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To Mr. J.H. Waghorne
Director of Research

HIGH-VOLTAGE CURRENT AND VOLTAGE TRANSDUCERS FOR ELECTRONIC RELAYS AND METERS

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Current and voltage transducers were developed to supply power system voltage and power system current replica voltages to an electronic relaying system. The current transducers consisted of a high-ratio current transformer with a shunt and having a gapped core to reduce remanence. Two approaches to the voltage transducer were tried, both relying on a high voltage capacitive voltage divider. The first approach used active components to provide a low impedance source of replica voltage, while the second used passive components which resulted in a higher output impedance and a somewhat narrower bandwidth.

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SUMMARY

Current and voltage transducers were developed to supply power system voltage and power system current replica voltages to an electronic relaying system. The current transducers consisted of a high-ratio current transformer with a shunt and having a gapped core to reduce remanence. Two approaches to the voltage transducer were tried, both relying on a high voltage capacitive voltage divider. The first approach used active components to provide a low impedance source of replica voltage, while the second used passive components which resulted in a higher output impedance and a somewhat narrower bandwidth.

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INTRODUCTION

The steadily increasing short circuit capacities on high-voltage power systems, due to the addition of generation and interconnections with other systems, have resulted in an ever increasing demand for faster, more accurate, more sophisticated, and more dependable relaying systems. The manufacturers of relay systems have responded by developing solid state fault detectors and combined them to make up relaying systems complete with solid state logic and manual or automatic testing features. These relay systems are faster, more accurate, and more reliable as long as they are supplied with signals that truly represent the voltages and currents of the power system being monitored. Unfortunately the development of current and voltage transducers that are connected to the high-voltage circuits is lagging the development of the relays.

This paper describes the development and field testing of high-voltage current and voltage transducers at the Ontario Hydro Research Division. These transducers were designed to be installed on a trial basis, on Hydro's 230-kV system together with a solid state relay and instrumentation system also developed at the Research Laboratory.

It should be pointed out that the transducers to be described here are not of sophisticated design using the latest of physical principles, but are using simple magnetic principles that have proven themselves on the high-voltage system. The main purpose of the trial installation of transducers and relays was to determine if a solid state relay system could function properly from low level (5 volt) signals in the hostile environment of a high-voltage switch yard. By the hostile environment is meant the presence of high-voltage, high-current, and high-frequency interference signals that are present in such yards under certain operating conditions. The transducers to be described here represent only a portion of the equipment involved in a large protection and instrumentation system.

GENERAL REQUIREMENTS

The requirements of the transducers were to provide accurate and isolated replica signals of the voltage and current in a 230-kV circuit under steady state and fault conditions. The nominal voltage level for the replica was set at 5 volts ac. The transducers had to meet the normal instrument transformer insulation requirements for a 230-kV system which are 460 kV power frequency and 1050 kV BIL (basic impulse insulation level).

Since the transducers were to be used for metering and relaying applications, their accuracy under steady state conditions was to satisfy the CSA 0.6 per cent accuracy class. Under transient fault conditions, a 2.5 per cent composite error was specified for the current transducers, while the output of voltage transducers had to be zero (<2 per cent of rated output) one millisecond after the high voltage was shorted to ground.

Finally, the transducers had to be immune to high-frequency interference such as may be present in high-voltage stations under certain operating conditions. By immune is meant that the transducers would function properly in the presence of such interference and preferably would filter out much of this interference from their outputs.

GENERAL CONSIDERATIONS

To meet the above general requirements meant that the transducer not only had to have high accuracy with respect to magnitude and phase at the 60 Hz power frequency, but also had to have frequency response curves that would be flat over a large portion of the audio frequency spectrum. This would assure good accuracy under transient fault conditions, and freedom from low or high frequency oscillations. The current transducers especially, had to have good response at very low frequencies to cope with direct current transients that may be a part of fault current.

To cope with the high-frequency interference meant that extreme care had to be used in grounding and shielding the various components.

Since the input impedance of the electronic metering and relaying equipment was high (100 kΩ), the output impedance of the transducers could approach 100 ohms without large loading effects being present even if a number of electronic devices were connected to the same transducer.

