ABB

Power T&D Company Inc.

Relay Divisions
Coral Springs, Florida

ASEA

Type RADSS
Ultrahigh-speed bus differential relay

B03-6010E
Page 1
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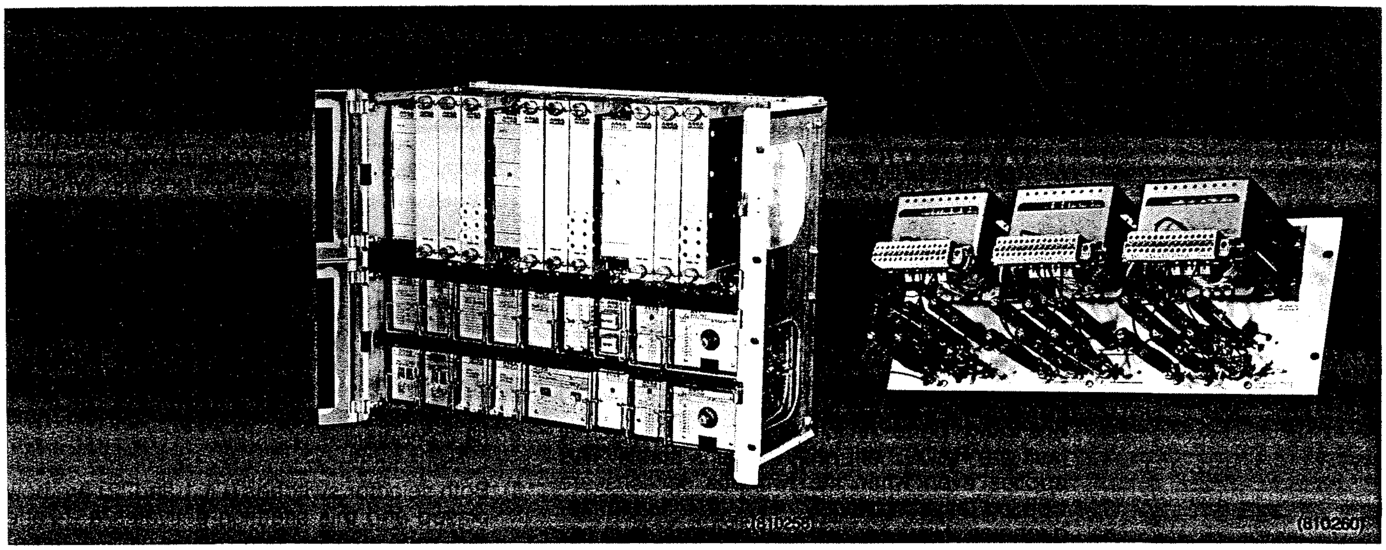


Abstract

- **Protection for buses or short lines**
- **1-3 ms fault detection, 8-13 ms to trip**
- **Fault sensitivity 20 % of rated current**
- **No maximum fault-current restrictions**
- **No practical limit to number of circuits to the bus**
- **No dedicated or matched CT's required and CT's can be of different ratios and manufacture**
- **Long CT leads acceptable - up to 68 ohms at 5 A or 1705 ohms for 1 A circuits**
- **Moderately-high impedance (165-301 ohms) in diff circuit**
- **Selectable percentage restraint slope, 50 to 85 %**
- **Compact summation CT version available**
- **Adaptable to different bus configurations**

Application

The RADSS relay is a high-speed, sensitive, moderately high-impedance differential relay for phase- and ground-fault protection of buses and short lines. The high sensitivity of the RADSS generally precludes the need for a separate ground-fault relay. The relay is available in both three-phase and single-phase versions. It combines the qualities of high impedance and percentage differential characteristics in one unique operating principle.

Applications are not limited by CT saturation for internal or external faults. The high-speed (1-3 ms) fault-detection makes the relay applicable to any bus. Stability is ensured for external faults, even with CT saturation and secure operation is obtained for internal faults prior to saturation.

The line CT's may have relatively poor characteristics and different ratios. They neither need to be dedicated nor matched; other relays can be used on the same CT circuits. Fully distributed secondary windings are not required. The relay is especially useful in stations where major changes involve old and new breakers with mixed CT types and ratios. Also, additional line circuits can be added to the protected bus without any practical limitations to the relay application.

