26479
new 4-74

ONTARIO HYDRO
RESEARCH DIVISION REPORT

To Mr. R.A. Brown
Manager of Engineering - Bruce GS 'A'
Generation Projects Division

ISOLATED-PHASE-BUS POWER LOSSES OF UNIT 2, BRUCE GS

O.W. Iwanusiw

The power loss of the isolated phase bus of Unit 2 at Bruce GS was measured to be 384 kW. The loss was measured at a current of 27.8 kA using the wattmeter method. The measurement includes calculated corrections to allow for the finite loop of the potential leads.

As requested, special equipment was assembled and used to measure the power loss of the isolated-phase-bus (IPB) of Unit 2 at Bruce GS. The measurements were made during the short-circuit tests on the generator, IPB, and unit power transformers.

This report presents the results of measurements and the estimates of accuracy. Appended to the report are details of the equipment used, the measuring circuit, loss calculations, summary of loss measurement, and calculation of corrections to measurements.

Referring to Figure 1 of Appendix E, the IPB consisted of a star section (R, W, B) and a delta section (WR, RW, BW, WB, RB, BR). The lengths of the various sections and other pertinent data are given in Appendix A.

IPB LOSSES

The losses for the IPB have been determined at 384 kW for a current of 27.8 kA. The above include a loss of 156 kW in the Red-phase bus (star and delta sections combined), 112 kW in the White-phase bus, and 116 kW in the Blue-phase bus. The portion of the IPB that was measured was from the flexible braid connections between the air cooled bus and the water cooled generator output terminations, and the flexible braid connections at the unit transformer bushings.

Although it was planned to determine the loss of each IPB section separately, it was found that such measurements included excessive errors. The errors are related to the finite loop of the potential leads which did not enclose all the magnetic flux generated by

job	file	date	report no.
740613-109-1307	815.01	December 8, 1976	76-484-H

the IPB. By comparing the calculated magnetic flux enclosed by the potential lead measuring loops to the total calculated magnetic flux generated by the IPB, it was possible to appreciate the magnitude of errors in the measurements. The estimate of errors has thus been determined for any individual section at ±20 kW; for any phase at ±7 kW; and for the complete IPB at ±5 kW.

IPB EFFICIENCY

The bus flux efficiency is defined in Appendix B. It is approximately 98 per cent for the star portion and 92 per cent for the delta portion. Shorter sections of bus operate at an efficiency as low as 78 per cent, approximately.

It should be pointed out that the current efficiency (the ratio of enclosure current to the bus current) is 99.98 per cent for a flux efficiency of 98 per cent, 99.68 per cent for 92 per cent, and 97.5 per cent for 78 per cent.

DISCUSSION

The measured loss of 384 kW for the IPB is 23 per cent higher than the calculated loss of 311 kW. The difference is probably due to the calculation not accounting for the losses due to various discontinuities in the bus and other reasons. These include the losses in the end plates, losses due to proximity effects between the phases, losses in joints and bends, losses due to cut-outs, and stray losses in metallic hardware structures. The stray losses are not expected to be large due to the high flux efficiency of the bus; they do, however, include the losses of support insulators for a total of about 4 kW (80 insulators @ 50 W), approximately. (See Research Division Report No 76-21-K.)

Of interest is the variation in the estimated error for the measurements. The low estimated error for the complete IPB of only ±5 kW, is due to the mutual cancellation of errors due to induced polyphase voltages in the potential leads. The errors would be smaller, especially for the individual sections and phases, if the potential leads had been extended further away from the IPB.

It should be pointed out that according to the IEEE guide*, the cooling fan motor power should be added to the 384 kW quoted in this report to obtain the total IPB loss.

Now that the equipment for performing loss measurements on IPB's is available, measurements in the same or other stations can be performed at a minimal cost. The results of such measurements are useful in determining the compliance of IPB's to specified loss figures, and to assure that the losses in IPB's are not excessive in stations where the IPB's are very long.