CURRENT TRANSDUCERS

Requirements

Since the transducer was to be installed in a station where all of the equipment was rated at 3200 amperes, the transducer had to have primary ratings of up to 3200 amperes for a 5-volt output. It was also desirable to have a large number of primary ratings available. The performance of the transducer was specified on the 1200 ampere rating. At this rating a faithful reproduction was specified of a 50 kA fault current, complete with a dc transient of maximum amplitude and having a 0.02 second time constant.

The Transducer

Six transducers were procured to conform with the requirements. Each consisted of a conventional current transformer having a nominal 0.5 ampere secondary current. When loaded with a resistor of 10 ohms, the required output of 5 volts across the resistor was realized.

The core of the transformer was of toroidal construction and used grain-oriented silicon steel. The core area was about 5-1/4 square inches, and had a mean circumference of 49 inches. The core was cut through in two places and air-gaps of a few thousands of an inch were fabricated upon re-assembly. The purpose of the gaps is to reduce the remanence in the core, thus allowing for the transformation of transients of either polarity without saturation.

The secondary winding of the transformer consisted of two isolated windings. The first had 1200 turns tapped at 400, the second had 5200 turns tapped at 1600. By various connections of the two windings, turn ratios between 400-to-1 and 6400-to-1 could be obtained. These ratios would correspond to currents of 200 to 3200 amperes in the single primary turn. This high-ratio core, together with other conventional cores with 5-ampere secondaries were assembled into a free-standing, eye-bolt type, 230-kV current transformer.

To help keep out the unwanted, high-frequency, interference signals from the secondary of the transducer core, an electrostatic shield was placed over the transducer core and windings. A schematic diagram of the transducer appears in Figure 1.

Performance

Steady State Performance

The steady state accuracy of the transducer was computed from the equivalent circuit of the transformer, and the following table made.

Primary Rating (Amperes)	Composite Error (%)
400	0.75
600	0.38
800	0.21
1200	0.13
1600	0.10
2400	0.06
3200	0.05

The above table applies for currents between 20 and 200 per cent of rated. The composite error increases about two-fold for currents at 10 per cent of rated. The table indicates that CSA 0.6 accuracy class would be met by ratings of 600 amperes and higher.

Transient Performance

Based on the measurements of the core's magnetic properties, the following table was drawn up. The "TC" shown in the table refers to the time constant of the transient component of the fault current.

Primary Rating (Amperes)	Transient Factor* at 20 times rated current	Maximum Current for Faithful Reproduction (kA)		
		TC-0.02	TC-0.04	TC-0.06
400	9.0	9	5	3
600	12.0	18	10	6
800	14.0	28	16	10
1200	17.0	50	29	19
1600	19.5	78	45	29
2400	22.5	130	76	50
3200	24.0	190	110	75

* Transient Factor is the ratio of the steady state current that would saturate the core to the specified primary current.

Example

The table indicates that the transducer used on the 1600 amp primary rating would faithfully reproduce a fault current of 45 kA, 100 per cent offset with a dc transient having a 0.04 second time constant.

The above table indicates that the requirements specified of the 1200 ampere rating would be met.

VOLTAGE TRANSDUCERS

Requirements

The requirements were for a ratio of 40,000 between the primary and the replica voltages. The dynamic range of the transducer had to be up to 2.4 times the nominal voltage. The output of of the transducer was specified to be free from low or high frequency signals under transient input conditions. The output was also to be zero (<2 per cent of rated) 1 millisecond after the high-voltage was shorted to ground.

The Transducers

A. Active Transducer

A simplified schematic diagram of the active transducer is shown in Figure 2. It consists of a high-voltage capacitive divider, an auxiliary secondary divider, an amplifier, and an isolating transformer. The power supply furnishes power to a set of three transducers, one for each phase.

The high-voltage dividers had a ratio of 1000-to-1, and their output, about 140 volts, was transmitted by means of a four conductor shielded cable to a central location near the relay system where the amplifiers and the power supply were located. It should be pointed out that a resistor was placed at each end of the cable to terminate the cable, thus reducing the reflection of high-frequency interference signals. A filter was placed at the input of the amplifier to protect the amplifier from excessive voltages. The output transformer for the transducer was shielded and of toroidal construction to minimize short circuit inductance.