A high CT secondary lead resistance (over 1700 ohms, for certain applications) can be tolerated. Auxiliary CT's are used to balance the ratios of the main CT's.

An overcurrent starting relay may be used to supervise the measuring unit. The starting relay primary setting may be chosen to correspond to the largest rated line current. This will prevent operation in case of accidental CT secondary open-circuit. The magnitude of the fault current determines the setting of this relay. To enable the tripping of RADSS it is required that both the differential relay d_R and the start relay S_R operate simultaneously.

The single-phase version has one summation auxiliary CT for each three-phase circuit to the bus. This enables the use of only one single-phase relay for all phase- and ground-fault protection, at reduced cost compared to the other versions.

The summation CT version as well as the three-phase version can be used in pilot-wire differential protection schemes.

Application (cont'd)

Busbar Arrangements

The arrangements of power system buses vary widely depending on the magnitude of the through going load current, the number of line circuits and the need for splitting up the station in several zones subsequent to an internal bus fault.

The normal rating of a bus conductor is from 1000 A to 3000 A and a typical number of lines to a certain bus zone is 6-12 L. For the largest installations 2, 4 and 6 relay zones may be installed.

Single bus 1-zone

The most simple and reliable installation is the single bus 1-zone arrangement (Fig. 1). In this case it can also be permitted that a bus seciton switch (S) is opened at certain times to split the bus in two parts. As long as there is no internal fault the RADSS diff relay remains stable. This applies even when the two bus sections are working asynchronously, e.g. at different frequencies. However, when an internal fault occurs, both sections will always be tripped simultaneously.

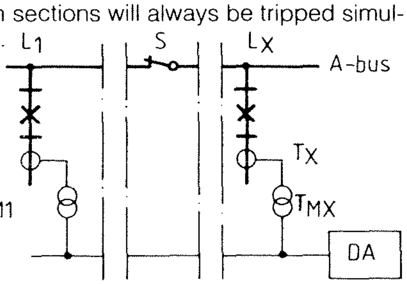


Fig. 1 Single bus. 1-zone with bus section switch normally closed

2-zones with Bus Section Switch

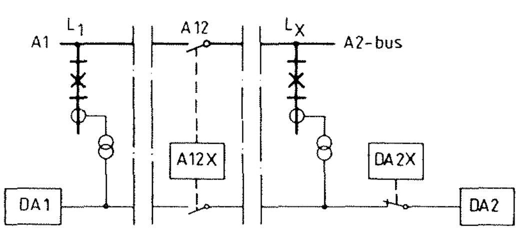


Fig. 2 Single bus, 2-zones with bus section switch normally open

When the bus section switch (A12) in fig. 2 is kept open during longer periods of time, it may be an advantage to include two differential relays. The two sections may then work independently and when a fault occurs only the affected section is tripped.
When the A12 switch is closed, all the input circuits will be connected to the DA1 relay and the DA2 relay is disconnected. The operating sensitivity is then determined only by the DA1 relay. If both relays should be kept in service at the same time the total relay operating current becomes twice as large.

The relay units shown in the drawing, A12X and DA2X, consist of RXMVB 4 change-over relay and RXMM 1 aux relay. These relay units are arranged to work in a special sequence so that the CT secondary circuits never become open-circuited.

Double-bus with CT-switching

One of the most commonly used arangements is the double bus, with bus coupler and one circuit breaker per line (Fig. 3). When one line, which is connected to say the A-bus (L1:1 closed), has to be switched to the B-bus, the following sequence is used:

1) The bus coupler circuit breaker is closed.

2) The selector switch L1:2 is closed. Its corresponding auxiliary contact in the CT secondary is arranged to close ahead of the main (H.V.) contact.

3) Both selector switches (L1:1 and :2) are now closed and this situation activates a 2-zone to 1-zone auxiliary relay unit, which interconnects the CT circuits of the A- and B-zones and disconnects the DB-relay.

The operating sensitivity then becomes controlled by only one relay, instead of two relays in parallel. Also, the two trip circuits are interconnected so that both buses are tripped for a fault on one bus.

4) The selector switch L1:1 is then opened and the 2Z-1Z unit brings back into service the DB-relay, and separates both the CT interconnection and the trip circuit interconnection.

It should be noticed that during this switching operation the CT secondaries are never open-circuited, so no dangerous voltages can occur. The diff relay trip circuits are never disconnected so if a fault occurs, one or both, buses will be tripped instantaneously.