---

* Proposed Guide for Calculating Losses in Isolated-Phase-Bus. IEEE Committee Report. IEEE Transactions. Vol 87. No 8. August 1968. p 1730.

CONCLUSIONS

The power loss in the isolated phase bus of Unit 2 at Bruce GS has been determined at 384 kW for a current of 27.8 kA. The losses of individual sections have not been determined with sufficient accuracy to locate any localized losses.

Approved:

J.R. Leslie
Manager
Electrical Research Dept

Submitted:

O.W. Iwanusiw
Engineer - Instrumentation
Instrumentation & Standards Section

OWI/ldh

APPENDIX A

CALCULATION OF LOSSES

Calculated in this appendix will be the theoretical loss of the isolated phase bus. The calculations assume a resistivity of 2.83 μΩ·cm for the aluminum at 25°C, an operating temperature of 60°C, and an enclosure current equal to bus current. The calculations do not include the effects of joints, bends, cut-outs in conductor or enclosure, and proximity of other phases. The calculations also do not include losses in end plates and other discontinuities.

DATA

Star Bus - conductor - 495.3 mm outside diameter - 12.7 mm wall
- enclosure - 1003.3 mm outside diameter - 9.8 mm wall

Delta Bus - conductor - 342.9 mm outside diameter - 7.6 mm wall
- enclosure - 787.4 mm outside diameter - 4.8 mm wall

CALCULATION OF RESISTANCES

Section	Area (mm^2)	dc Resistance	Skin Effect*	ac Resistance
Star Bus	19 762	1.62 μΩ/m	1.14	1.85 μΩ/m
Star Encl.	30 889	1.04 μΩ/m	1.05	1.09 μΩ/m
Delta Bus	8 187	3.92 μΩ/m	1.02	4.00 μΩ/m
Delta Encl.	11 874	2.70 μΩ/m	1.01	2.73 μΩ/m

CALCULATION OF LOSSES

Phase	Section	Length (m)	Resistance**(μΩ)	Loss***(kW)	Totals
R	R	34.3	100.8	77.9	
R	WR	10.7	72.0	18.4	
R	BR	17.4	117.1	30.0	126.3
W	W	32.6	95.8	74.0	
W	RW	9.5	63.9	16.4	
W	BW	3.9	26.2	6.7	97.1
B	B	28.4	83.5	64.5	
B	WB	3.9	26.2	6.7	
B	RB	9.6	64.6	16.5	87.7
				TOTAL	311.1

* Proposed Guide for Calculating Losses in Isolated-Phase Bus. IEEE Committee Report. IEEE Transactions. Vol 87. No 8. August 1968. p 1730.

** Bus and Enclosure Combined.

***Assumes 27.8 kA for Star and 16 kA for Delta sections.

APPENDIX B

SUMMARY OF MEASUREMENTS

Presented in this appendix are the results of field measurements performed on the IPB of Unit 2 at Bruce GS. The results are the averages of a number of readings. Corrections to allow for the finite loop of the potential leads are not included.

IPB LOSSES

Phase	Section	Loss (kW)	Totals	Loss (kVA)	Totals
R	R	118		1837	
R	WR	4		165	
R	BR	26	148	267	2269
W	W	104		1729	
W	RW	16		142	
W	BW	-9	111	67	1938
B	B	124		1640	
B	WB	1		56	
B	RB	-5	120	157	1853
		TOTAL	379 kW		6060 kVA

IPB EFFICIENCY

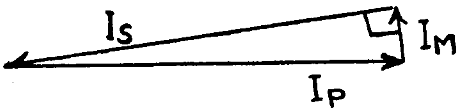
The isolated phase bus in question is of the mini-flux design, wherein the current in the enclosure is nearly equal to the current in the bus. In this manner the flux outside the IPB is very small and is due to the magnetizing current required to induce the current in the enclosure. This magnetizing current was measured during the tests using a self-shielding Rogowski-type ammeter. It should be pointed out that for this application the magnetizing current can be assumed to be 90° from the enclosure current.

