NELWAY SUBSTATION

PHASE SHIFTING TRANSFORMER PROTECTION

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ABSTRACT

The application of the Nelway phase shifting transformer is new technology for B.C. Hydro. The theory behind this technology will be discussed. The protection devices may be off-the-shelf items but their application is unique and requires a thorough knowledge of how phase shifting transformers work.

As well as a discussion on the protection and control, a remedial action scheme will be discussed. This scheme, developed by B.C. Hydro, offers some unique features which provide an automatic means to control overloads through the phase shifting transformer.

INTRODUCTION

Studies of the B.C. Hydro and Bonneville Power Administration systems, performed by B.C. Hydro's System Transmission Planning Department, had identified the need for controlling the loop power flow between the systems. Fig. 1 shows the undesirable loop flow that can occur between the two systems, and identifies circuit 2L112 Nelway to Boundary. Fig. 2 shows other paths and directions that the loop flow can take depending upon generation schedules and import/export conditions to other utilities.

Of the many alternatives considered, the installation of a phase shifting transformer at Nelway substation was viewed to be economic and effective. The savings in system losses result in a payback period of approximately three years.

The concept of how a phase shifting transformer can control loop power flow is illustrated in Fig 3.

Aside from the obvious benefit of reducing system losses by reducing the loop power flow, the Nelway substation phase shifter installation also offers:

- Operating flexibility in being able to adjust the voltage angle locally, prior to reenergizing the transmission circuit
- Relieving the loading on some system transformers
- Increased voltage stability margins on transmission lines by releasing transmission capacity otherwise taken up by the loop flow
- Eliminating restrictions on the transfer capability with Trans Alta Utility Corporation (a neighbouring utility in the province of Alberta) due to overloading of 2L112

PHASE SHIFTING TRANSFORMERS - HOW THEY WORK

Phase shifting transformers are designed with many different winding configurations, with the type of design governed in large part by the system requirements and economics. Configurations include a hexagonal design, typically used for fixed phase shift applications and the grounded wye configuration, which is the design applied at Nelway Substation. The grounded wye configuration, which is sometimes referred to as a conventional shifter, consists of two separate tanks: a series unit and an exciting unit which are electrically connected as shown in Fig. 4. As illustrated, the only connections to the power system are the '**S**' and '**L**' bushings.

The grounded wye configuration offers advantages of graded excitation winding insulation, grounded neutral, constant zero sequence impedance, and a design convenient for +/- regulation. The disadvantages are that the series and exciting units are in separate tanks which have to be interconnected by a metal tube or throat and the large size of each individual unit. These transformers are the largest units which have been installed on the B.C. Hydro system. The exciting unit weighs close to 800,000 pounds with the series unit weighing 700,000 pounds. The basic electrical specifications of the transformer as applied at Nelway Substation are:

- 240/320/400 MV.A ONAN/ONAF/ONAF
- 230,000 GRD Y/132,790 VOLTS
- No load phase shift: variable to +/- 40 degrees
- 33 tap changer steps
- Approximate phase shift per step: 2.5 degrees

The MV.A rating for the phase shifting transformer was selected on the basis of a 400 MV.A summer rating of circuit 2L112. The unit was designed to have a 30 minute 600 MV.A overload rating to allow for corrective action during system disturbances. A single 400 MV.A unit was chosen due to lower cost. Two 200 MV.A units would have been significantly more expensive and taken up twice as much space. Two phase shifting transformers could only be accommodated with extensive station revisions due to existing space limitations.

A phase shifting transformer shifts the voltage through the interaction of the series and exciting units. The exciting unit impresses a quadrature voltage across the secondary of the series winding, causing a voltage phase shift to be created across the primary of the series winding. Fig. 5 illustrates the basic principles involved in developing this quadrature voltage. As shown in the figure, the voltage V_{BC} is in quadrature with the voltage V_A.

The way in which these quadrature voltages are developed in the phase shifting transformer is described in Fig. 6. To avoid confusion, the figure only shows how the quadrature voltage is developed to shift the A phase voltage in the phase shifter. From the figure, it is obvious that the adjustment of taps in the secondary of the excitation unit will determine the magnitude of the voltage impressed upon the primary winding of the series unit hence, the degree of phase shift.

Some interesting observations can be made from the basic electrical specifications of the phase shifting transformer. Fig. 7 shows, from the basic parameter of a maximum 40 degree phase shift, the derivation of the voltage rating of the series winding. As illustrated, it is 90.8 kV. As shown later, this rating can have a significant impact on the protection applied to the transformer. The voltage rating of the phase shifter can also be used to derive the actual winding rating. From Fig. 7 it is also clear that the series transformer is physically constructed as a 273.5 MV.A unit to deliver the 400 MV.A specified rating. This applies to the excitation winding as well as shown by the calculation in Fig. 8.

The positive sequence through impedance of the phase shifter as viewed by the HV system varies from 11.5 % (400 MV.A) at the zero shift position to 18.5 % (400 MV.A) at the maximum phase shift (reference Fig. 9). The zero sequence impedance however remains constant over the range. As shown in Fig. 10, zero sequence current flows in the secondary of the series unit which is delta connected. Since this current is in phase in each winding, it can never get out to the excitation unit. Therefore tap movement in the excitation unit has no influence on the series unit zero sequence impedance.

As well as the through impedances of the series unit, it is important to establish whether or not the phase shifting transformer is a source of zero sequence current to HV faults. This depends solely upon the core construction of the excitation unit. For a five limbed core, as shown in Fig. 11, the flux has a return path through the iron of the transformer resulting in a high winding reactance. For a three limbed core, as shown in the figure, the winding reactance is low due to the magnetic flux return path through air. For the case of the Nelway phase shifter, the core used is a five limbed unit ie, not a source of zero sequence current to system faults.

The excitation unit impedance is another parameter which is important to allow fault calculations to be made for faults on the secondary side of the excitation unit. For the Nelway unit, the positive and zero sequence impedances vary from .1% to 7 % as the exciting unit changes taps from neutral to the maximum shift position.

Figures 12 and 13 show how the voltages and currents vary in the phase shifter with tap position. The tables are useful to check the CT secondary currents under load flow conditions.

PROTECTION CONSIDERATIONS

The protection of phase shifting transformers may seem quite complicated. However, once the operation of the unit is thoroughly understood, the protection is relatively straightforward.

The protection of the phase shifting transformer consists of several sets of transformer differential protection, exciting unit HV and LV neutral overcurrent protection and sudden pressure gas relays in the exciting and series tanks.

For overall protection of the series unit and excitation unit primary windings, three single phase multi-restraint input transformer differential relays are applied. This is shown conceptually in Fig. 14. As depicted, a CT connection is required on the centre tap of the series winding to make the currents to the relay balance under load flow and external fault conditions. The CT ratios are all the same for this protection hence, for maximum sensitivity all relay taps can be set at minimum. Fig. 15 shows the actual arrangement (protection device designated 87TS) at Nelway substation and as well, depicts the station configuration. One notable feature is the bypass consisting of 2CB7.

To cover faults on the secondary windings of the series and exciting units a different set of differential protection is applied (designated 87T) as shown in Fig. 16. The following important points should be noted with this protection.

- Non-standard CT ratios (2750-5) were specified at the time the phase shifter was manufactured. Fig. 17 shows how the 2750-5 ratio was derived. Fine tuning the CT ratios and the addition of one set of auxiliary CTs allowed the protection to be set at maximum sensitivity.

- There can be potential problems with saturation of the series winding which upsets the ampere turns balance of the series unit

- If a bypass is incorporated around the phase shifting transformer (as is the case with Nelway) the protection may not work properly for both the inservice case (phase shifter in service) and the bypass case (phase shifter bypassed), depending upon where the CT connections are made.

The potential problem with saturation of the series winding was reviewed, as detailed in Fig. 18, and discussed with the phase shifter manufacturer and found not to be a problem. The analysis in Fig. 18 is with the phase shifter at the maximum shift position, which is the worst case. Other installations must be analyzed on a case by case basis - the worst case may be at a different position other than maximum shift. If saturation were a problem, protection solutions are available in the literature(1).

The protection may not work properly if a bypass is applied. Fig. 19 shows how the CT connections were initially made and, how they were secure with the phase shifting transformer in service. For clarity, the CT connections to 2CB4 are not shown. For the same installation, Fig. 20 shows how these same CT connections are **not** secure with the bypass in service. The solution to the problem is to use only CTs on the phase shifter for 87T protection. This makes the protection independent of the bypass. Fig. 21 shows the protection connections as finally designed, utilizing a three restraint input transformer differential relay.

To make up for the duplicate protection coverage which is lost with the reduced protection zone (note the shaded area in Fig. 21), another set of primary protection must be provided. This is shown in Fig 22 and designated 87TA.

This protection is similar to the protection shown in Fig. 15 but applied for a different reason: to provide duplicate coverage for 230 kV faults not covered by device 87T. One aspect of these CT connections is important to mention. The CT connections made up by CT1 and CT2 in Fig. 22 are simply the difference current between these two CTs and are equivalent to the current in CT3.

There are no problems with the security of the 87TS or 87TA protection if a bypass is applied. The CT connections are straightforward delta connections. With the bypass in service the protections are secure under load flow and external fault conditions.

Ground overcurrent protection is applied to neutral CTs on the primary and secondary of the excitation unit. The primary neutral overcurrent relay is specified considering the following application criteria.

- Whether or not the excitation unit is a source of ground fault current
- Neutral unbalance current due to magnetizing inrush

As discussed earlier the excitation unit is not a strong source of ground fault current because of it's five limbed core construction. Hence, this protection can be set without regard to coordinating it with other ground relays on the HV system.

The potential problems with unbalance currents due to magnetizing inrush are difficult to quantify. In addition, the tap position of the phase shifter is an important factor, with the highest inrush current occurring when the phase shifter is in the maximum shift position. The possibility of such problems were only discovered by the author when they were mentioned by protection application engineers in the Western Area Power Administration (WAPA). From their operating experience, they have found that the ground neutral overcurrent relay may have to be replaced with a harmonically restrained device which is insensitive during the inrush period.

The WAPA situation is aggravated by the fact that the fault levels are very high and that two phase shifters are operated in parallel. With the lower fault levels at Nelway and considering there is only a single phase shifter, problems are not anticipated. Nevertheless, a monitoring program to measure neutral current when the phase shifting transformer is initially in service will be instituted.

Fig. 23 shows the primary neutral overcurrent relay designated as device 51N. The pickup of the time overcurrent element is arbitrarily set at 40% of the ONAN rating of the transformer, with the instantaneous element arbitrarily set at 9 times the ONAN rating.

A secondary neutral overcurrent relay is also applied. It is immune to the potential inrush problems described for 51N. This protection can be set quite sensitive provided the relay rating and CT ratio is sized properly to accommodate the maximum secondary single line to ground fault current. Under the conditions of the phase shifting transformer being one tap away from the neutral position these currents can be extremely high. When the ultimate fault levels of the station are reached the excitation unit fault current will be approximately 300,000A. This high value is explainable if one considers the low secondary excitation unit voltage one tap away from neutral (2.57 kV line to neutral) and the reduced impedance of the excitation unit near the minimum shift position.

Fig. 24 shows the secondary neutral overcurrent relay designated as device 51NS.

The relay settings for 51NS are equivalent to the settings applied to device 51N when the phase shifting transformer is in the maximum shift position.

Sudden pressure gas relays in the series unit and the exciting unit are connected for tripping and provide protection for isolated turn to turn faults.

A breaker failure relay is provided for zone extension tripping to cover those faults in the highlighted zone shown in Fig. 25. For a fault in the highlighted zone, phase shifter protection would operate. Tripping of circuit breakers 2CB7 and 2CB8 will not clear the infeed from the remote 2L112 terminal at Boundary. Operation of the breaker failure relay, designated 50BF7/8, will trip into 2L112 line protection keying a permissive signal to Boundary. Since the highlighted zone is small, redundant breaker failure protection was not considered necessary.

COMMUNICATIONS REQUIREMENTS: MW, LTC CONTROL

MW control of the phase shifting transformer is provided to automatically control the power flow through it. The application considerations are as follows.

The MW setpoint is controlled at the remote control centre and telemetered to Nelway. The range for the MW setpoint control is zero to +/- 400 MW, selectable with 10 MW resolution. The automatic control adjusts taps in the phase shifting transformer to maintain the specified MW. For example, the control centre operator sets the MW setpoint to the desired value of 200 MW based on the prevailing system conditions. Automatic MW control is then selected. The phase shifter will change taps to automatically maintain 200 MW flow. At some other time the operator might change the MW setpoint or manually control the phase shifter for a different set of system conditions. For the purpose of providing directional sensing of the MW flow through the transformer, a sensitive power relay is provided.

Other features of the scheme are:

- MW setpoint control has an adjustable dead band at Nelway Substation. The range of adjustment is +/- 20 to +/- 80 MW in steps of 10 MW. Once operating experience has been gained with the MW control scheme the dead band setting would remain at one setting and not be changed.

- If local manual tap changer control is selected, the remote control facilities are disabled.
- The MW control scheme senses the direction of power flow to correctly adjust the phase shifter taps in the correct direction to obtain the desired MW flow.

Fig. 26 shows, in block diagram form, the supervisory control interface between Nelway Substation and the Control Centre.

The phase shifter is connected with the L terminal primary bushings connected to the line side and the S terminal bushings connected to the station side. This reflects the natural power flow of the system - from the "Source", Nelway to the "Load" at Boundary.

Tap 33 on the phase shifter is the extreme advance position and will increase the natural power flow from Nelway to Boundary. Tap 1 is the extreme retard position and will decrease the natural power flow from Nelway to Boundary. If the power flow was in the opposite direction then the extreme advance position will tend to decrease the flow and the extreme retard position will tend to increase the flow. Fig. 27 shows these phase shifter power flow conventions at Nelway Substation. Fig. 28 shows several examples of how phase shifter tap position affects power flow.

The implementation of the MW control unit was done by the Protection and Control Design Department of B.C. Hydro using a digital I/O processor. A description is contained in the handout, Appendix 1.

BYPASS INTERLOCKS

To avoid imposing a direct short across the series unit, bypassing of the phase shifter should not be attempted at other than the no load zero shift position. The following interlocks are therefore provided.