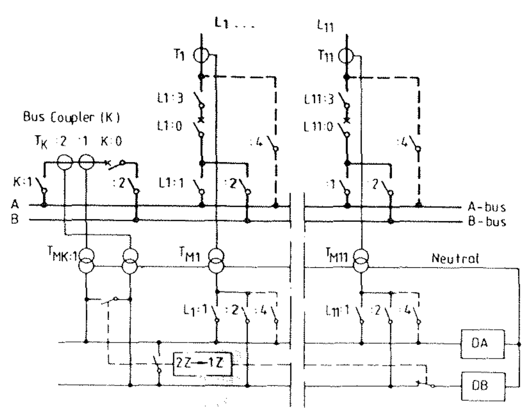


Fig. 3 Double bus, 2-zones with switching of CT secondary circucits. A bypass switch :4 may be added.

d.c. trip circuit arangements

The basic trip circuit of the RADSS is shown in fig. 4. The SR- and dR-relay contacts must be closed simultaneously, for less than 1 ms, in order to energize the impulse storing device and to make sure that the 107:RXMS1 relay will seal-in via its own contact 14-15.

This quarantees decisive tripping of all circuit-breakers. The seal-in circuit is normally interrupted by the 301:RXKE1 time delay relay after 100 ms. All tripping relays then reset automatically.

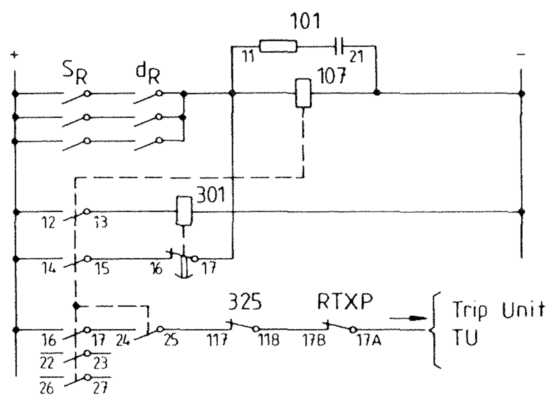


Fig. 4 Simplified auxiliary d.c. trip circuit of RADSS 3-phase, 6-12L, 1-zone

S_R	Start relay (1 ms)
d_R	diff realy (1 ms)
101	RXTCB1 impulse storing
107	RXMS1 aux.tripping relay (3.5 ms)
301	RXKE1 time delay relay (100 ms)
325	RXMVB 2 blocking relay
RTXP 18	Test switch

A typical high speed (3.5 ms) tripping unit (TU) is shown in fig. 5. This takes care of 6 individual trip coil circuits, i.e. six lines when all the three phases of each line are energized by one contact.
Similarly, if only one trip relay contact is required to trip each line, the double bus arrangement may be as in fig. 5. The selector switch (or mirror relay) aux. contacts: 1 and :2 are then used to obtain selective tripping of only the faulty bus.

For the larger and more important H.V. stations, single-pole tripping is often required. One tripping unit (TU) is then installed per line. Also, if two separate sets of trip coils are to be used, six individual trip relay contacts become necessary for every circuit breaker.

The arrangement then used is shown in fig. 7, which also applies to the double bus in fig. 3. In this tripping scheme it is indicated how to include, most easily, a Breaker Failure Relay (BFR).

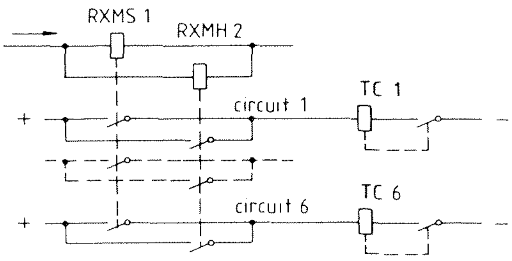


Fig. 5 Typical trip relay unit (TU) with high speed (3.5 ms) contacts and parallel connected reinforcing contacts. For 6 individual trip coil circuits.

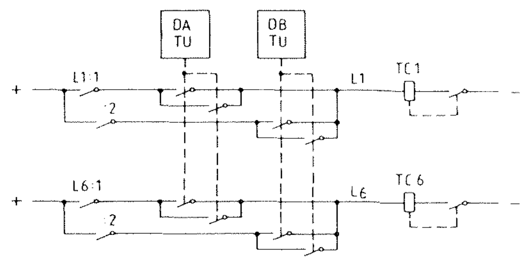


Fig. 6 Tripping of six lines in a double bus scheme, requiring only one trip circuit per line.