Thus: $I_p^2 = I_S^2 + I_M^2$ or $I_p = \sqrt{I_S^2 + I_M^2}$

where I_p = measured bus current

I_S = enclosure current

I_M = measured magnetizing current.



For the purpose of this report, the flux efficiency of the IPB is defined as

$$E_f = 1 - I_M/I_p$$

and the current efficiency of the IPB is defined as

$$E_i = I_S/I_p$$

Section	Current (I_p)	Current (I_M)	Flux Efficiency (%)
R near Generator	27.8 kA	0.92 kA	96.7
W near Generator	27.8 kA	0.40 kA	98.6
B near Generator	27.8 kA	0.30 kA	98.9
R near PT Cubicle	27.8 kA	0.54 kA	98.1
W near PT Cubicle	27.8 kA	0.76 kA	97.3
B near PT Cubicle	27.8 kA	0.53 kA	98.1
R near Heat Exchanger	27.8 kA	0.62 kA	97.8
W near Heat Exchanger	27.8 kA	0.81 kA	97.1
B near Heat Exchanger	27.8 kA	0.58 kA	97.9
WR delta	16 kA	1.2 kA	92.5
WB delta	not measured		
BR delta	16 kA	1.4 kA	91.2
RW Transformer bushing enclosure	16 kA	2.6 kA	83.7
WB Transformer bushing enclosure	not measured		
BR Transformer bushing enclosure	16 kA	2.7 kA	83.1
R-line CT enclosure*	27.6 kA	6.4 kA	77.0
W-line CT enclosure*	27.6 kA	1.9 kA	93.2
B-line CT enclosure*	27.6 kA	5.0 kA	82.0
R-neutral CT enclosure*	27.6 kA	6.0 kA	78.4
W-neutral CT enclosure*	27.6 kA	2.0 kA	92.8
B-neutral CT enclosure*	27.6 kA	6.0 kA	78.4

* These measurements were made at the terminals of the generator where the generator CT's are mounted. These measuring points were not on the IPB whose losses were of interest.

APPENDIX C

CORRECTIONS TO MEASUREMENTS

Since it was impossible and impractical to locate potential leads in such a way that they would catch all the working flux from the IPB, it was necessary to determine and apply corrections to the power measurements. In this report, working flux ($\phi\alpha$) is the flux that couples both the bus and the enclosure and is therefore all the flux external to the IPB.

The wattmeter connected to the IPB measured

$$W_M = I_P{}^2R_P + \frac{\phi}{\phi\alpha}\left(I_S{}^2R_S + I_T{}^2R_T\right) \tag{1}$$