- A contact is provided as part of the transformer to indicate the no load zero shift position. This contact allows closing of 2CB7 only when the transformer is in the no load zero shift position. <u>Note</u>: this logic is bypassed provided 2D2, 2CB8 or 2D24 is open.

- Similar interlock schemes are provided to allow closing of 2CB8, 2D2 and 2D24 when the transformer is in the no load shift position. This logic is bypassed provided at least one other switching device in the loop is open (i.e. 2D2, 2CB7, 2CB8, 2D24 as appropriate).

- When 2D2, 2CB8, 2D24, 2CB7 are all closed, the tap changer is blocked from operating.

Fig. 29 shows the position of 2D2, 2CB7, 2CB8, and 2D24 at Nelway Substation.

REMEDIAL ACTION SCHEME

A remedial action scheme is applied to limit the overload to the tap changer in the phase shifter.

For severe overloads, overcurrent relay device 50TA initiates a timer, device 50TAT. The timer blocks the tap changer and initiates an alarm "≥1.5 pu overload".

Fig. 30 shows the remedial action scheme in logic diagram form.

For less severe overloads, as indicated by hotspot temperature indicators in the series unit and excitation units, the remedial action scheme initiates an alarm "moderate overload" and the following action:

- If the phase shifter is on tap position control, the scheme automatically changes to a preset level, "RAS Runback Setpoint" (adjustable locally at the station, range 0 - 390MW, in 10 MW increments). The control then lowers the MW flow to the RAS runback setpoint setting and limits it to that value. Once the powerflow has dropped below the RAS runback setpoint the scheme will reset.

- The scheme follows through its sequence even if the initiating elements reset prior to reaching the runback setting.

- If the phase shifter is on MW setpoint control an alarm is initiated "MW Control Failure".

- If the severe and moderate overload protection have both operated, 2CB2 and 2CB4 are tripped.

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2. Li, H.J. '**Protective Relaying For Phase Angle Regulator**' Second Annual Western Protective Relay Conference, October 20-22, 1975, Spokane, Washington

3. Sen, P.K. and Craig, B.R., '**Application and Protection Considerations of Large Phase-Shifting Transformers**' American power Conference, Chicago, Illinois, April 24-26, 1989

4. Ibrahim, M. and Stacom, F., '**Protective Relaying Aspects of the Sound Cable Project**' Protective Relaying Conference, Georgia Institute of Technology, May 2-4, 1990

5. '**Applied Protective Relaying**' Westinghouse Corp., 1982

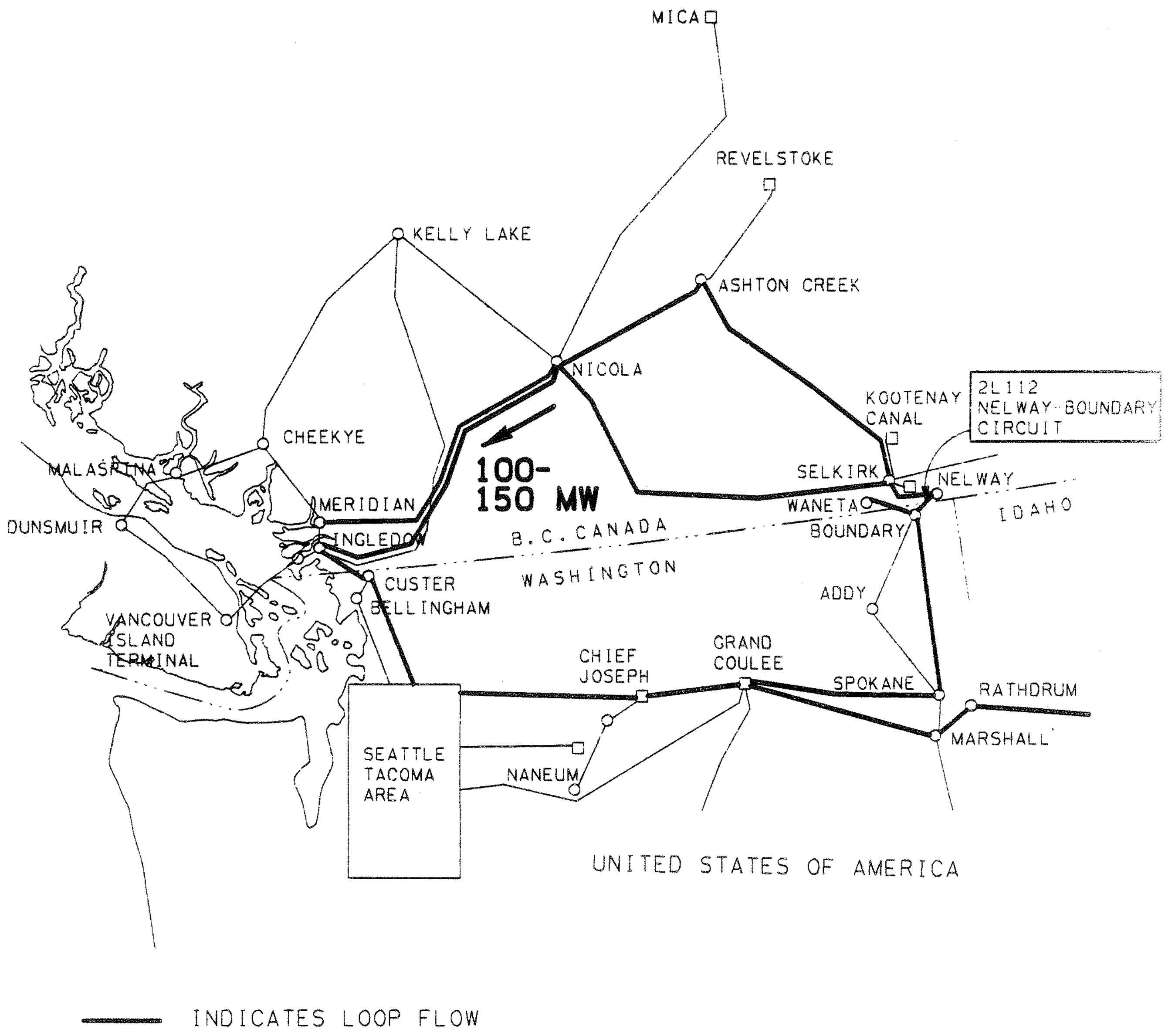
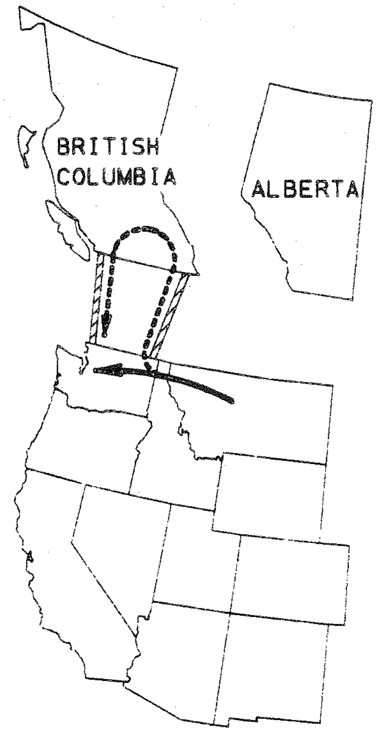

MICA
REVELSTOKE
KELLY LAKE
ASHTON CREEK
NICOLA
2L112
NELWAY-BOUNDARY
CIRCUIT
KOOTENAY
CANAL
CHEEKYE
MALASPINA
100-
150 MW
SELKIRK
NELWAY
MERIDIAN
WANETA
IDAHO
DUNSMUIR
INGLEDOW
B.C. CANADA
BOUNDARY
CUSTER
WASHINGTON
ADDY
BELLINGHAM
VANCOUVER
ISLAND
TERMINAL
CHIEF
JOSEPH
GRAND
COULEE
SPOKANE
RATHDRUM
MARSHALL
SEATTLE
TACOMA
AREA
NANEUM
UNITED STATES OF AMERICA
INDICATES LOOP FLOW

FIGURE 1



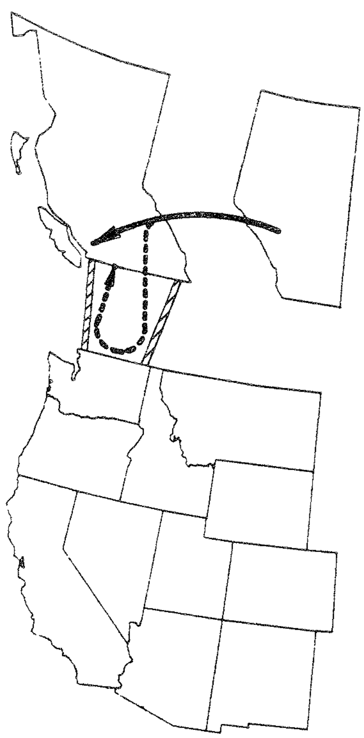
LOOP FLOW BETWEEN THE B.C. AND U.S. SYSTEMS

SCHEDULE

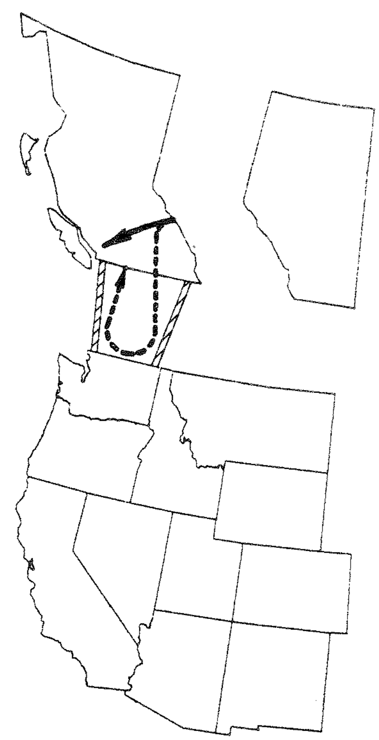
LOOP FLOW

TRANSMISSION LINE

1. DUE TO GENERATION IN U.S.A.



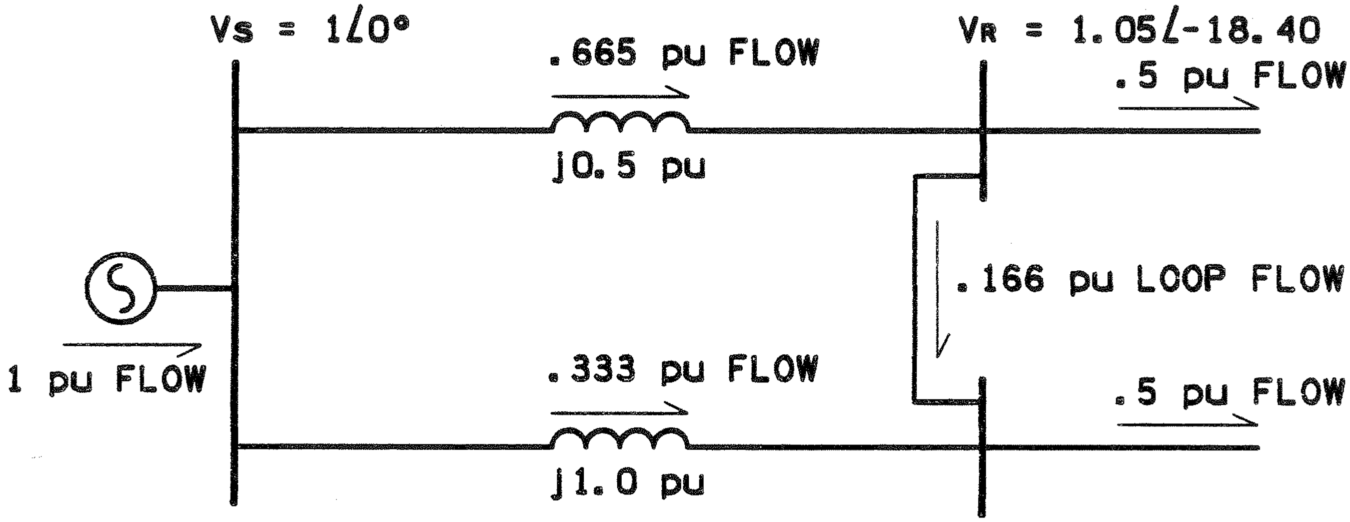
2. DUE TO ALBERTA EXPORT IN B.C.



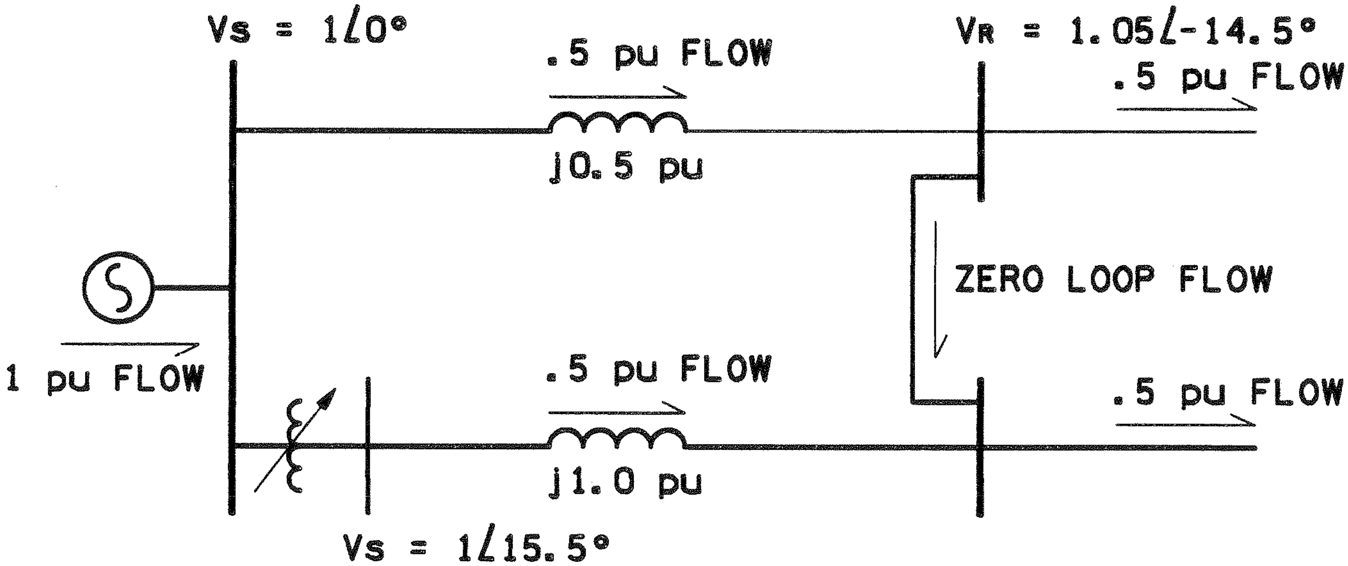
3. DUE TO COLUMBIA GENERATIO[N] IN B.C.