If, for example, the BFR for line L2 becomes activated due to a single-line-to-ground fault, the TU for L2 energizes all six trip coils, and if the L2:1 selector switch is closed all lines connected to the A-bus plus the bus coupler, will be tripped in all 3-phases (six trip coils). By this arrangement the BFR's do not need to include an extra set of selector switch auxiliary contacts, nor do they need any additional trip relays.

The diodes shown in the K:1 and :2 trip circuits of fig. 7, are required because during normal AB-bus interconnection K:1 and :2 will normally be closed and the A-B trip circuits should not be interconnected.

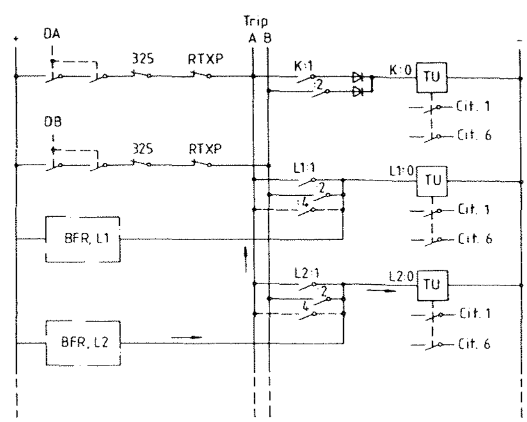


Fig.7 Trip circuit for the double bus shown in Fig. 3 with bypass switch (:4).
Each trip unit (TU) can trip six circuits at high speed. Breaker Failure Relays can easily be included.

Design

All versions are available with 50, 66 , 80 or 85 % slope setting; the slope setting applies only during external faults. During an internal fault, the relay has a different characteristic with a greater operating area. Any value, between 50 and 85 %, may be applied in the field by adjustment of the slide- wire comparator resistors. The relationship between the relay slope, sensitivity and allowable CT secondary resistance is seen from table 1.

Auxiliary CT's are used in each circuit to balance the ratios to the relay. Each input to the relay is limited to 2 amps continously. The overall CT ratio should be selected to limit the total current into the relay to 4 amps.

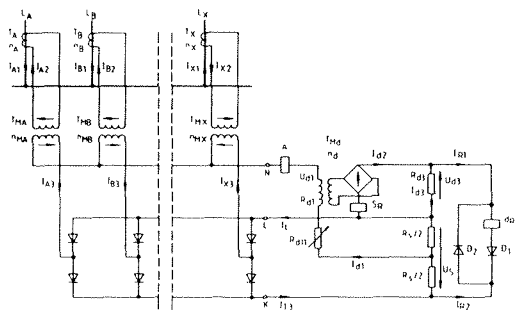
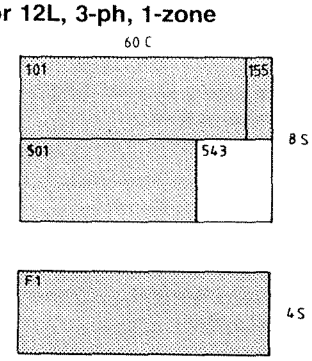


Fig. 8 Schematic diagram for one phase of a single-zone bus differential relay with feeders L_A, L_B and L_x. The current distribution is shown for an assumed positive reference halfcycle. If feeder L_A has the largest primary rating, a secondary rating with I_{A3} = 1 A is normally selected.

A	Alarm relay, RXMT 1 for CT open circuit
S_R	Starting relay
d_R	Differential relay
U_s	Restraint voltage
Ud3	Operate voltage
I_{R1}	Current through d_R-relay
I_{R2}	Blocking current through diode D_2
T_{MA}..	auxiliary CT ($n_{MA} = I_{A2}/I_{A3}$)
T_{Md}	$n_d = U_{d1}/U_{d2} = 10$
n_o	Overall CT ratio = $I_{A1}/I_{A3} = I_{x1}/I_{x3}$
R_s R_{d3}	Restraint and differential circuit resistances
R_{d1}	Resistance R_{d3} referred to T_{Md} primary side, $R_{d1} = U_{d1}/I_{d1} = n_d^2 R_{d3}$
R_{d11}	Variable differential circuit resistor
R_{dT}	Total resistance of differential circuit $R_{dT} = R_{d1} + R_{d11} = U_{dT}/I_{d1}$
U_{dT}	Total voltage of differential circuit
I_{d1}	Differential current
I_{T3}	total incoming relay current at terminal K
I_L	Current leaving at terminal L