where W_M = measured power in watts

I_P = bus current

R_P = bus resistance

I_S = enclosure current

R_S = enclosure resistance

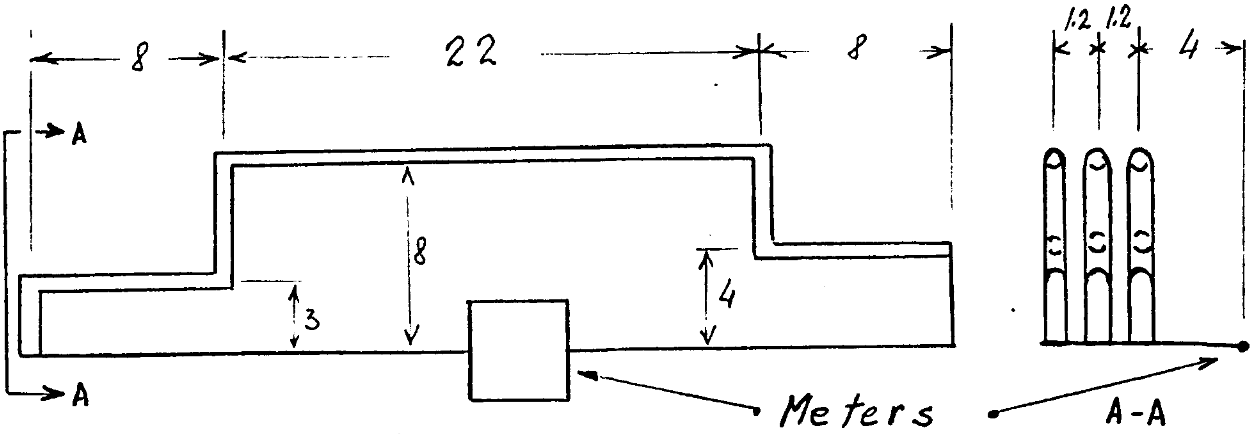
I_T = stray loss current

R_T = stray loss resistance

ϕ = flux enclosed by measuring loop

$\phi\alpha$ = flux enclosed by an infinitely large measuring loop.

The calculations of flux were carried out using net currents of 600, 800, and 600 amperes for the R, W, and B phases respectively. The IPB and potential leads were considered to have the dimensions as shown below. Details regarding the method of calculation will be reported separately.



Dimensions in metres

The following rms values of flux (ϕ) were determined:

R = 3762 μWb

W = 5245 μWb

B = 4713 μWb

The value for $\phi\alpha$ was determined by computing the flux in a square area 10 times the length of the bus on each side. The following values of $\phi\alpha$ were determined:

R = 4345 μWb

W = 5323 μWb

B = 4345 μWb

Using the above values of flux, the following ratios of $\phi/\phi\alpha$ were determined:

R = 0.866 (2)

W = 0.985 (3)

B = 1.085 (4)

For the purpose of applying corrections, it was assumed that R_T in Equation (1) was zero. Using resistance figures from Appendix A, it was determined that 62 per cent of the losses are due to the bus and 38 per cent due to the enclosure, approximately.

Using Equation (1), values (2), (3), and (4), and the above percentage losses the following table was computed.

Phase	Measured Losses					
	Direct Measurement			Corrected Losses		
	Total	Bus	Enclosure	Bus	Enclosure	Total
R	148	97	51	97	59	156
W	111	69	42	69	43	112
B	120	72	48	72	44	116
TOTAL	379				TOTAL	384

APPENDIX D

THE MEASURING EQUIPMENT

The equipment used for the measurement consisted of

a) nine special potential transformers,

b) a combination transducer for volts, amperes, watts and vars,

c) three generator metering current transformers,

d) six transducer-input isolating current transformers,

e) a zig-zag grounding current transformer,

f) a three-winding delta balancing current transformer.

The nine potential transformers were used to isolate and measure the voltage across each of the nine sections of IPB. The transformers had a 10-to-1 step down ratio, were rated for use in a 5 kV circuit (19 kV test), were shielded and exhibited a very small phase angle error. The transformers were mounted inside a metal cabinet and were connected to the IPB by means of RG-8/U coaxial cables.

The transducer provided dc constant current output (0-1 mA) for voltage, current, watts and vars. The outputs of the transducer were loaded with suitable resistors so that a digital voltmeter, connected across the resistor, would read the IPB current, voltage drop, power and reactive power directly in amperes, volts, and kilowatts, kilovars, by merely moving the decimal point. The rated input of the transducer was 10 volts on the voltage and 10 milliamperes on the current.

The watt and var elements of the transducer had phase angle adjustments. These were adjusted during the calibration of the assembly to compensate for any phase angle errors of the potential and current transformers.

The three generator metering current transformers had 5-ampere secondaries, and were used to measure the current in the IPB. These transformers were calibrated at the Research Division prior to installation.

The six input current transformers had a ratio of 5 amperes to 10 milliamperes. The use of these transformers eliminated the need to switch the 5-ampere currents during the measurements. Three of these transformers were used to determine the current in the star section of the IPB, and three for the delta section of the IPB.

The zig-zag grounding current transformer was provided to drain off the small amount of zero sequence current that may have been present. It was also needed to provide a path for the zero sequence current in the event of a ground fault.