FIGURE 2

PHASE SHIFTING TRANSFORMERS CONTROLLING LOOP FLOW



WITHOUT PHASE SHIFTING TRANSFORMER



WITH PHASE SHIFTING TRANSFORMER

FIGURE 3

CONVENTIONAL SHIFTER

(GROUNDED WYE EXCITER)

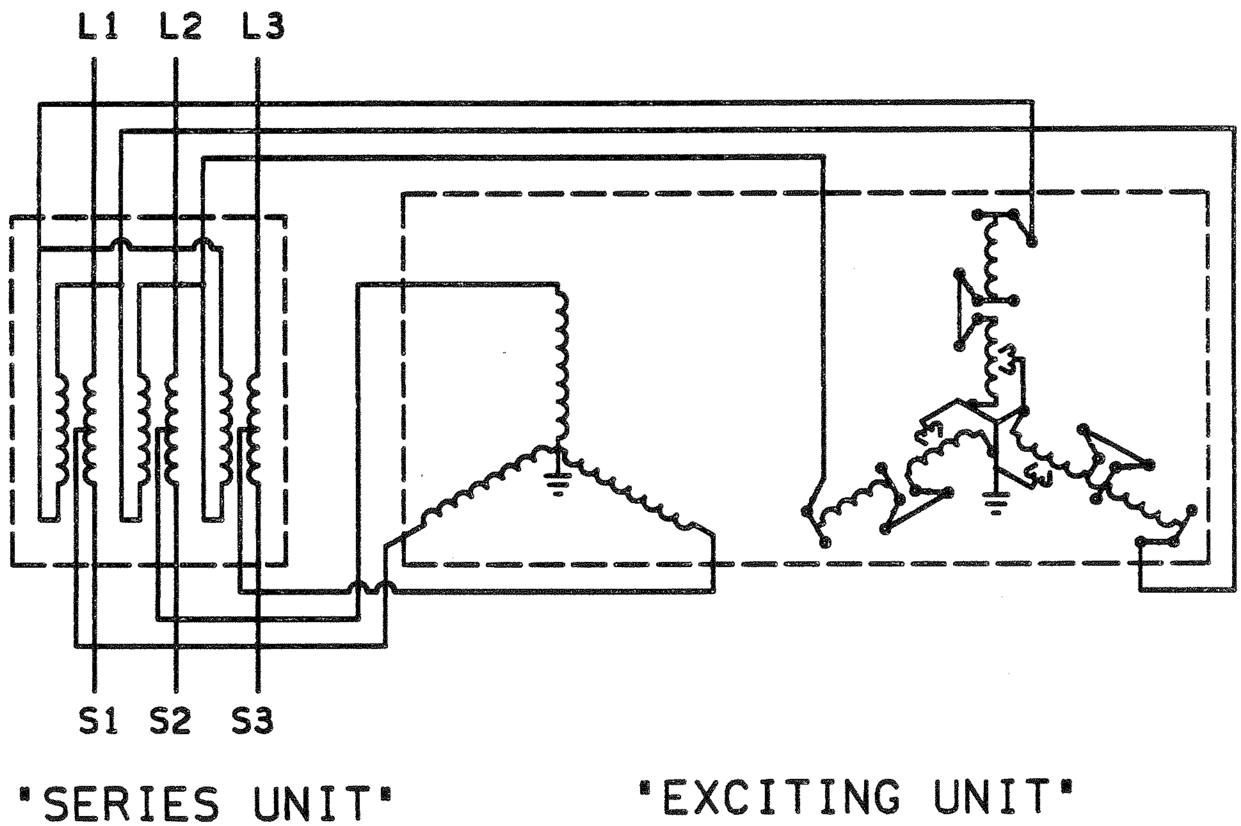
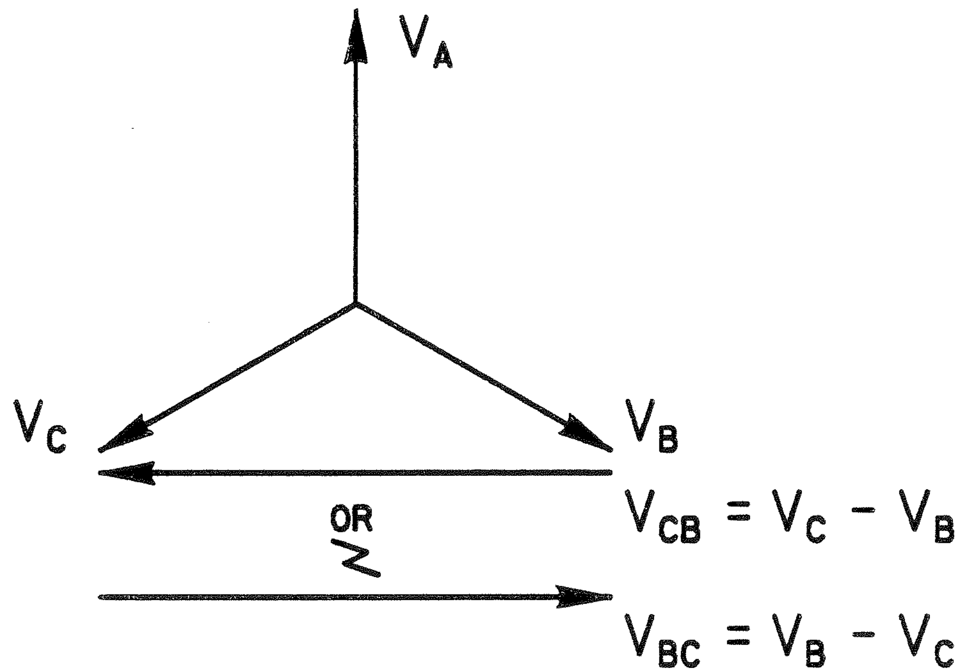
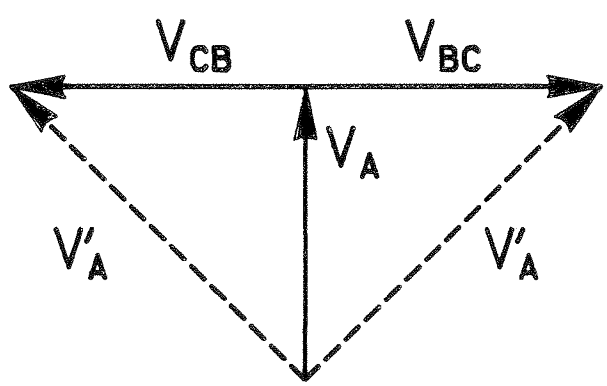


FIGURE 4

QUADRATURE VOLTAGE

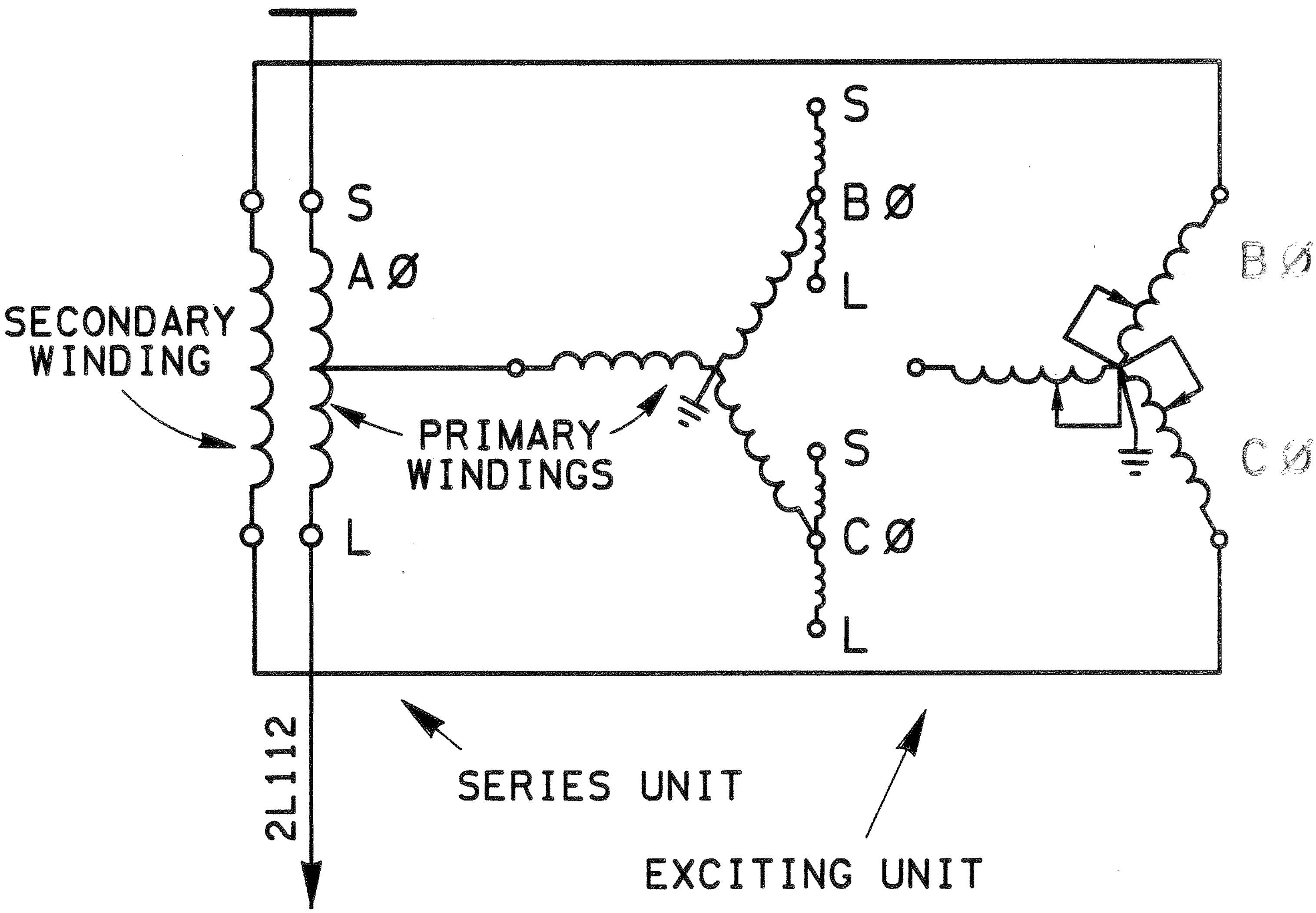




V'_A DUE TO QUADRATURE VOLTAGE ADDING TO V_A

FIGURE 5

HOW ARE QUADRATURE VOLTAGES DEVELOPED IN A PHASE SHIFTING TRANSFORMER?

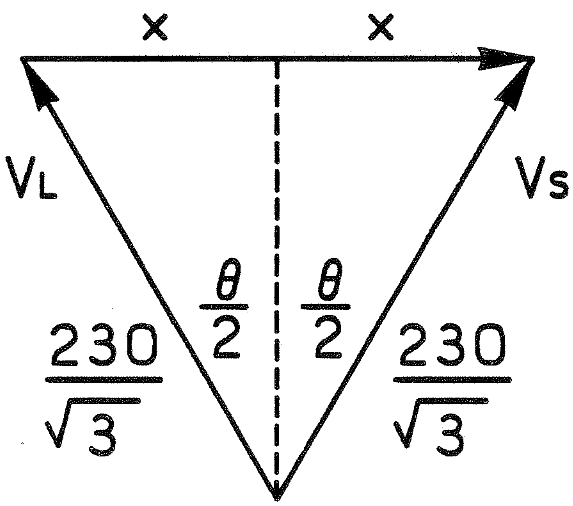


DEVELOPMENT SHOWN IS FOR AØ ONLY

FIGURE 6

SERIES UNIT RATINGS

DERIVATION OF VOLTAGE RATING



WHERE θ IS MAX. NO LOAD SHIFT (40°).