Versions of RADSS
RADSS 6 or 12L, 3-ph, 1-zone

Version A1



101: Measuring Unit with
3-RTXP18 test switch
3 or 6-RQBA line diodes
3-RQDA S_R + d_R relays

155: Blanking plate

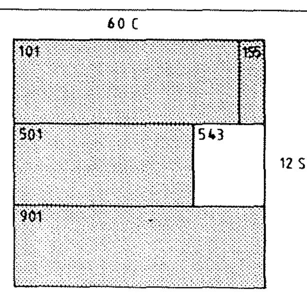
501 Supervision + aux. relay unit
1-RXTCB 1 capacitor + resistor
1-RXMS 1 aux relay
3-RXMT 1 alarm relays
1-RXSP 14 flag indicator
1-RXTNT 1 push-button with lamp
2-RXKE 1 time lag
2-RXMM 1 aux relay
1-RXMVB 2 aux blocking relay
1-RXME 1 aux relay

543 Space for trip relays

F1 Loose transf + comparator unit with:
3-T_{Md} aux.transformers
3 x 6-Resistors, each 50 W

The F1-unit is normally mounted on the B-(back) plane of the cubicle and 3 x 8 = 24 wires must be made by purchaser to the (101 + 501) unit.

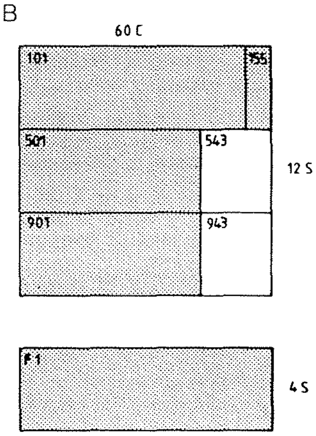
Version A2



As version A1 but all the units are fully interconnected and mounted together in one 12S equipment frame.

RADSS 18 or 24L, 3-ph, 1-zone

Version B



101 As 101 in version A1

501 Extension unit for 6L or 12L with:
3-RTXP18 test switch
3 or 6-RQBA line diodes

543 Space for trip relays

901 As 501 in version A1

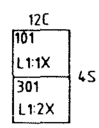
943 Space for trip relays

F1 As F1 in version A1

Switching relay units (ref. Fig. 9)

Switching line CT's to DA, DB

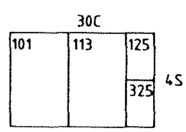
5075



101,301 RXMVB 2 latching relay

Bus Coupler CT disconnection

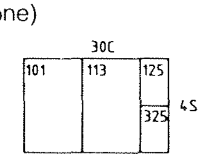
5074



101,113 RXMVB 4 latching relay
125 RXKE 1 time-lag relay
325 RXMM 1 aux relay

Bus Interconnection
(2-zone to 1-zone)

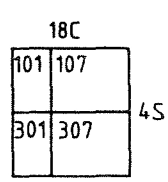
5074



101,113 RXMVB 4 latching relay
125 RXSF 1 aux flag indic.
325 RXKF 1, delayed alarm, 5 min

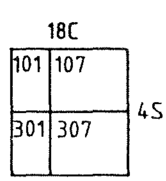
Trip relay units

5076



101,301: RXMS 1 with 6 NO contacts
107,307: RXMVB 2 latching relay with 6 NO and 2 NC contacts

5076



101,301: RXMS 1 with 6 NO contacts
107,307: RXMH 2 with 8 NO contacts

Technical data

Rated frequency	25-60 Hz
Rated curent	2 A per input
Maximum continuous current:	
restraint circuit	4 A
differential circuit	0.5 A
Short time current differential circuit	
50 seconds	1 A
1 second	7 A
Dielectric tests	
current circuits	50 Hz, 2.5 kV, 1 min
remaining cirucits	50 Hz, 2.0 kV, 1 min
Impulse voltage test	1.2/50 µs, 5.0 kV, 0.5 J
1 MHz burst test	2.5 kV, 2 s
Auxiliary dc voltage	48, 110, 125 or 250 V
Permitted ambient temperature	−5 to +55°C
Input diode rating	10 A rms, 1200 V PIV

Operate time (S_R+d_R)	1-3 ms
to trip	8-13 ms to trip

See Relay data table B03-1003E and B03-1503E for specific information.