B. Passive Transducers

The diagram for the passive voltage transducer is shown in Figure 3. One might refer to this transducer as a heavily damped capacitive voltage transformer (CVT). It uses a 1000-to-1 high voltage capacitive divider, just as the active VT, an auxiliary resistive divider, a shielded isolating transformer, and a compensating reactor. The overall ratio of the transducer is determined by the capacitive and resistive dividers, and the ratio of the isolating transformer. The phase angle shift caused by the loading of the capacitive divider and the resistive divider are corrected by the compensating reactor. To minimize this loading, it is desirable to have the resistance of the divider many times the output impedance of the capacitive divider, and to have the magnetizing impedance of the isolating transformer many times the output resistance of the resistive divider. Another criterion that should be satisfied if problems due to high frequency interference are to be minimized, is that the output impedance of the transducer should be equal to the surge impedance of the cable that will be connected to it.

Performance

As could be expected, the performance of the active transducer was excellent with respect to accuracy under steady state and transient conditions. Shown in Figure 5 are some oscillograms comparing the output of the transducer with the output of a high quality magnetic potential transformer. The response of the transducer is very flat from a few cycles to kilocyles.

The calculated performance of the passive transducer is shown plotted in Figure 4. As can be seen from these plots, the ratio and phase angle accuracy of the transducer is good, and flat, in the region of 60 Hz, but increases rapidly below 20 cycles and above a few thousand cycles. There is also a small, but pronounced peak in the amplitude curve occuring at about 10 cycles. The amplitude of the peak is not large enough, however, to cause any oscillatory problems. This was confirmed by test on a model of the transducer.

The high-frequency characteristics of this transducer can be modified by C1 and C2 capacitors. These may be stray capacitances, or inserted on purpose. The solid curves in Figure 4 are for C1 = 1000 pF, and C2 = 0.22 μF. The dotted curves are for C1 = 0.01 μF, and C2 = 0.22 μF.

EXPERIENCE

A three-phase installation of the active voltage transducers with modified current transducers was made in a 230-kV station for a period of six months. A modified current transducer, consisting of a conventional 5-ampere current transformer with a shielded 5- to 0.5-ampere auxiliary transformer and shunt, was used because of delays in the delivery of the described current transducer assembly. A number of successful staged faults were cleared during the trial period, and no problems have been experienced with the transducers during that time. Since the trial period, plans have been formulated for the installation and trial of the described current transducer assemblies together with the active and passive voltage transducers.

DISCUSSION

It is appropriate to compare the performance of the above transducers with conventional voltage and current transformers.

This is very easily done for the current transducers, because conventional 5-ampere transformers are used alongside the transducers. These transformers are of similar size and are rated at 2.5L800 on the 1200-to-5 ampere ratio. In service, a total burden of about 2 ohms is imposed on the secondary of this transformer. Based on this data, and at 20 times rated current, a transient factor of 4 can be computed for this transformer. This transient factor should be reduced to 1 if the possibility of early saturation due to remanence is to be avoided.