SIN $\theta/2$ = $x/230/\sqrt{3}$

SIN 20 [$230/\sqrt{3}$] = 45.4 kV

IMPRESSED VOLTAGE TO GET MAX SHIFT IS 2(45.4) = 90.8 kV

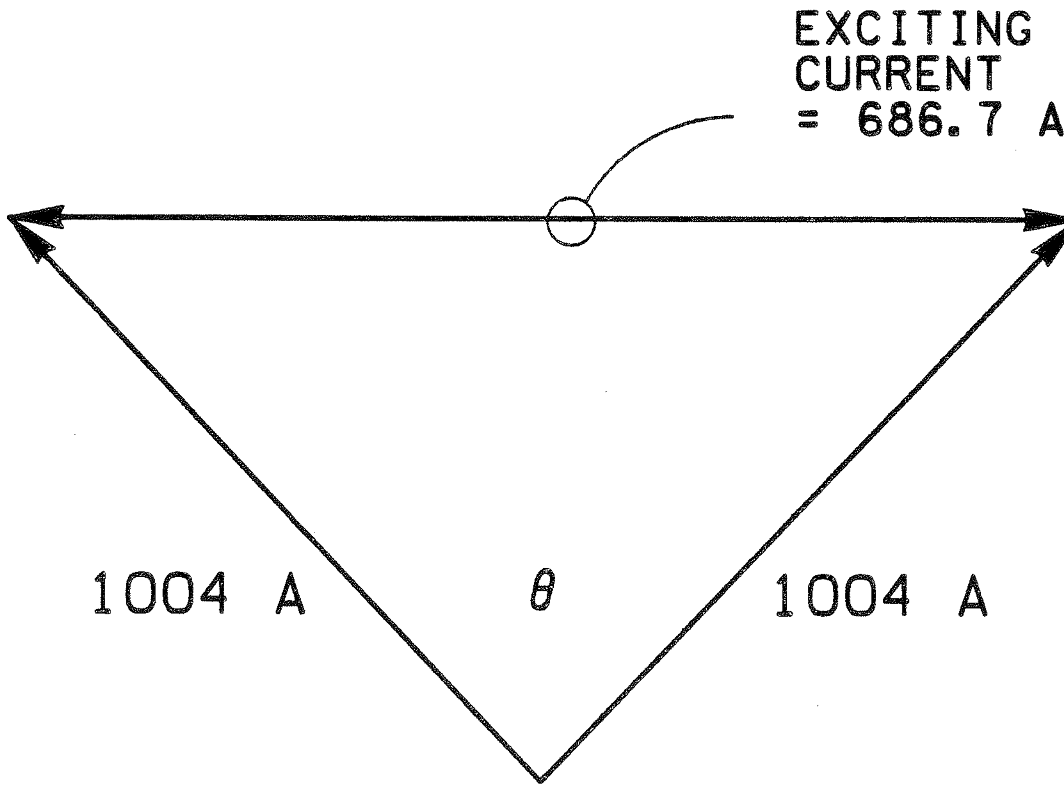
DERIVATION OF MV·A RATING

400 MV•A ===> 1004 A @ 230 kV

P = 3 X 90.8 X 1.004 = 273.5 MV•A

FIGURE 7

EXCITING UNIT RATING



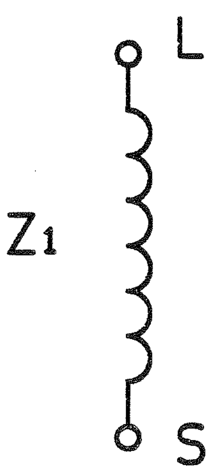
θ = 40 DEGREES

$P = 3 \times 686.7 \times 230/\sqrt{3}$

$= 273.5$ MV•A

FIGURE 8

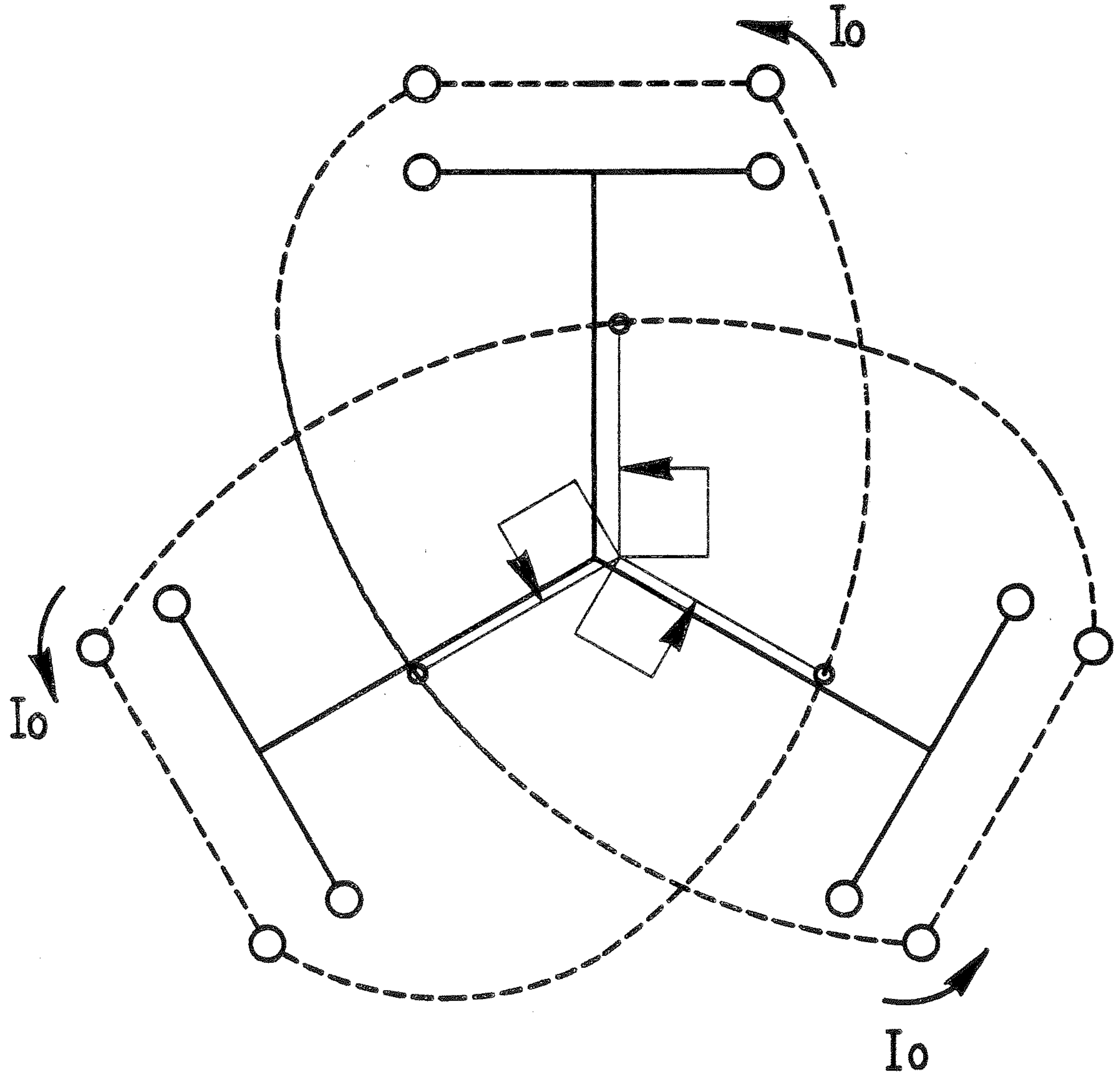
POSITIVE SEQUENCE THROUGH IMPEDANCE



Z_1 = 11.5% 400 MV·A
AT 0° SHIFT POSTION

Z_1 = 18.5% 400 MV·A
AT MAX PHASE POSITION

FIGURE 9

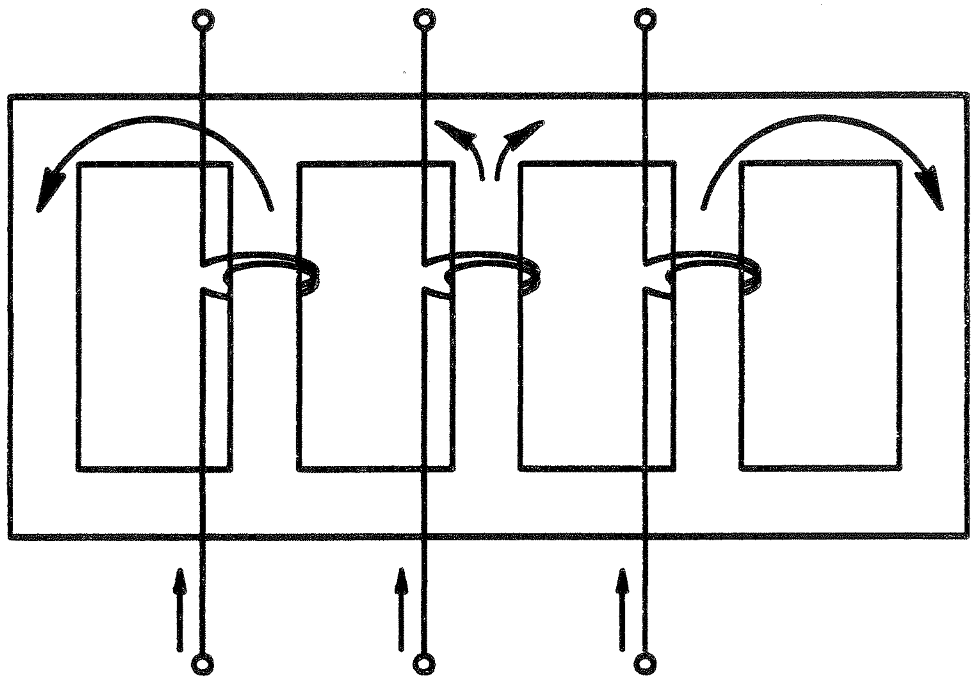


ZERO SEQUENCE CURRENT FLOWS ALONG THE DOTTED PATH

FIGURE 10

5 LIMBED CORE

WINDING
REACTANCE
HIGH



VS

3 LIMBED CORE

WINDING
REACTANCE
LOW

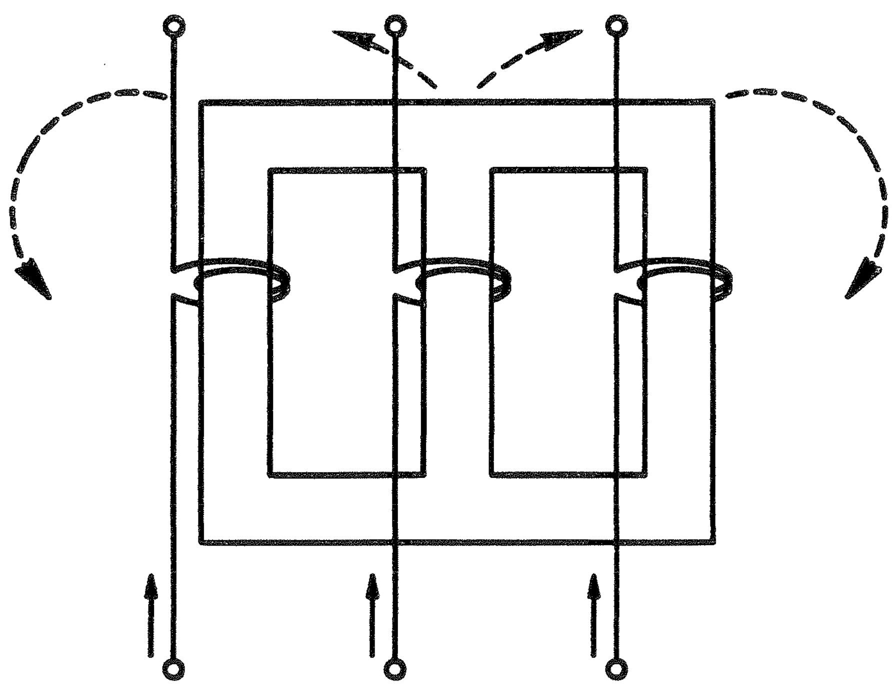


FIGURE 11

PHASE SHIFTER VOLTAGE DATA

TAP POS	EXCIT UNIT RATIO	EXCIT PRI KV L-N	EXCIT SEC KV L-N	SERIES SEC KV	SERIES PRI KV	NO LOAD SHIFT	Deg Shift per tap position
33	3.225	124.68	38.66	66.960	91.41	40.26	2.33
32	3.440	125.58	36.51	63.230	86.32	37.93	2.36
31	3.686	126.45	34.31	59.421	81.11	35.57	2.40
30	3.969	127.27	32.06	55.534	75.81	33.17	2.43
29	4.300	128.04	29.78	51.574	70.40	30.74	2.45
28	4.691	128.76	27.45	47.544	64.90	28.29	2.48
27	5.160	129.44	25.08	43.447	59.31	25.81	2.51
26	5.733	130.05	22.68	39.289	53.63	23.30	2.53
25	6.450	130.61	20.25	35.074	47.88	20.77	2.55
24	7.371	131.12	17.79	30.807	42.06	18.22	2.57
23	8.600	131.55	15.30	26.495	36.17	15.65	2.58
22	10.320	131.93	12.78	22.142	30.23	13.07	2.60
21	12.900	132.24	10.25	17.755	24.24	10.47	2.61
20	17.200	132.48	7.70	13.340	18.21	7.86	2.62
19	25.800	132.65	5.14	8.9053	12.16	5.25	2.62
18	51.600	132.76	2.57	4.4561	6.08	2.62	2.62