A three-winding delta balancing current transformer was used to force the balance of the three secondary delta currents.

Appendix E shows the circuit diagrams for the measuring equipment.

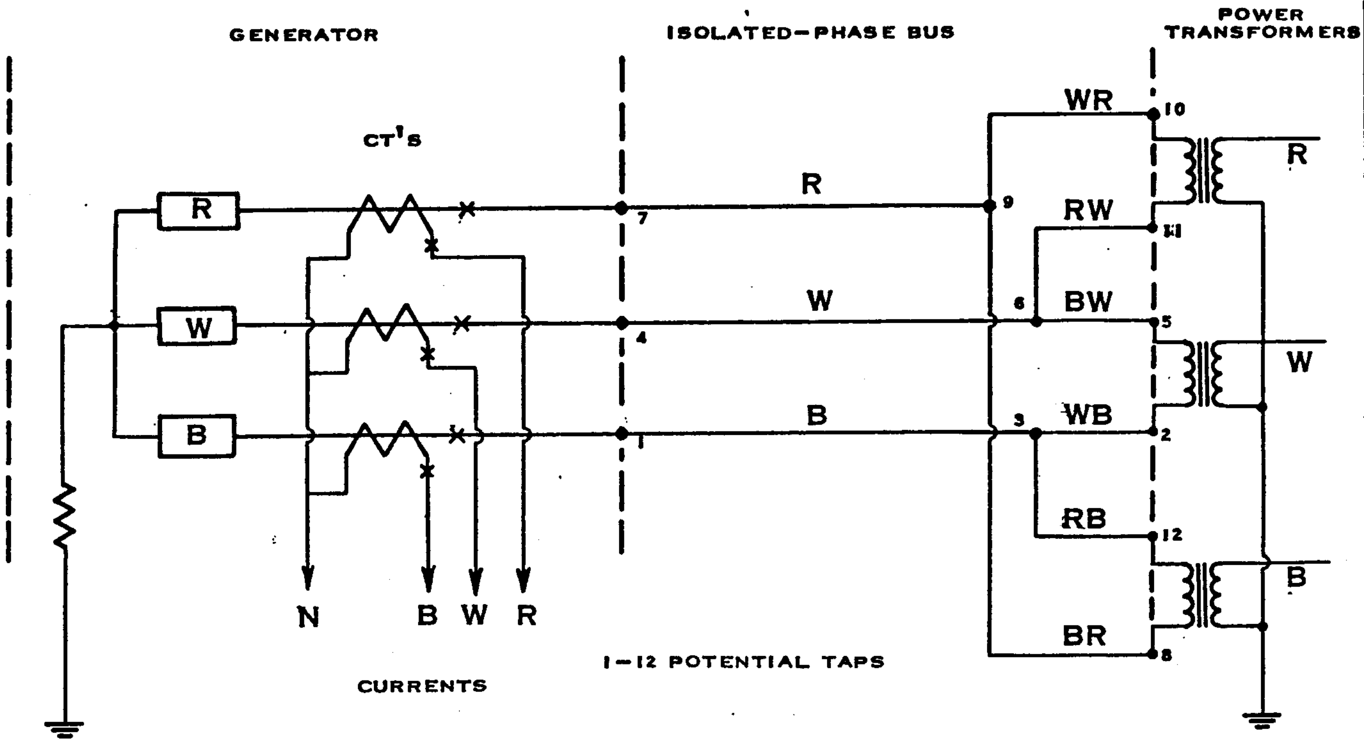


FIGURE I

ISOLATED—PHASE BUS MEASUREMENTS
ARRANGEMENT FOR OBTAINING CURRENTS AND VOLTAGES