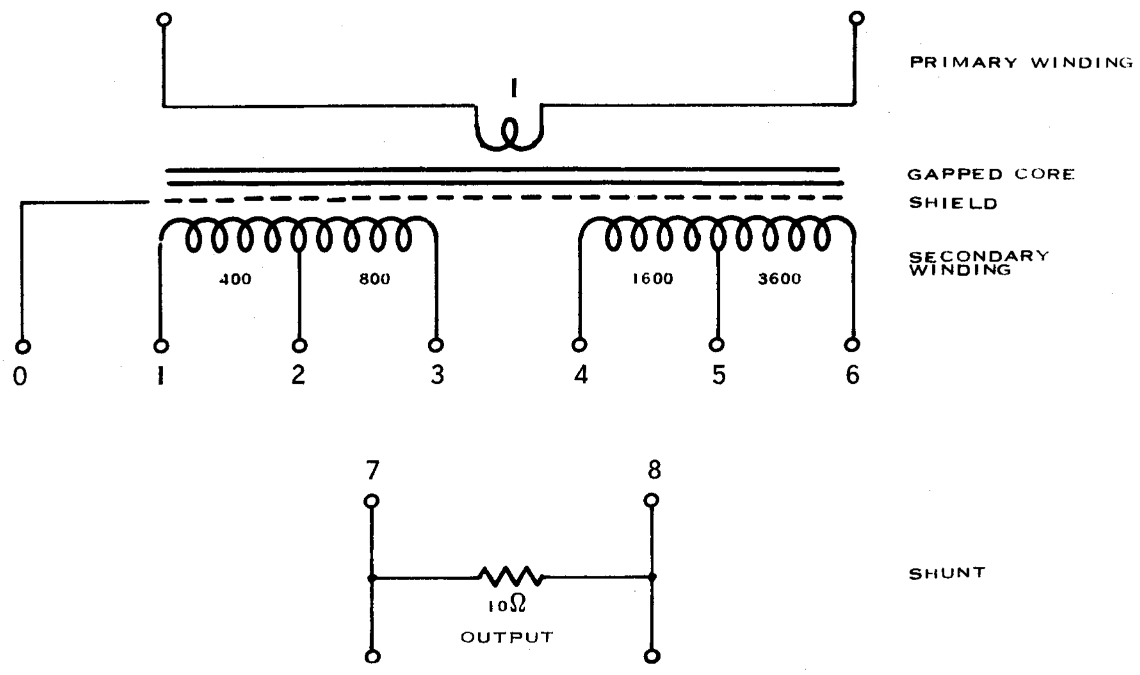
The figures below may be used to compare the transducer with the transformer, both on the 1200 ampere rating.

	Transient Factor at 20 x Rated Current	Maximum Current for Faithful Reproduction (kA)		
		TC=0.02	TC=0.04	TC=0.06
Transducer	17	50	29	19
Current Transformer	4	11	6	4.6
Current Transformer (derated for remanence)	1	2.8	1.5	1.1

The oscillograms showing the performance of the active voltage transducer indicate that the transducer's performance is very much the same as the performance of a magnetic potential transformer. This is, of course, much better than capacitive voltage transformers which usually exhibit a high or low frequency transient in the output when the input is changed abruptly.

CONCLUSIONS

The procurement and successful trial of the transducers has brought us closer to the day when 5-ampere and 120-volt circuits will be replaced by low level (5 volt) signals for metering and relaying purposes in high voltage stations. The transducers described here are approximately of the same size and cost as conventional current transformers and capacitive voltage transformers (CVT), but offer superior performance. The current transducer is capable of transforming fault currents with transient components without loss of output due to saturation, while the voltage transducer's output is free from high or low frequency oscillations that are usually associated with CVT's.



PRIMARY RATING (AMPERES)	CONNECTION
200	7—1, 3—4, 2—8
400	7—2, 1—4, 3—8
600	7—1, 2—4, 3—8
800	7—4, 3—6, 5—8
1000	7—1, 2—4, 5—8
1200	7—2, 3—4, 5—8
1400	7—1, 3—4, 5—8
1600	7—2, 1—5, 6—8
1800	7—5, 3—4, 6—8
2000	7—1, 2—5, 6—8
2200	7—2, 3—5, 6—8
2400	7—1, 3—5, 6—8
2600	7—4, 3—5, 6—8
2800	7—1, 2—4, 6—8
3000	7—2, 3—4, 6—8
3200	7—1, 3—4, 6—8