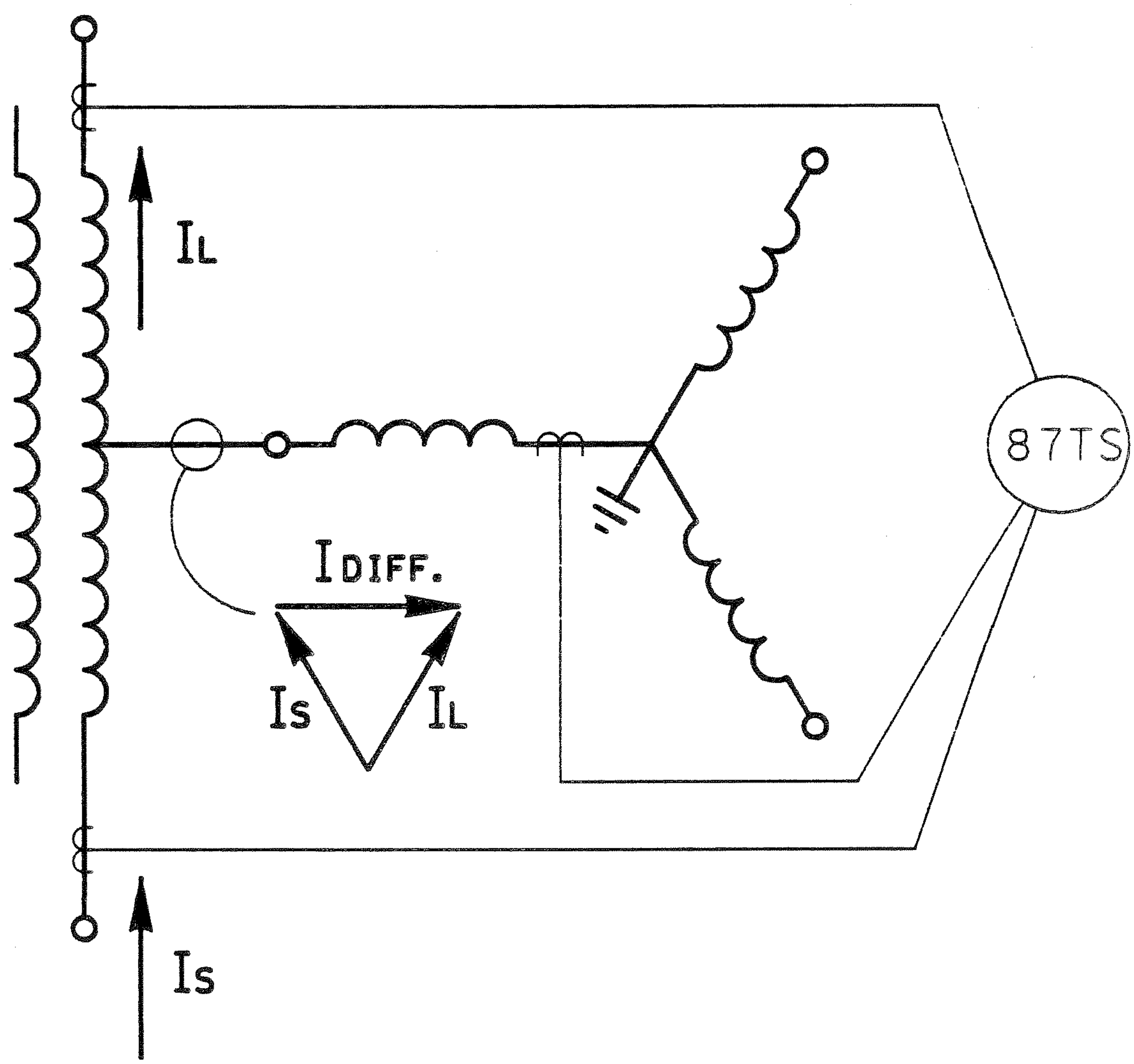
FIGURE 12

PHASE SHIFTER CURRENT DATA

TAP POS	PY S1 CURRENT		SEC. S1 CURRENT		PY L1 CURRENT		SEC. L1 CURRENT		TOTAL SEC SERIES CURRENT	
	AMPS	deg	r	+jX	AMPS	deg	r	+jX	r	+jX
33	1000	0	682.5	0	1000	40.26	520.8	441.1	1203.4	441.1
32	1000	0	682.5	0	1000	37.93	538.3	419.6	1220.9	419.6
31	1000	0	682.5	0	1000	35.57	555.2	397.0	1237.7	397.0
30	1000	0	682.5	0	1000	33.17	571.3	373.4	1253.9	373.4
29	1000	0	682.5	0	1000	30.74	586.6	348.9	1269.1	348.9
28	1000	0	682.5	0	1000	28.29	601.0	323.5	1283.6	323.5
27	1000	0	682.5	0	1000	25.81	614.5	297.2	1297.0	297.2
26	1000	0	682.5	0	1000	23.30	626.9	270.0	1309.4	270.0
25	1000	0	682.5	0	1000	20.77	638.2	242.1	1320.7	242.1
24	1000	0	682.5	0	1000	18.22	648.3	213.4	1330.8	213.4
23	1000	0	682.5	0	1000	15.65	657.2	184.2	1339.8	184.2
22	1000	0	682.5	0	1000	13.07	664.9	154.3	1347.4	154.3
21	1000	0	682.5	0	1000	10.47	671.2	124.1	1353.7	124.1
20	1000	0	682.5	0	1000	7.86	676.1	93.4	1358.7	93.4
19	1000	0	682.5	0	1000	5.25	679.7	62.4	1362.2	62.4
18	1000	0	682.5	0	1000	2.62	681.8	31.3	1364.4	31.3
17	1000	0	682.5	0	1000	0.00	682.5	0.0	1365.1	0.0

FIGURE 13

OVERALL PROTECTION OF SERIES EXCITATION UNIT



ALL CT RATIOS THE SAME

FIGURE 14

87TS PROTECTION - ACTUAL ARRANGEMENT AT NELWAY SUBSTATION

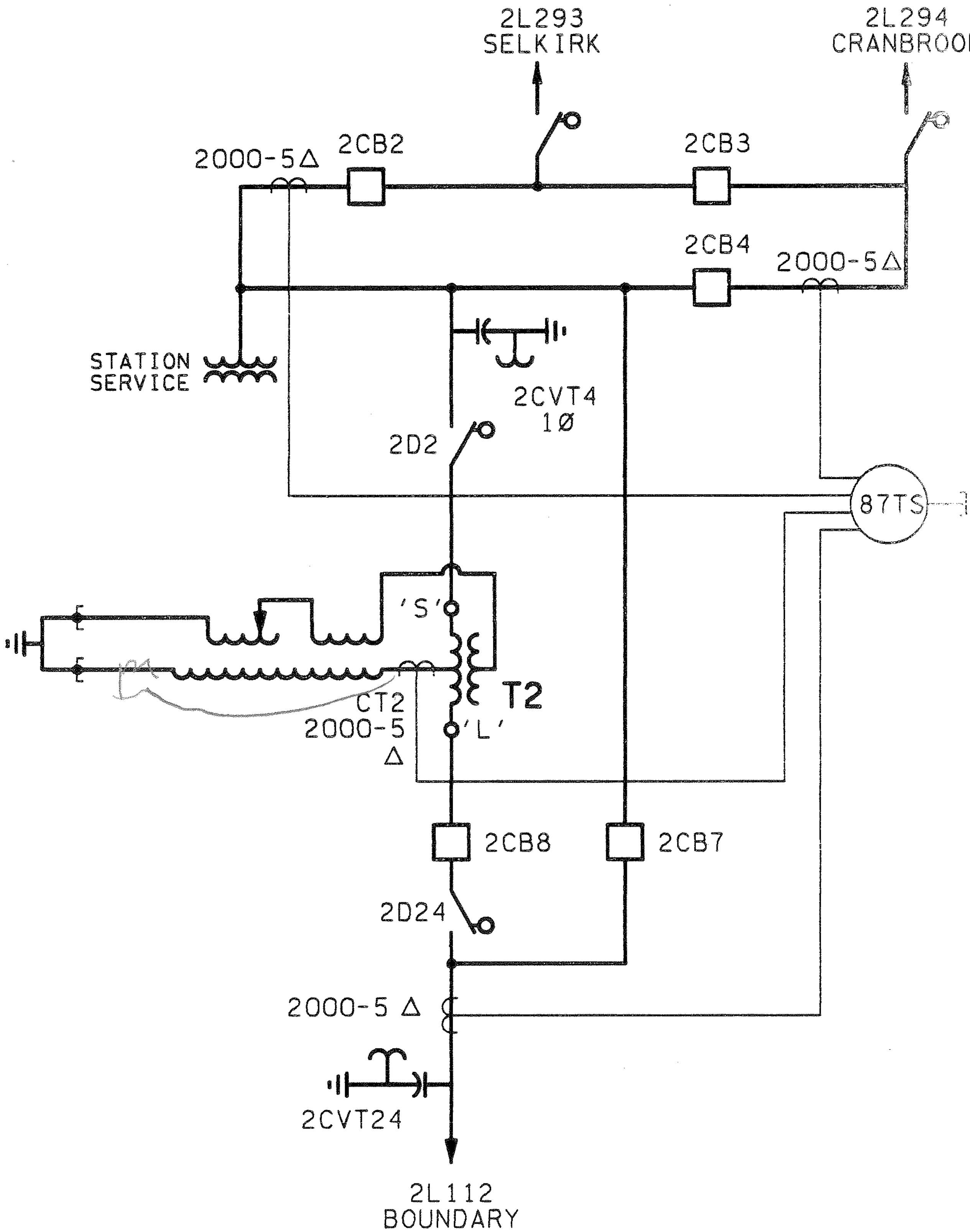
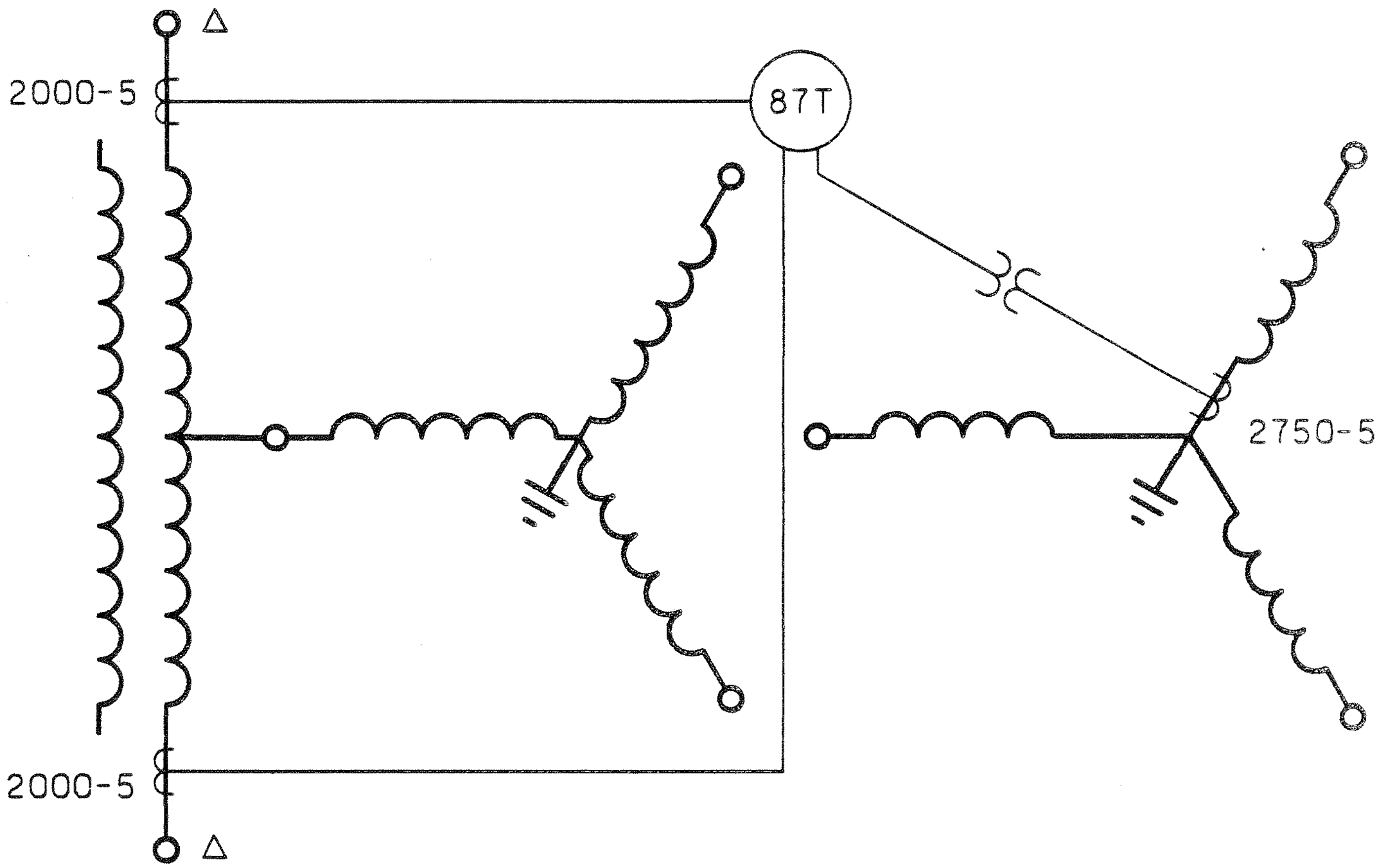


FIGURE 15

87T PROTECTION

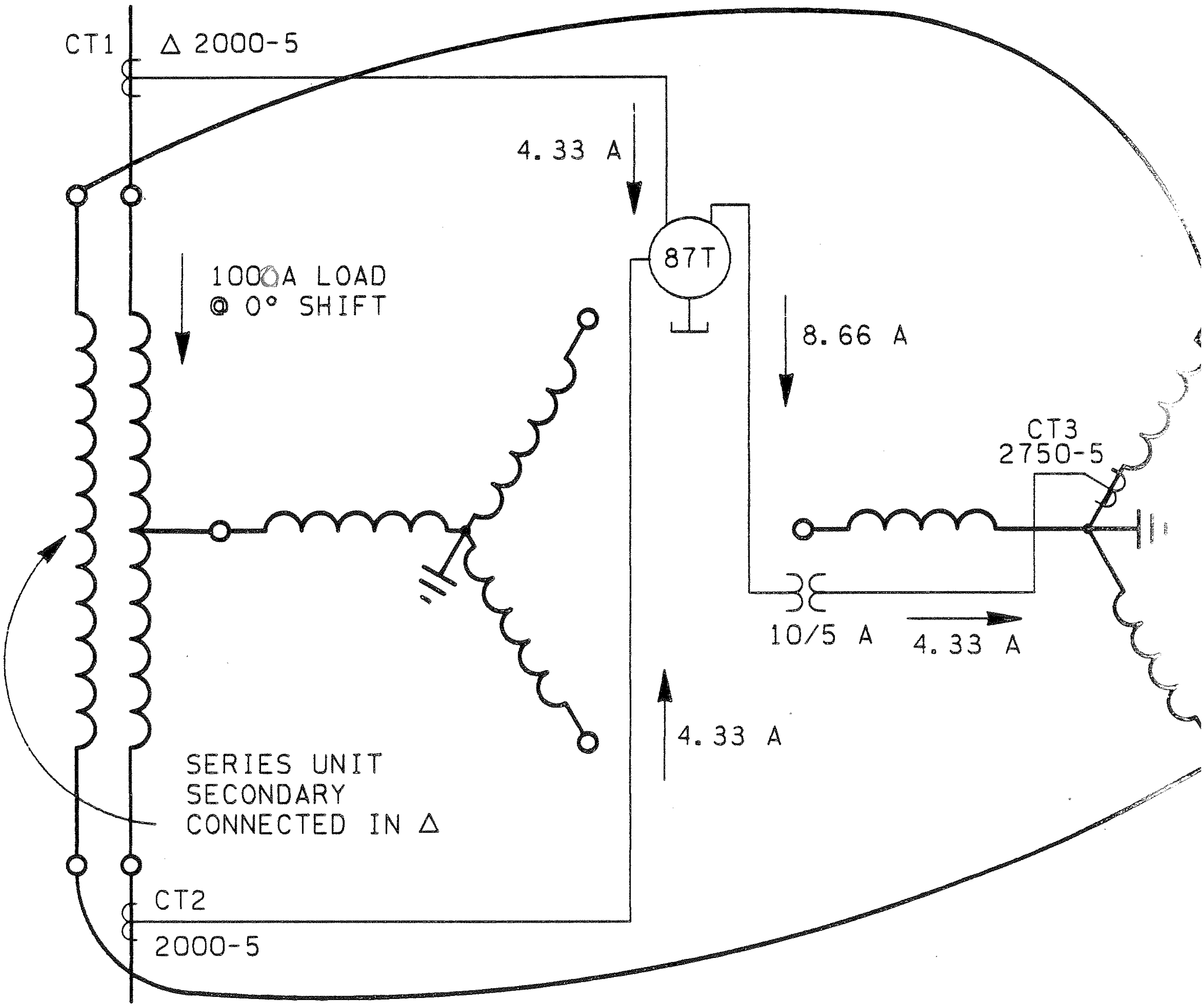


- NON-STANDARD CT RATIO 2750 - 5 IN EXCITING UNIT

- PROBLEM WITH THIS PROTECTION SATURATION OF SERIES WDG. UPSET AMPERE TURNS BALANCE.