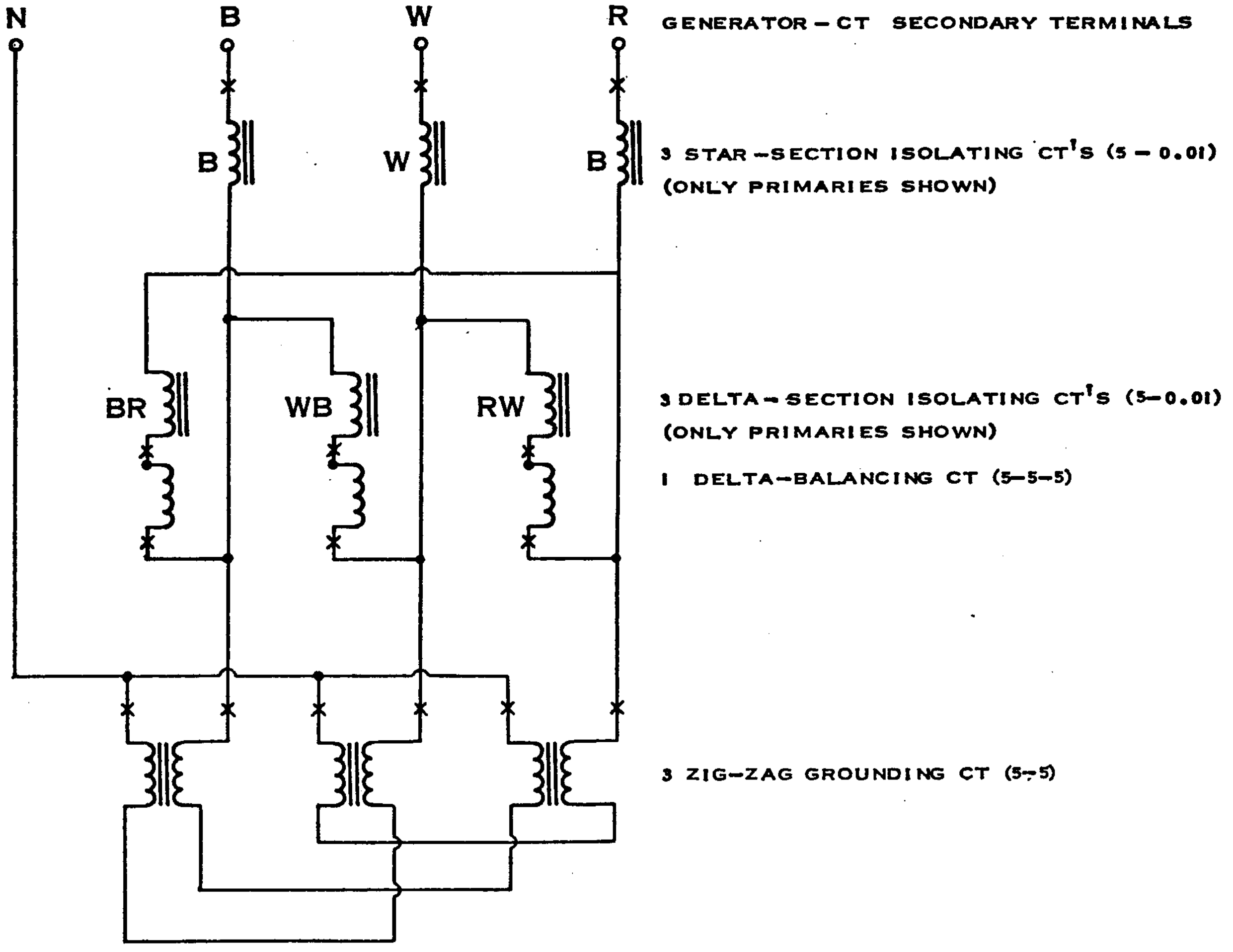


FIGURE 2

ISOLATED—PHASE BUS MEASUREMENTS
CURRENT CIRCUIT

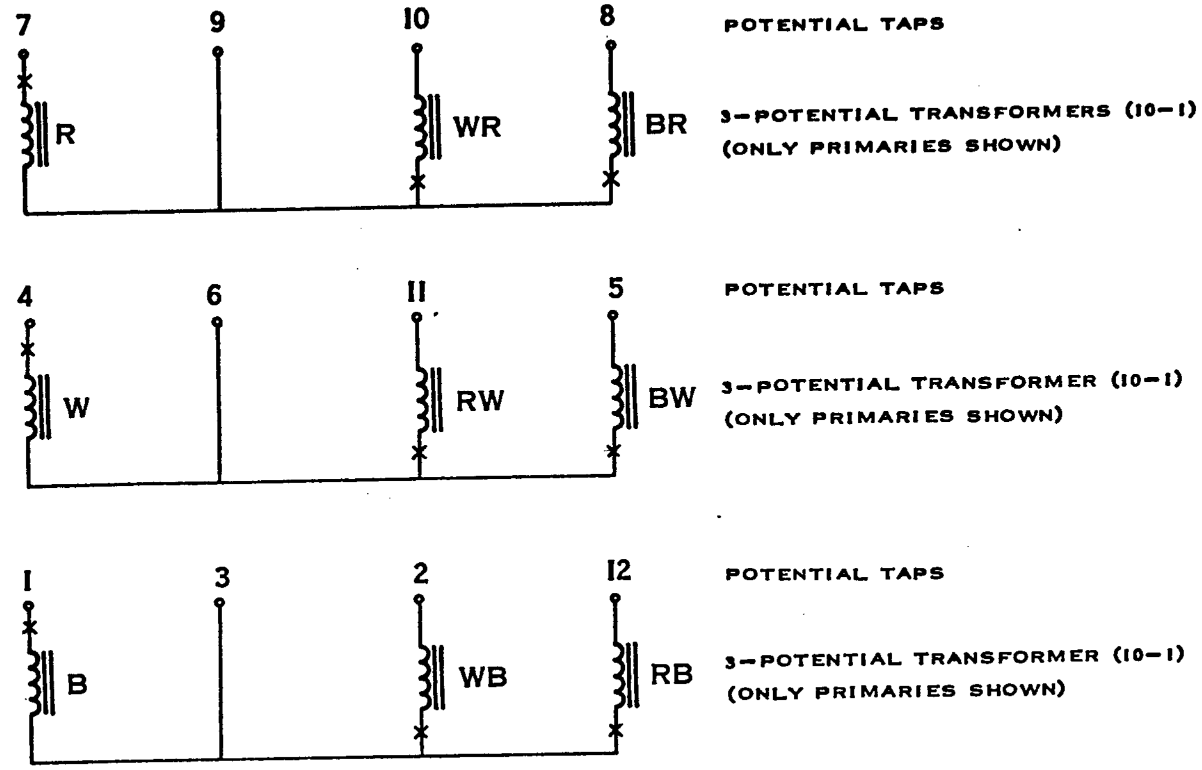
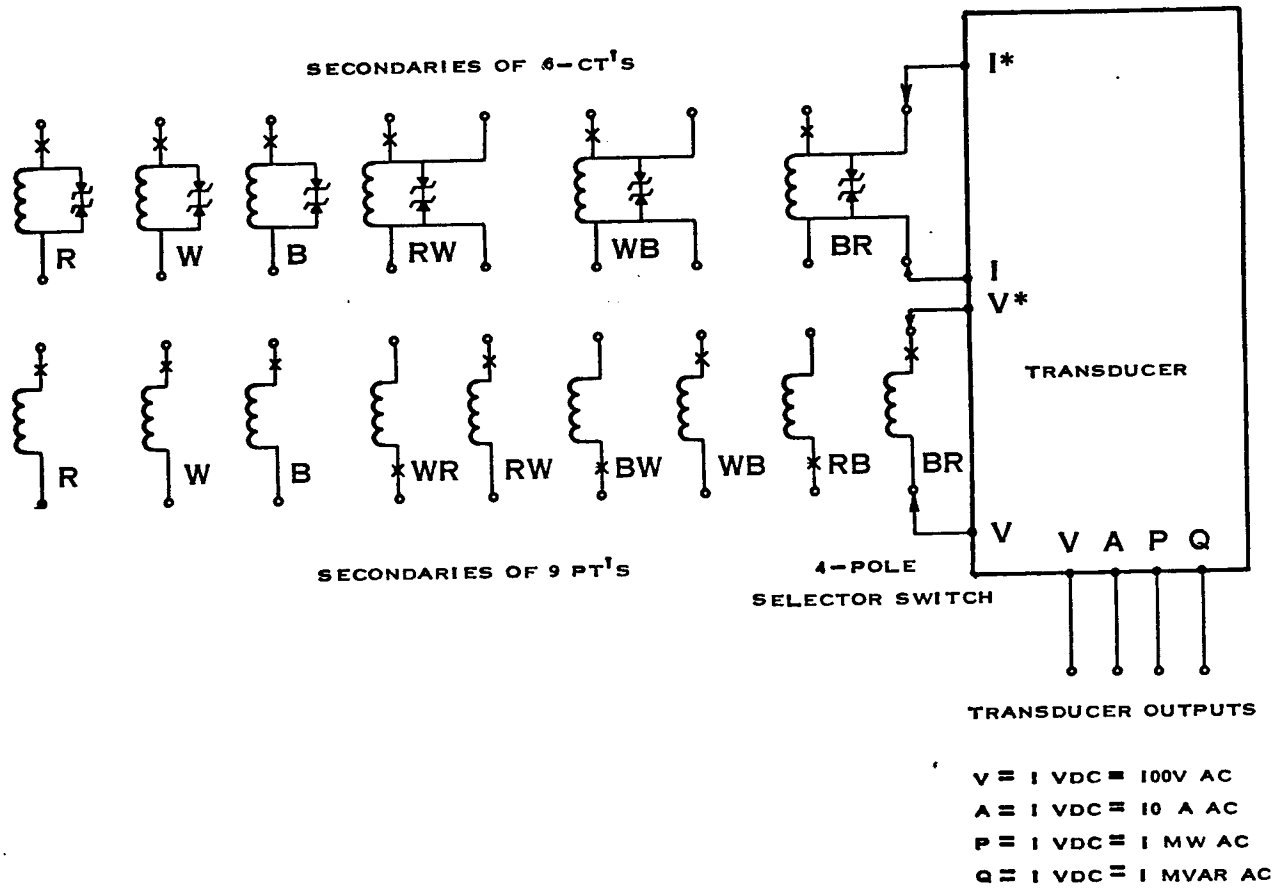