FIGURE I

CURRENT TRANSDUCER

126650—RD

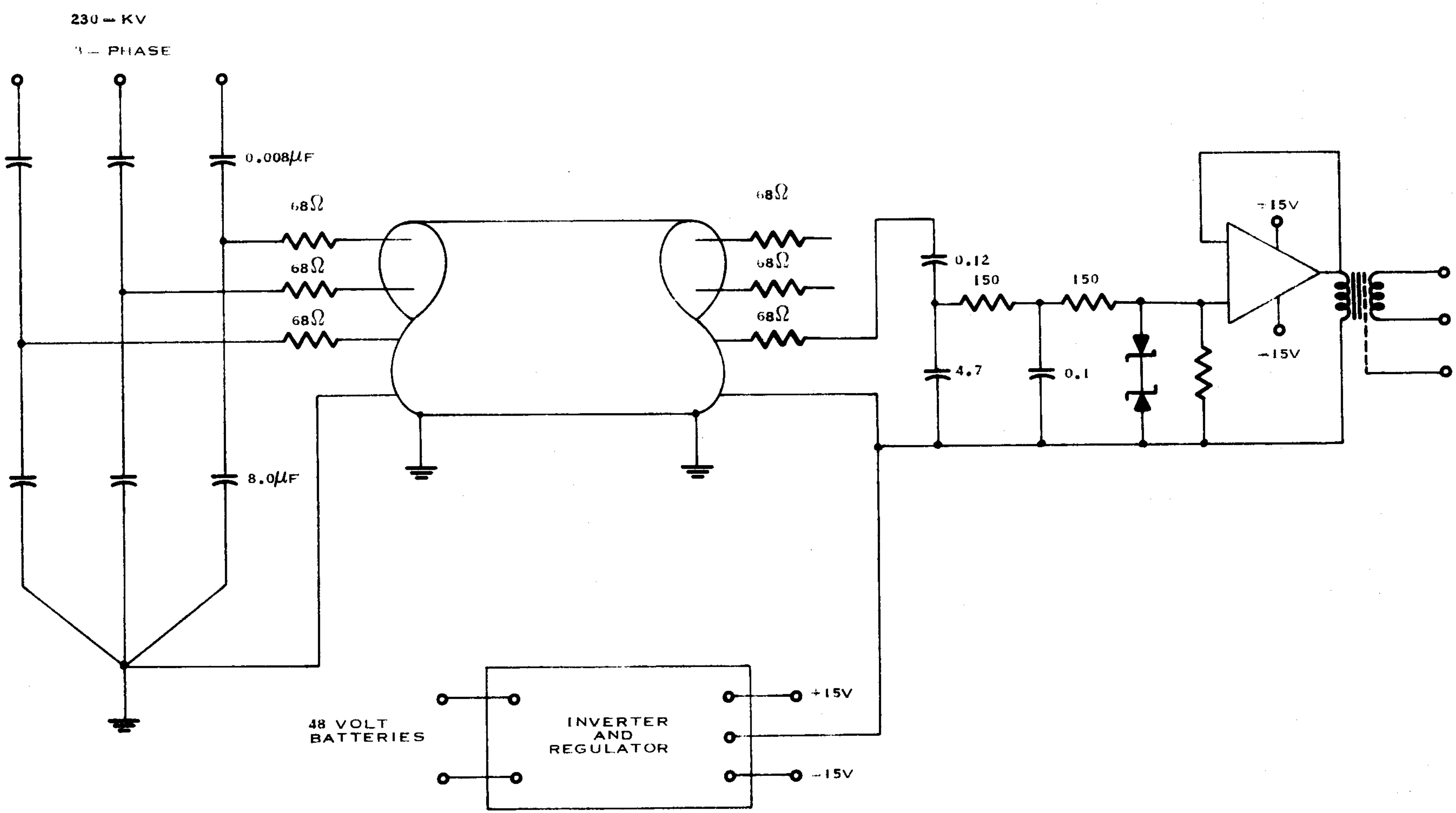


FIGURE 2

ACTIVE VOLTAGE TRANSDUCER

126651—RD