FIGURE 16

CALCULATION OF 2750-5 RATIO SHOWN FOR ONE PHASE



SERIES UNIT TURNS RATIO 1.365:1

SERIES UNIT SECONDARY DELTA CURRENT $\sqrt{3}$ (1.365)(1000) = 2364 A

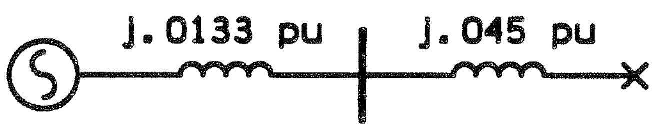
IDEAL CT RATIO: 2364/8.66 = 273:1 OR 1365-5

CHOOSE 2750-5 MAIN CT RATIO, 10-5 AUX CT RATIO

FIGURE 17

SERIES WINDING SATURATION

- SERIES WINDING RATED 90.8 KV
- SERIES WINDING IMPEDANCE 18% AT MAXIMUM SHIFT = 24 Ω
- 7500 mV•A FAULT LEVEL



100 MV•A, 230 kV BASE

$I_{FAULT} = 1/.0133 + .045 = 17.15$ pu

$17.15 \times I_{BASE} = 4.33$ kA

$I_{BASE} = (100/\sqrt{3}\ 230) \times 1000 = 251$ AMPERES

VOLTAGE DEVELOPED ACROSS SERIES UNIT:

$4.33 \text{ kA} \times 24\Omega = 104 \text{ kV}$

OK BASED ON OVERFLUXED CAPABILITY OF 90.8 kV WINDING

FIGURE 18

BYPASS, 2CB7 NOT IN SERVICE

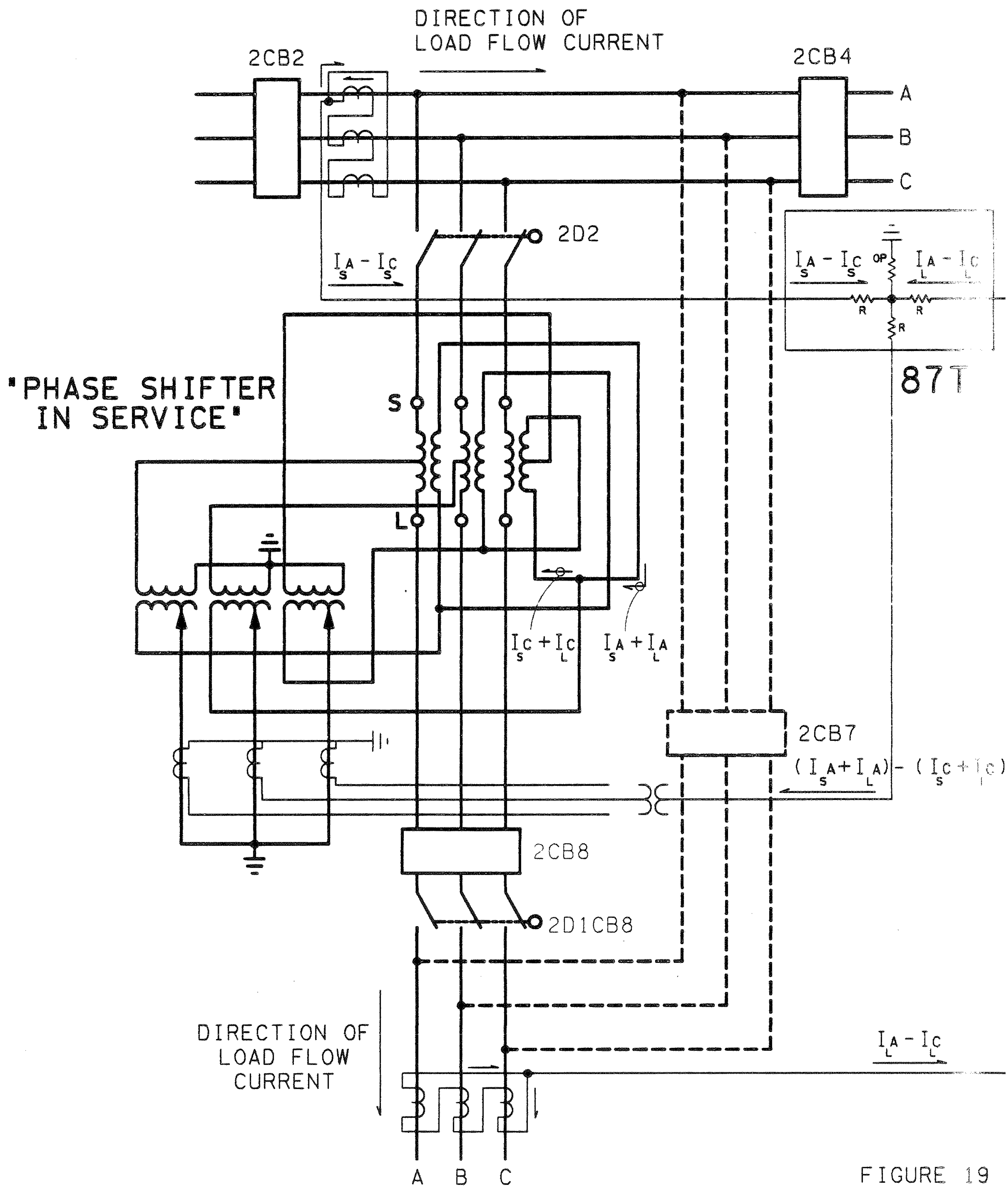


FIGURE 19

PHASE SHIFTER NOT IN SERVICE

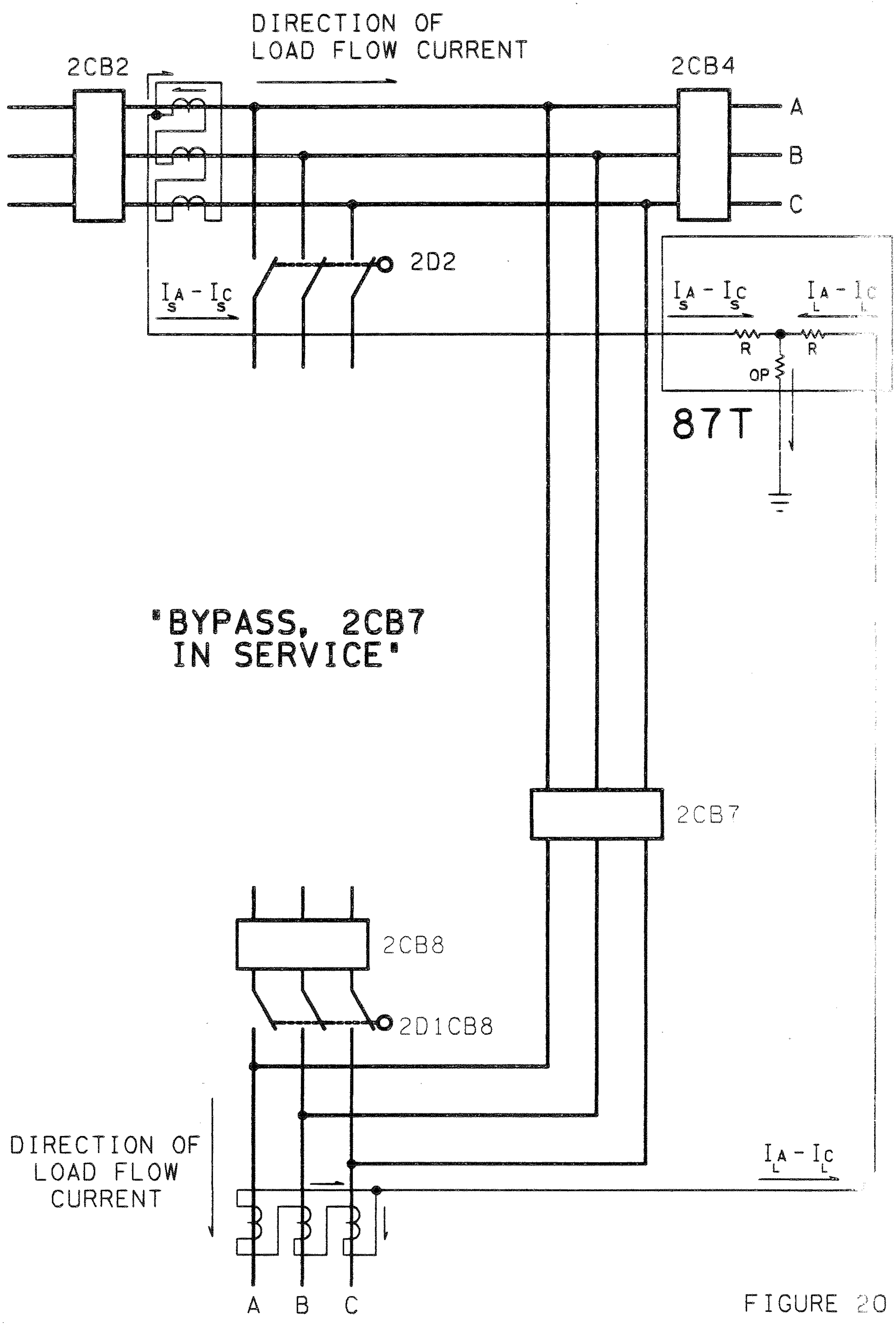
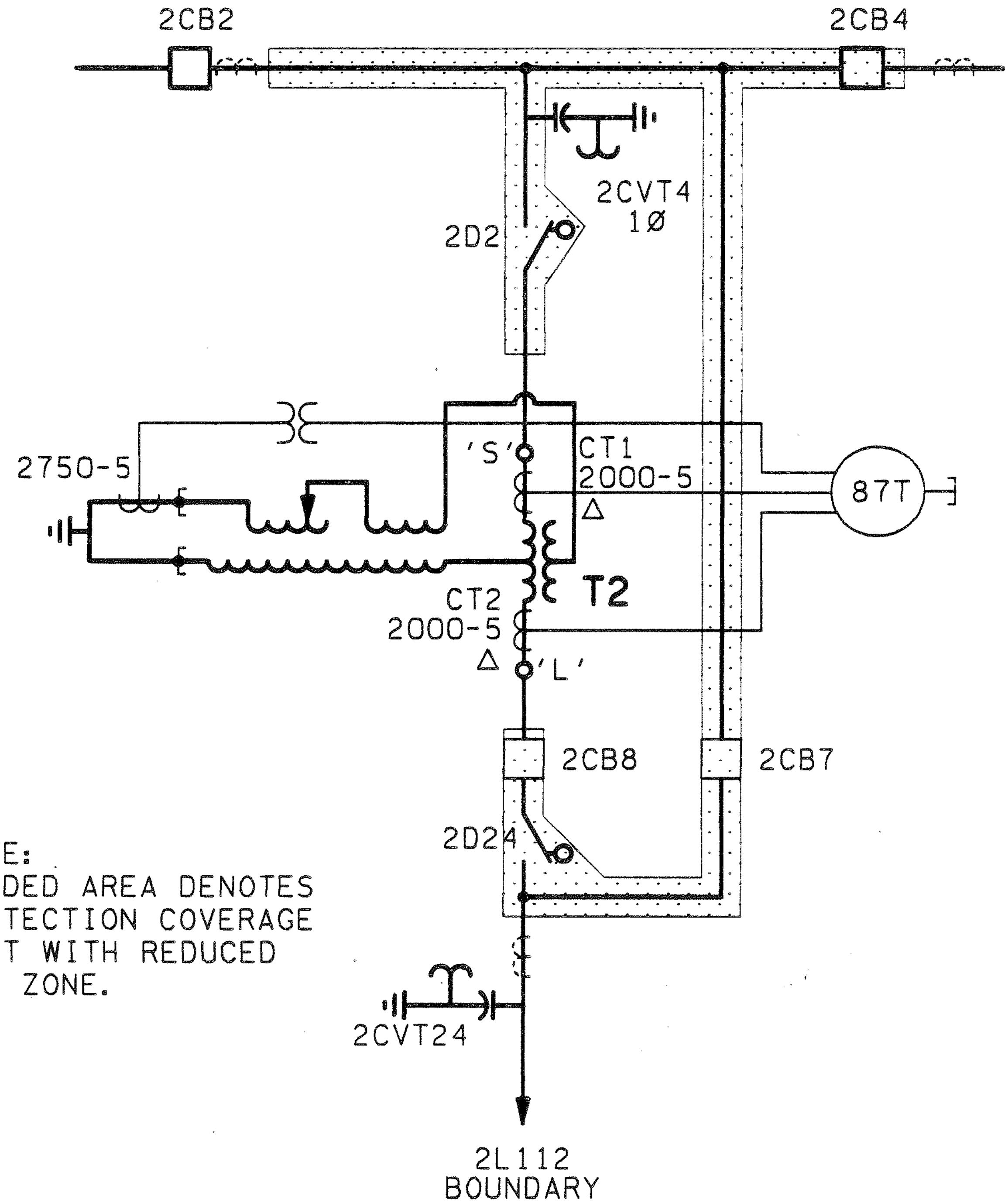
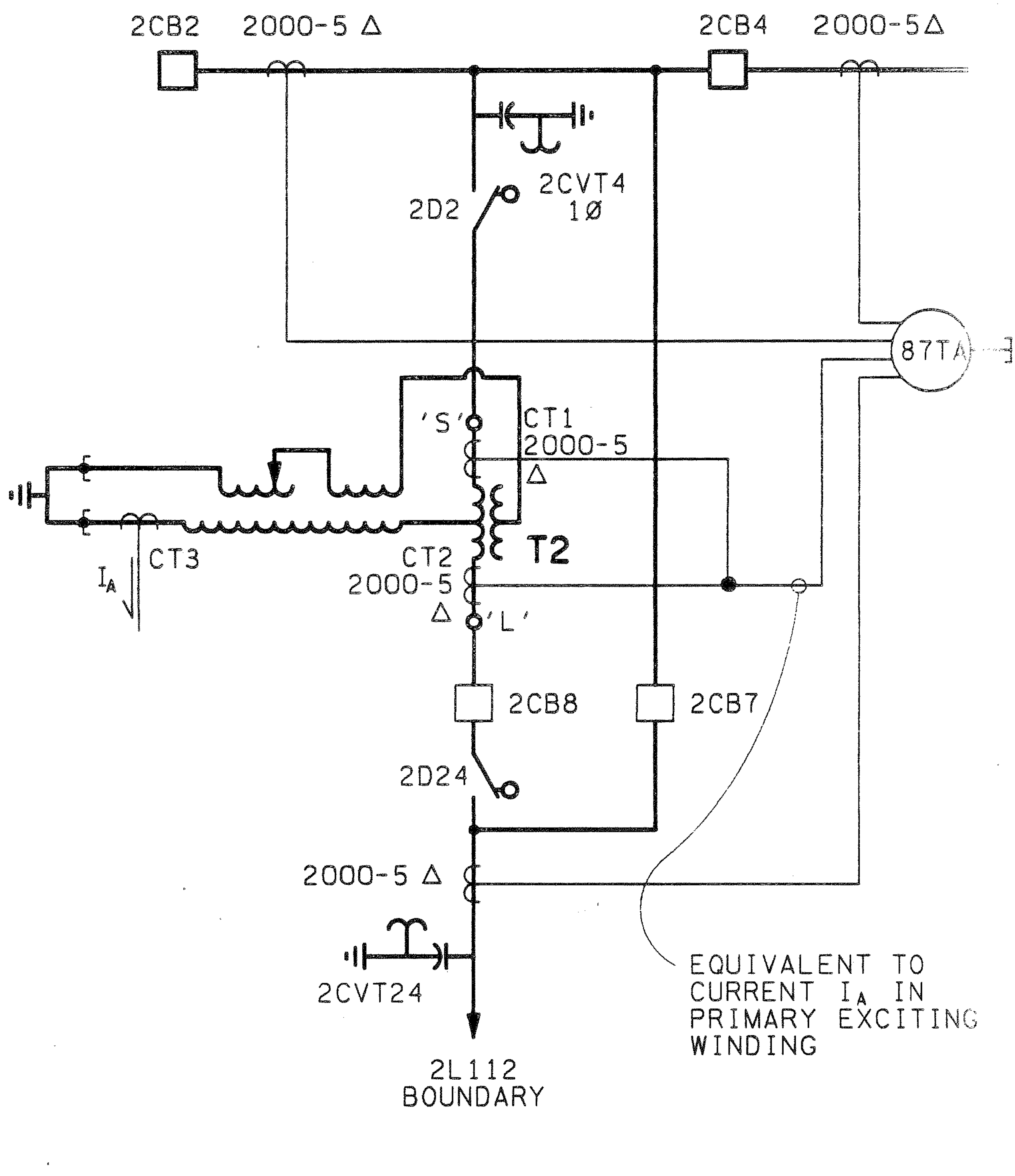