FIGURE 3

ISOLATED-PHASE BUS MEASUREMENTS
POTENTIAL CIRCUIT



V = 1 VDC = 100V AC
A = 1 VDC = 10 A AC
P = 1 VDC = 1 MW AC
Q = 1 VDC = 1 MVAR AC

FIGURE 4

ISOLATED-PHASE BUS MEASUREMENTS
TRANSDUCER CIRCUIT

APPENDIX E

THE MEASURING CIRCUIT

The attached Figures 1 to 4 show the arrangement of current transformers, potential transformers, selector switch and transducer used during the tests.

Potential leads were connected at tap points numbered 1 to 12 in Figure 1. Tap points 1, 4, and 7 were located on the bus near the flexible braid connections between the bus and the water-cooled generator terminal conductors. Tap points 2, 5, 8, 10, 11, and 12 were located on the bus near the flexible braid connections between the bus and the unit transformer bushings. Tap points 3, 6, and 9 were at the junction between the star and delta portions of the IPB.

It will be noted that the generator current transformers were used to measure the currents in the star section of the IPB, and that an artificial secondary delta circuit was used to measure the currents in the delta sections. This was done because there were no current transformers located in the delta section.

Figure 2 shows the artificial secondary delta circuit containing three isolating CT's connected to measure the delta currents. The balance of the artificial-delta currents was forced by the delta-balancing CT. The balance of the currents was assumed because of the assumed balance of the short-circuit primary impedances during the test.