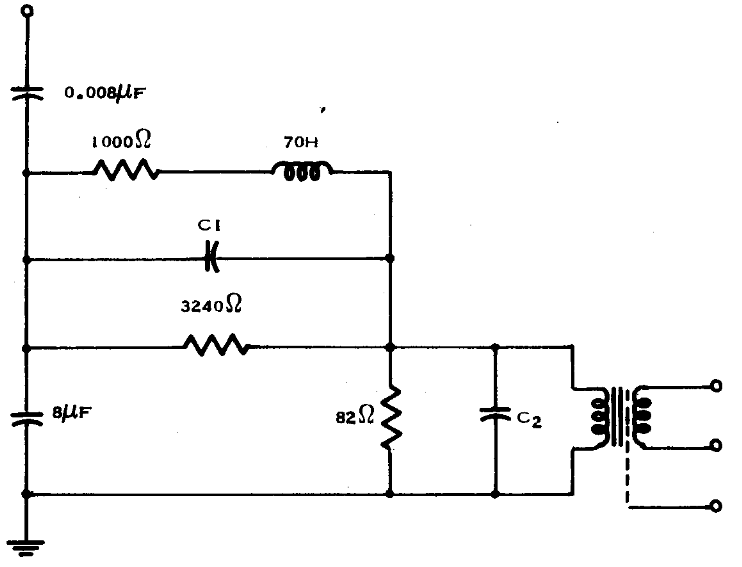


FIGURE 3

PASSIVE VOLTAGE TRANSDUCER

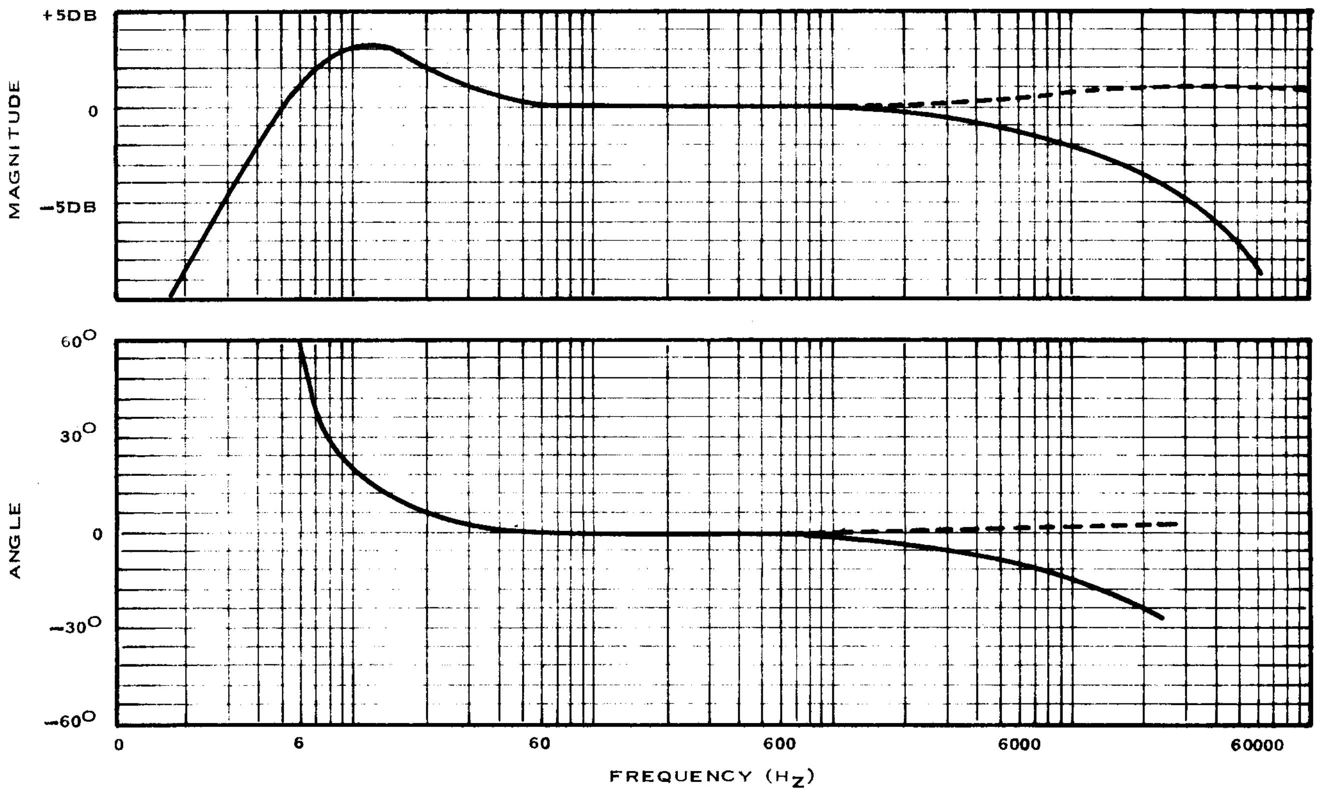
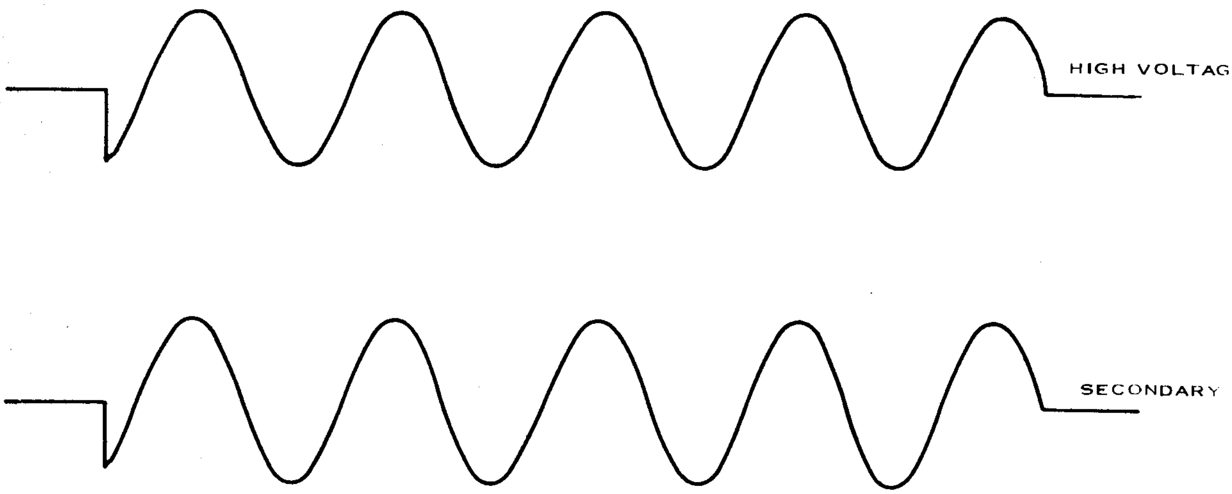


