in 295 and 300, where the various voltage drops are subtracted.

5. The flux in the core is computed in 310.

6. The magnetizing current is computed in 320.

7. New voltage drops are calculated in 340 based on the new magnetizing current.

8. In 345, 350, and 360, the new voltage drops are compared to the old voltage drops. If these are within 0.01 volts, the computer returns to 260, advances another increment in time, DA, and continues calculating. If the comparison is not within 0.01 volts, the computer assumes new values, returns to 300 to recalculate.

9. The printout is obtained only every NO (STATEMENT 120) time increments from statements 370 and 380.

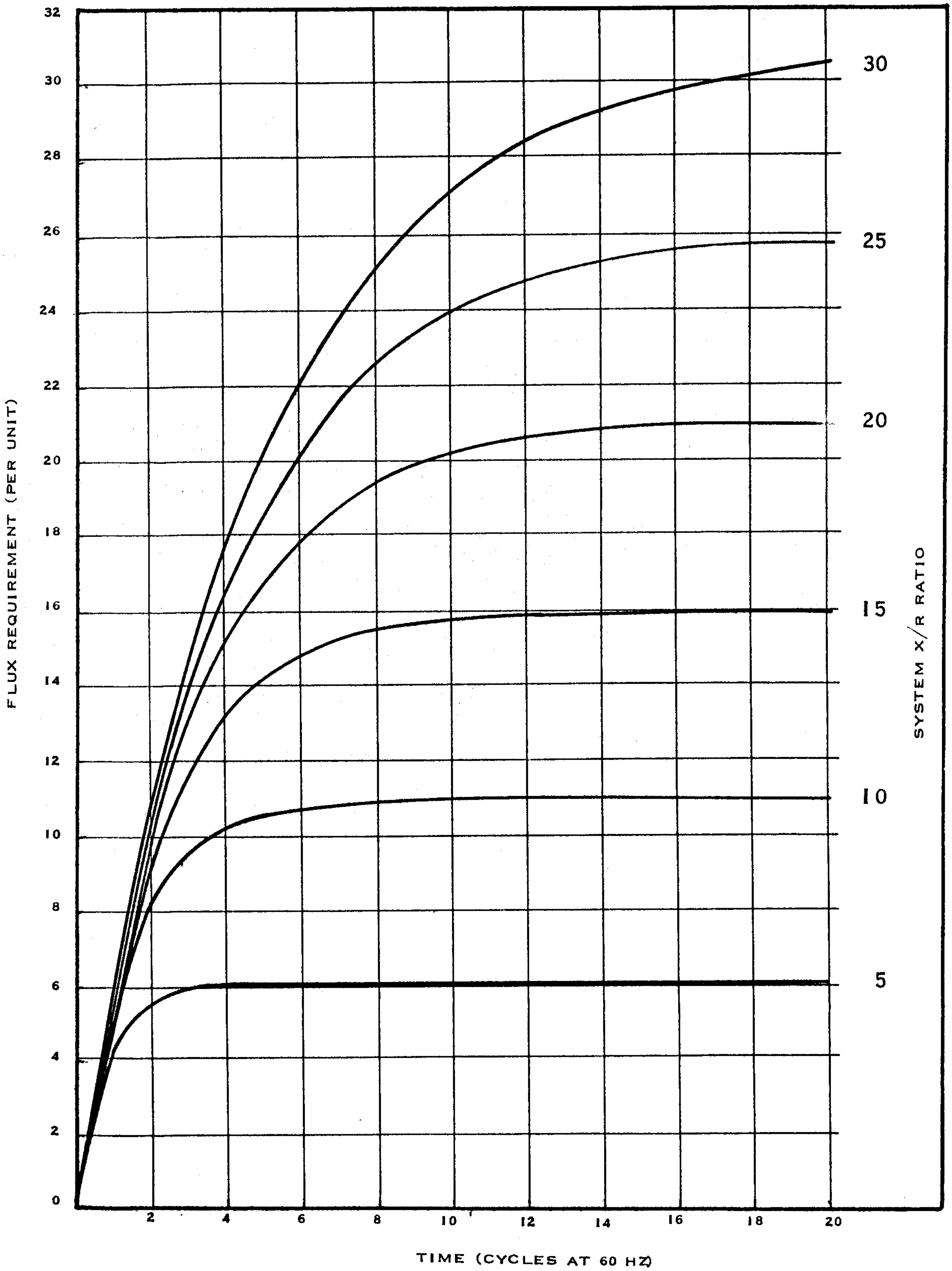


FIGURE I

FLUX REQUIREMENT OF NEUTRALIZING TRANSFORMERS SUBJECTED TO TRANSIENT GROUND RISE CONDITIONS

123941 — RD

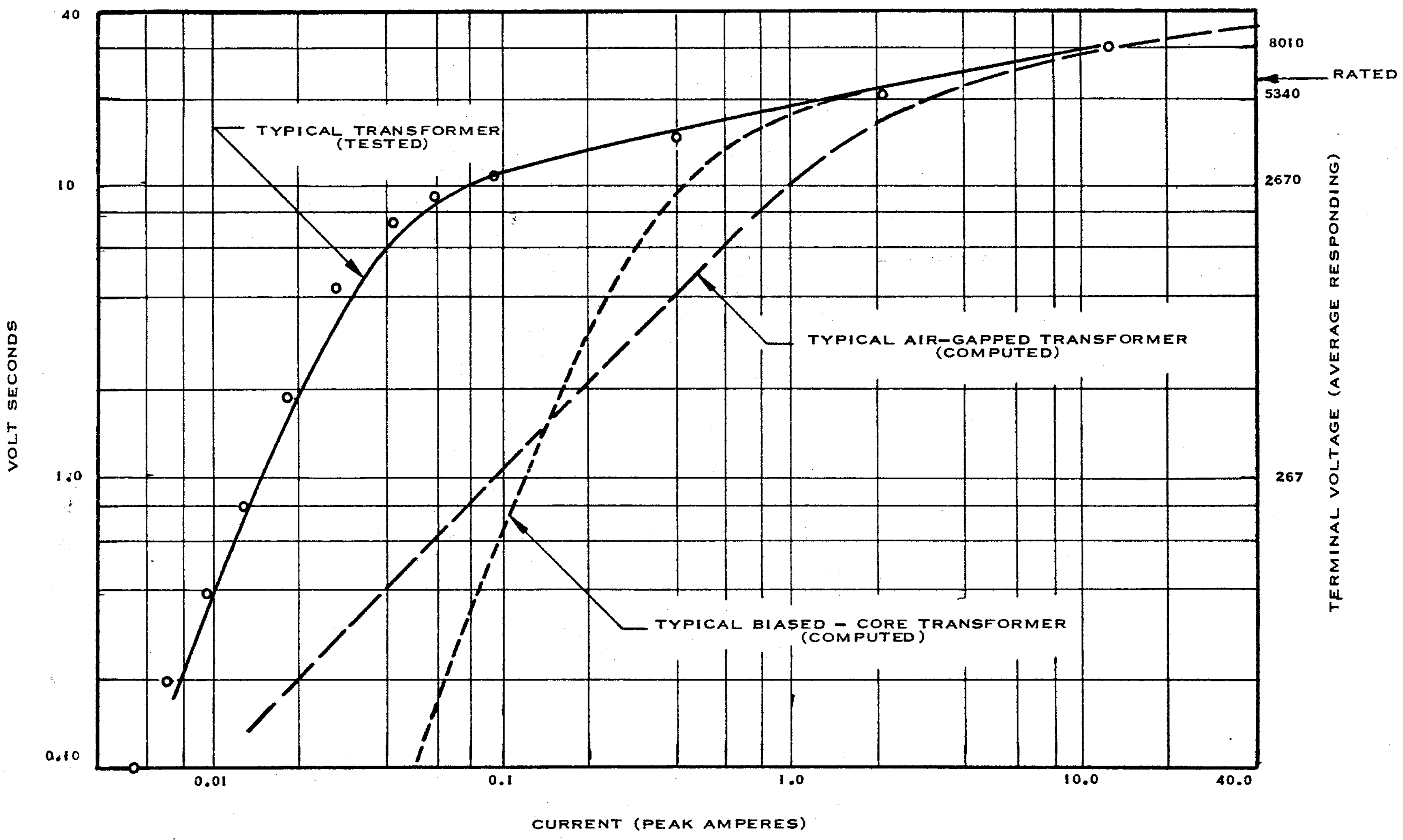


FIGURE 2

EXCITING CHARACTERISTICS FOR 6000 VOLT NEUTRALIZING TRANSFORMER