FIGURE 20



NOTE:
SHADED AREA DENOTES PROTECTION COVERAGE LOST WITH REDUCED 87T ZONE.

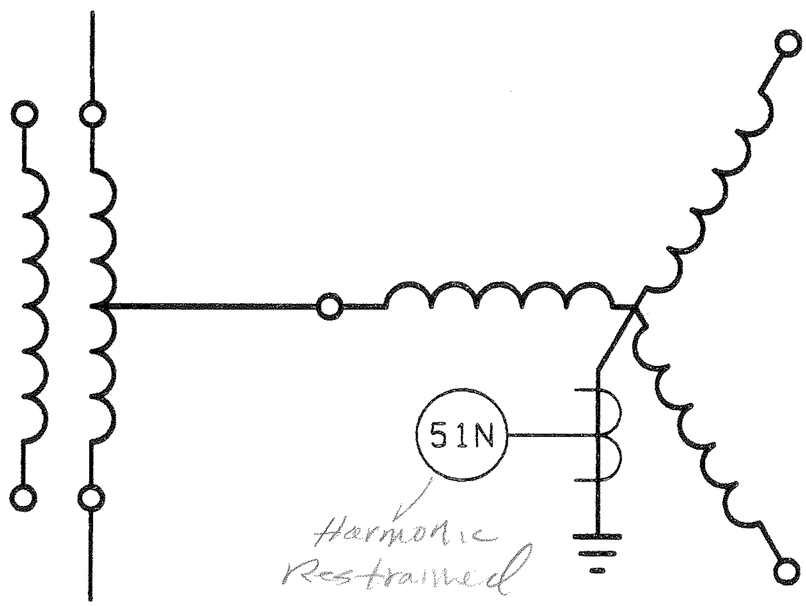
FIGURE 21



2CB2
2000-5 Δ
2CB4
2000-5Δ
2CVT4
1Ø
2D2
87TA
'S'
CT1
2000-5
Δ
T2
CT3
I_A
CT2
2000-5
Δ
'L'
2CB8
2CB7
2D24
2000-5 Δ
2CVT24
EQUIVALENT TO
CURRENT I_A IN
PRIMARY EXCITING
WINDING
2L112
BOUNDARY

FIGURE 22

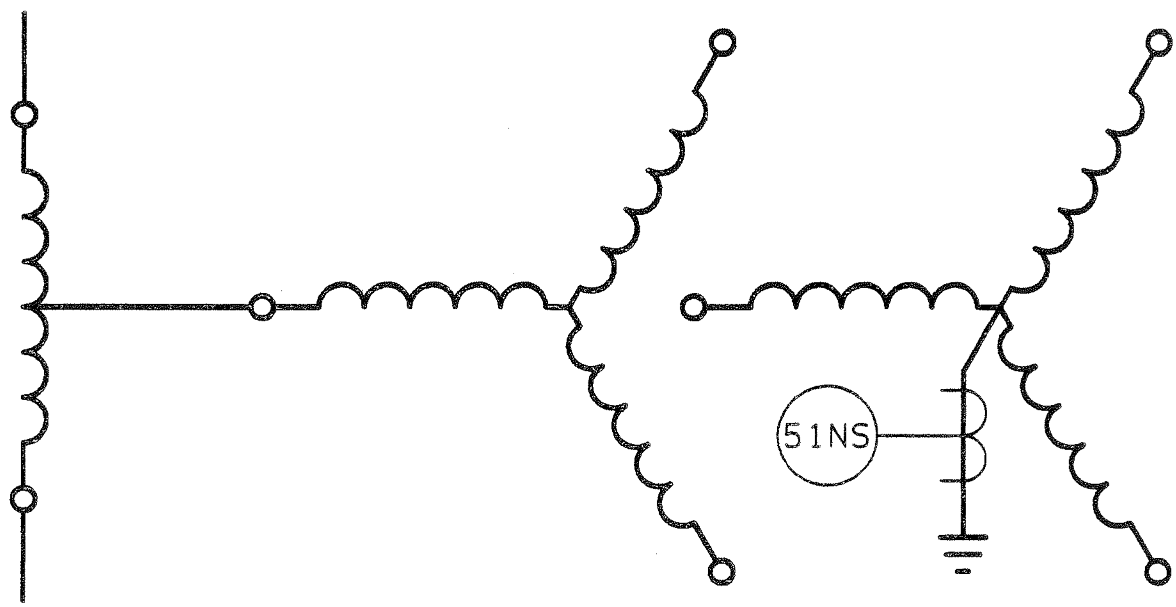
51N GROUND PROTECTION



NO COORDINATION CONCERNS WITH HV SYSTEM

FIGURE 23

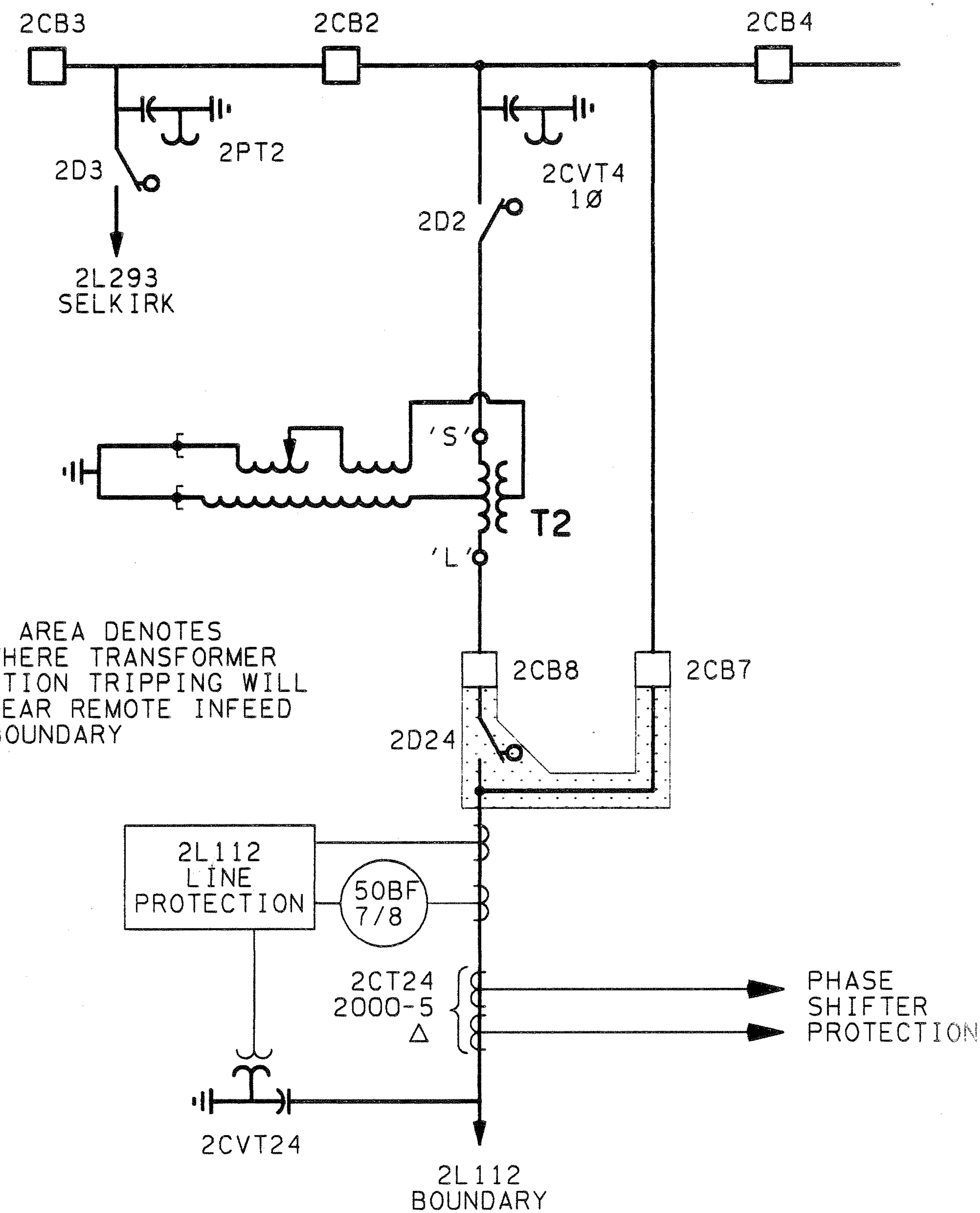
51NS GROUND PROTECTION



CURRENTS DEPEND ON LEAKAGE Z OF EXCITATION UNIT, SECONDARY VOLTAGE.

300,000 AMPERES FAULT CURRENT THEORETICALLY POSSIBLE WHEN ULTIMATE FAULT LEVELS REACHED AT STATION!!!

FIGURE 24



NOTE:

SHADED AREA DENOTES ZONE WHERE TRANSFORMER PROTECTION TRIPPING WILL NOT CLEAR REMOTE INFEED FROM BOUNDARY

FIGURE 25

SUPERVISORY CONTROL
INTERFACE AT NELWAY SUBSTATION

CONCEPTUAL REQUIREMENTS

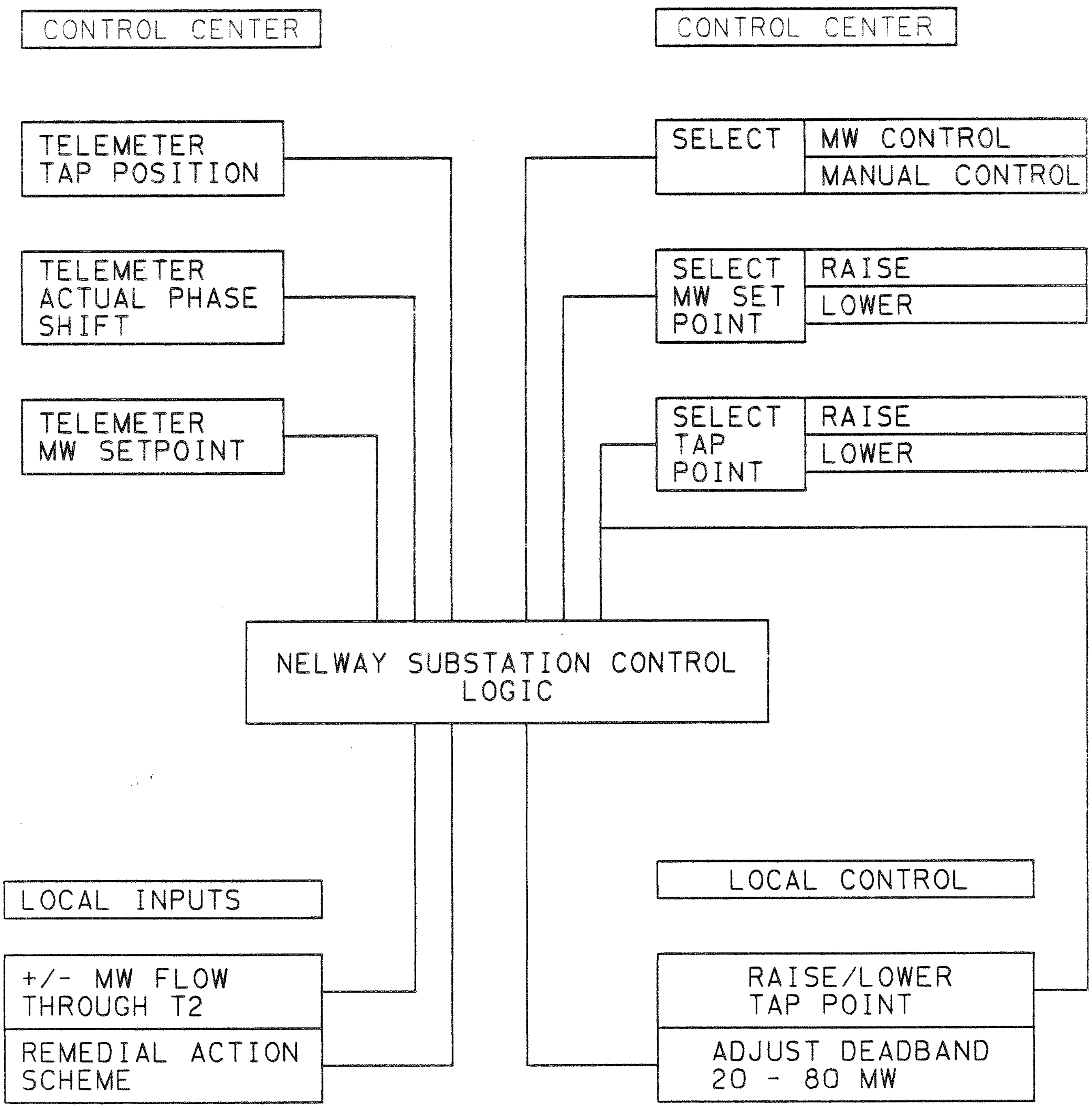


FIGURE 26

PHASE SHIFT CONVENTIONS

TAP POSITION	POWER FLOW BDY==>NLY	POWER FLOW NLY==>BDY
33 ADVANCE		
	↑ DECREASE POWER FLOW	↑ INCREASE POWER FLOW
17 ZERO SHIFT		
	↓ INCREASE POWER FLOW	↓ DECREASE POWER FLOW
1 RETARD		