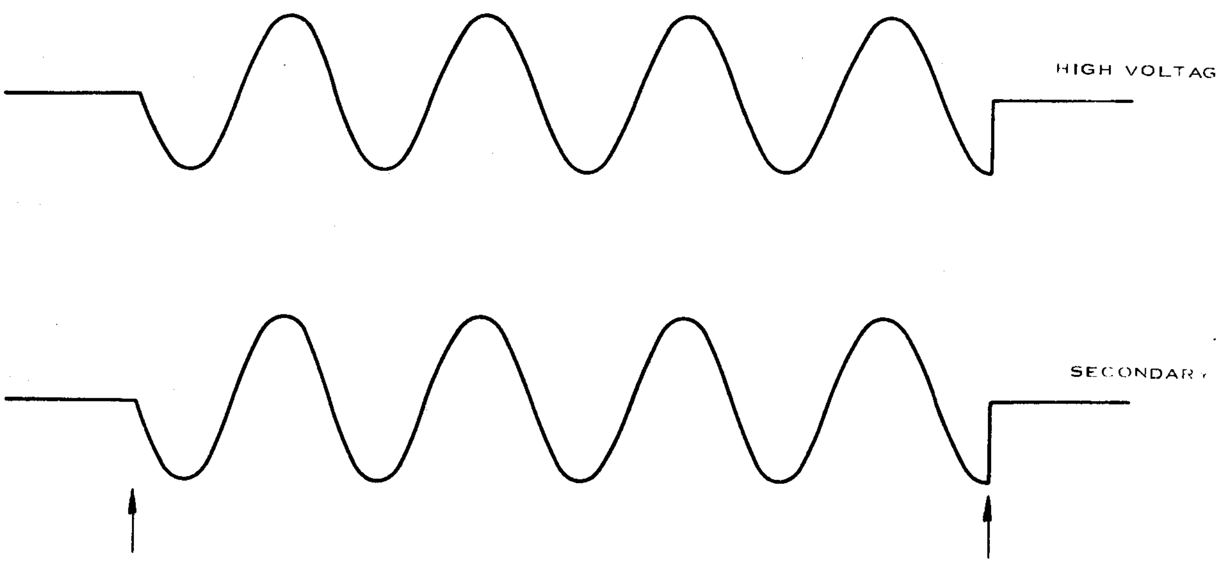
FIGURE 4

RESPONSE OF PASSIVE VOLTAGE TRANSDUCER

126652-RD



OSCILLOGRAM A



OSCILLOGRAM B

FIGURE 5

OSCILLOGRAMS OF ACTIVE VOLTAGE TRANSDUCER