123940 – RD

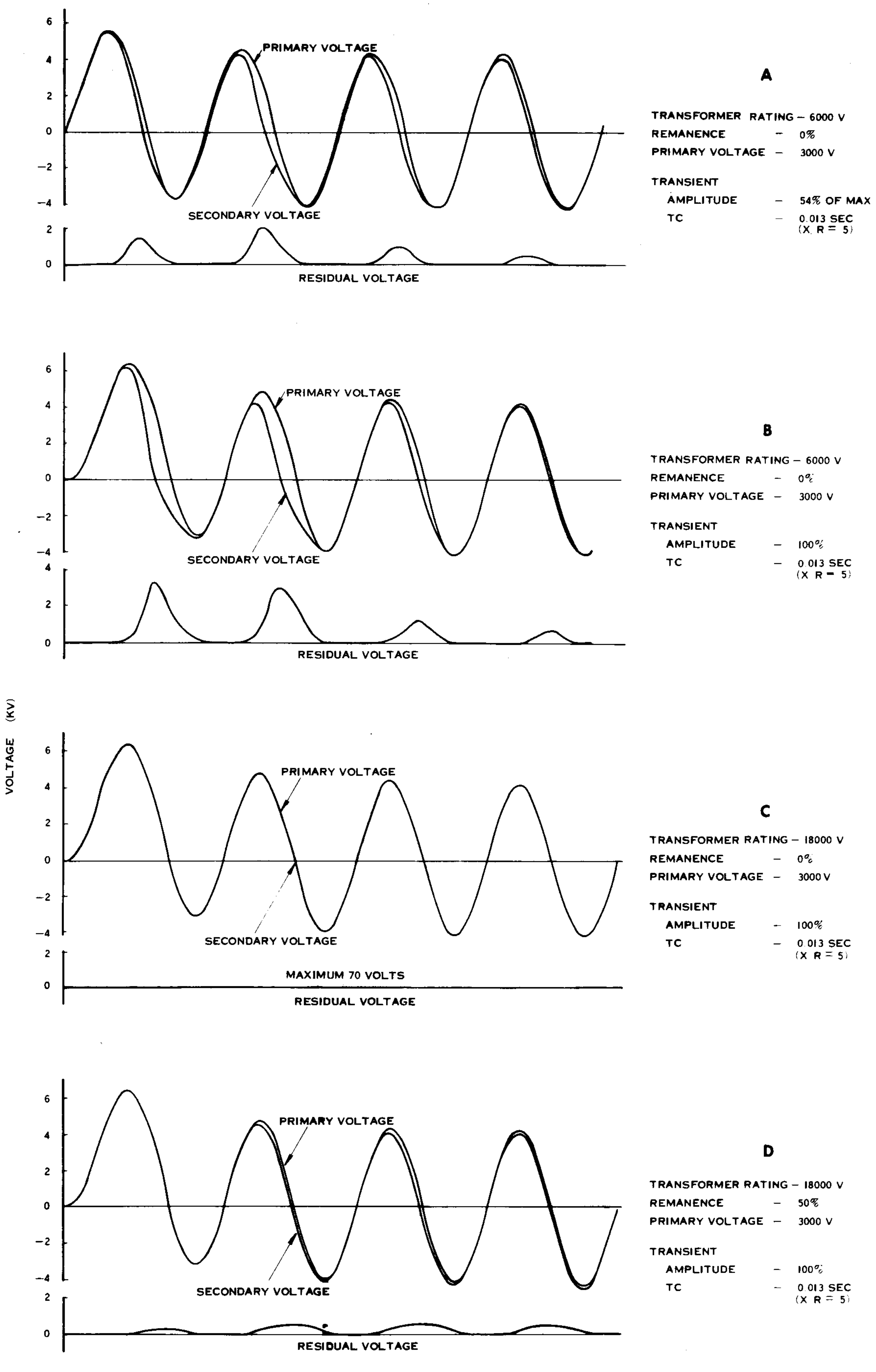


FIGURE 3

PERFORMANCE OF NEUTRALIZING TRANSFORMERS
TRANSIENTS WITH SHORT TIME CONSTANTS

30895–RD

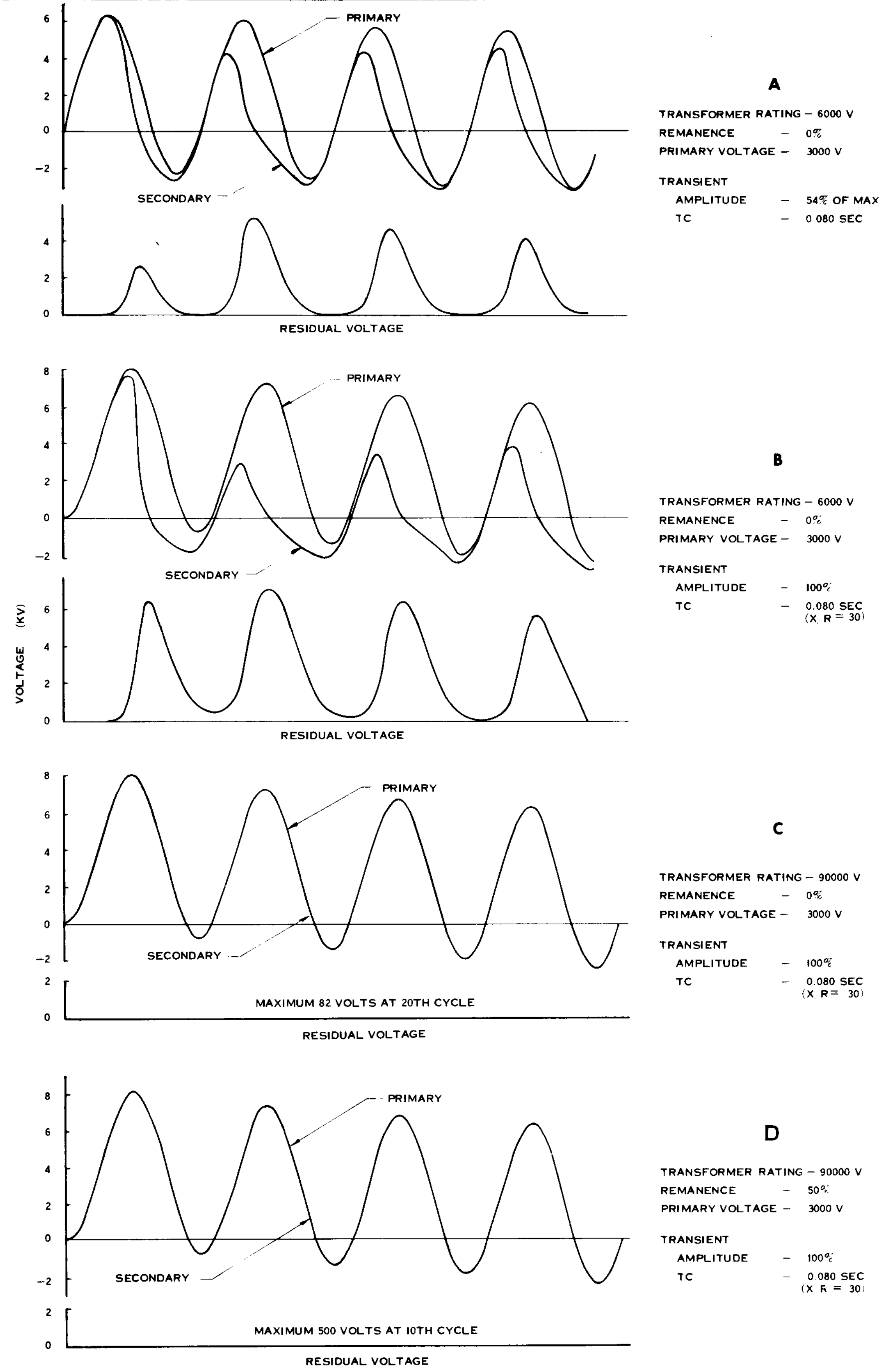


FIGURE 4

PERFORMANCE OF NEUTRALIZING TRANSFORMERS
TRANSIENTS WITH LONG TIME CONSTANTS

30896–RD