FIGURE 27

POWER FLOW EXAMPLES

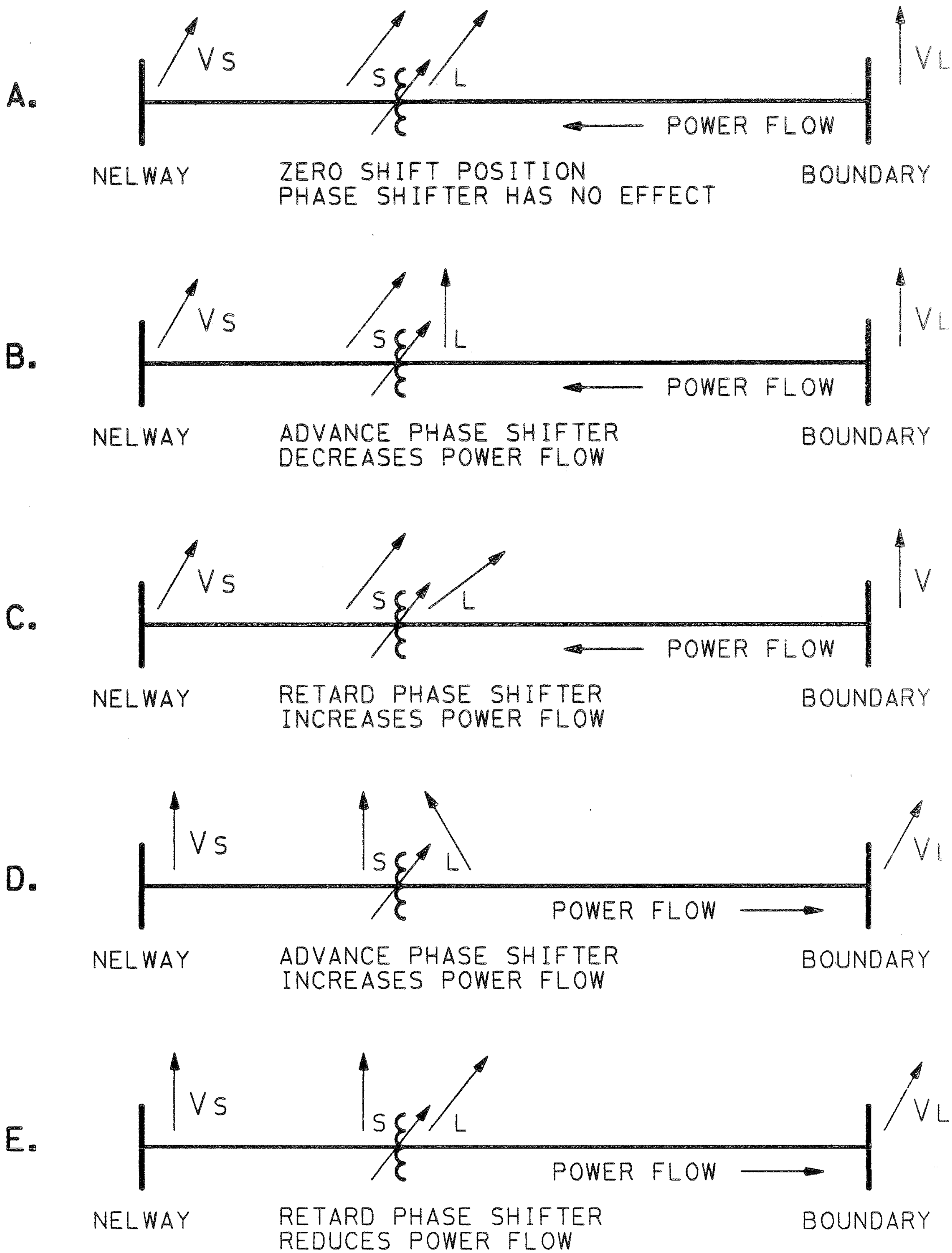


FIGURE 28

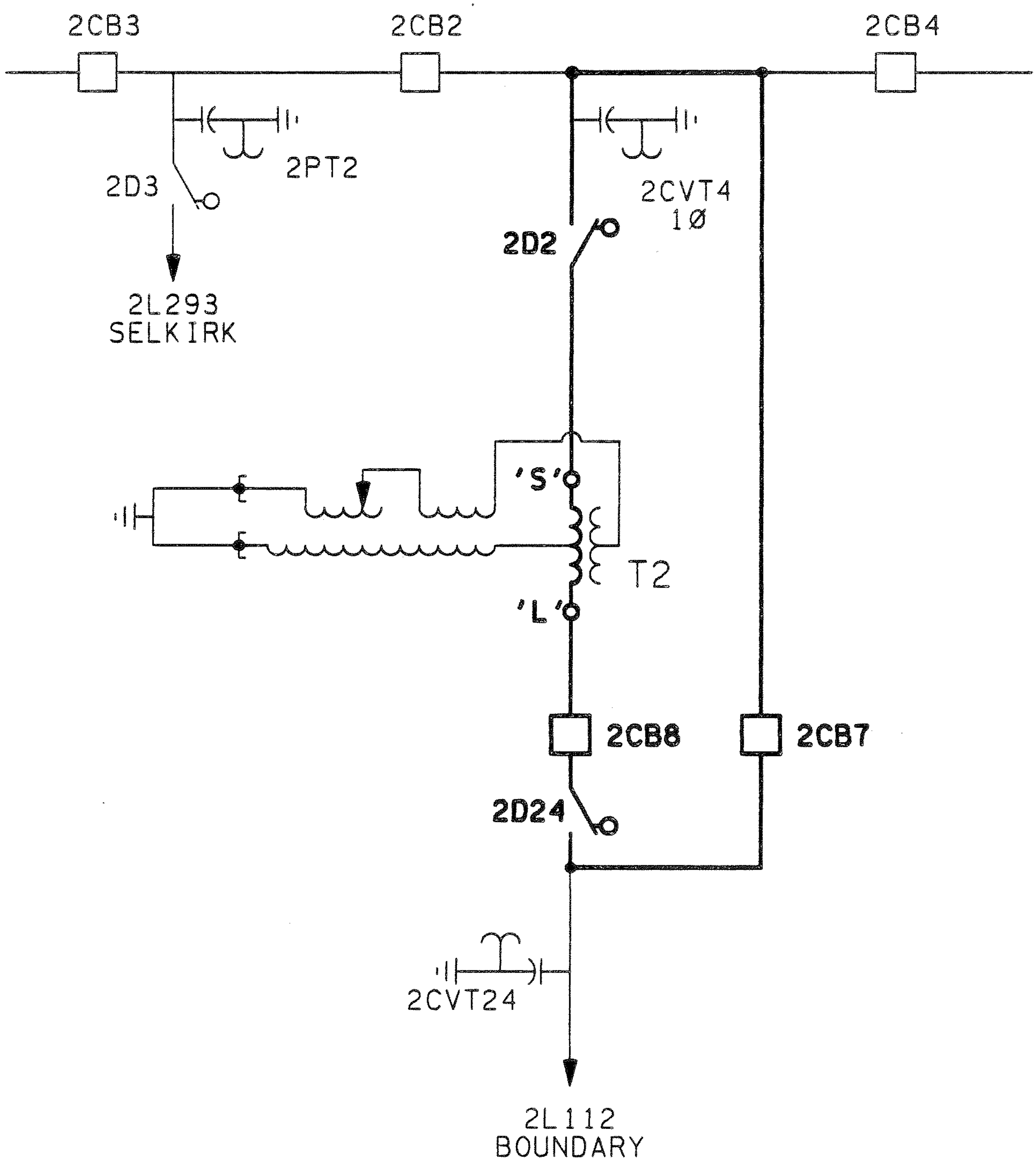
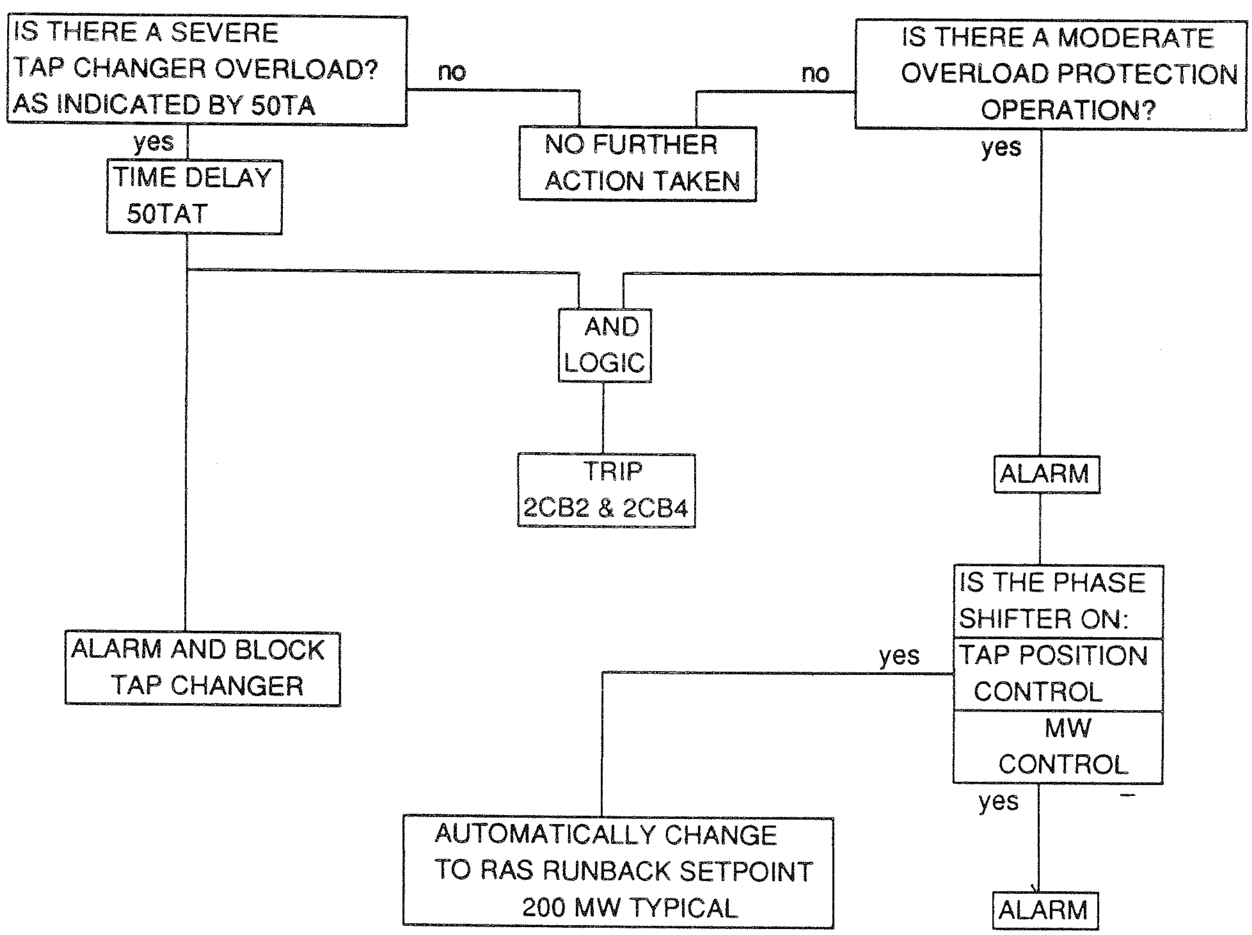

2CB3
2CB2
2CB4
2PT2
2D3
2CVT4
1Ø
2D2
2L293
SELKIRK
'S'
T2
'L'
2CB8
2CB7
2D24
2CVT24
2L112
BOUNDARY

FIGURE 29

REMEDIAL ACTION SCHEME (RAS) TO LIMIT T2 TAP CHANGER OVERLOAD



NOTES:

1. ALARMS ARE ANNUNCIATED LOCALLY AS WELL AS SENT TO THE CONTROL CENTER
2. THE RELAY SETTINGS AND THE RAS RUNBACK SETPOINT ARE LOCAL MANUAL ADJUSTMENTS AT NELWAY SUBSTATION. ONCE THEY HAVE BEEN OPTIMIZED THEY WILL NOT BE ALTERED
3. NORMAL MW SETPOINT IS SET REMOTELY AT THE CONTROL CENTER
4. ALL FUNCTIONS ARE NON-LOCKOUT

FIGURE 30