Auxiliary CT's:
Three different types may be used depending on required rated secondary current. For example:

1) Type SLCE 12:
   5/0.7 A, 140/1000 t, 0.3/16 ohms,
   Knee-point (at 1.6 T) = 410 V rms

2) Type SLCE 16:
   5/1 A, 160/800 t, 0.4/10 ohm,
   Knee-point (at 1.6 T) = 416 V rms

3) Type SLXE 4:
   5/2 A, 240/600 t, 0.4/3.5 ohm,
   Knee-point (at 1.6 T) = 400 V rms

Note:
The given current ratios correspond to the continuous thermal rated current.
The number of secondary turns for each type is always kept constant so as to obtain a certain secondary knee-point voltage. Different ratios are therefore obtained by varying the number of primary turns.

Table 1 RADSS settings and approximate operating values

Slope S	R_{d3} ohm	$R_{s/2}$ ohm	K A	R_{se} ohm	P_n W	I_{d1} min(A)	R_{d11} ohm	R_{dT} ohm	R_{LX} ohm	U_{T3} dR)V	I_d (S_R)A	U_{T3} (S_R)V
0.2	1.10	1.2	0.107	0.76	12	0.13	136	301	75	63	0.88	310
0.5	"	3.66	0.10	0.96	16	0.20	"	"	301	86	"	"
0.66	"	5.50	0.096	1.0	16	0.30	"	"	602	118	"	"
0.80	"	7.30	0.092	1.02	16	0.46	"	"	1204	171	"	"
0.85	"	8.15	0.091	1.03	16	0.61	"	"	1705	221	"	"

To order

Specify:
- RADSS - Lines, 3-ph, 1-Zone
- Number of Lines: 6 or 12, 18 or 24L
- Slope (S): 0.5 or 0.66 or 0.80
- Start relay I_{d1} (SR) = 0.88 A (standard)
- R_{d11}: 0 or 136 ohms (max)
- Auxiliary dc supply voltage
- Ordering Number (if available)

Type of auxiliary CT's:
- Current ratios and
- Turns ratios

Mounting and connection:
- See B03-9301E

Note:
When you need assistance to select the most suitable setting please send us a simple single line diagram of the bus(es), indicating: (1) Current rating of bus conductor, (2) Number of line circuits, (3) CT-ratios of all lines, (4) Rated load current of all lines (required only when load current is much less than CT-rating), (5) Requested primary operating current.

Having received these information we will advise: (1) Slope setting, (2) R_{d11} setting, (3) Start relay setting, (4) Permissible maximum loop-resistance as seen from relay R_{LX}, (5) Max permissible loop-resistance in line CT-secondary circuit $R_{A2}...R_{X2}$ (which includes CT-winding resistance, dc resistance of extra burden or relays and pilot-wire 2-way resistance), (6) Required line CT-secondary knee-point voltage $U_{A2}...U_{X2}$.

Ordering tables

RADSS 3-phase, 1-zone

Version	For number of lines	Transformer and comparator	Ordering no
A1	6 or 12	Loose	RK 637 016-AB
A2	6 or 12	Mounted in the equipment frame	RK 637 016-CB
B	18 or 24	Loose	RK 637 016-BB

Switching and trip relay units

Version	Application	Relays included	Ordering no
Switching relay units	Switching line CT's to DA, DB	RXMVB 2	5651 131-A
	Bus interconnection (2-zone to 1-zone)	RXMVB 4, RXSF 1, RXKF 1	5651 131-SA
	Bus coupler CT disconnection	RXMVB 4, RXKE 1, RXMM 1	5651 131-RA
Trip relay units	For each zone or for each line	RXMS 1, RXMH 2	5651 260-A
	For each zone or for each line	RXMS 1, RXMVB 2	5651 261-A

Sample specification

The bus differential relay shall be a moderately high-impedance differential relay for phase-and ground-faults. The relay shall have a percentage restraint characteristic that is effective for external faults, only. Instantaneous saturation shall not cause maloperation on external faults. Different ratios of the main CT inputs corrected by using auxiliary CT's. The operating time shall be 8-13 ms for all tripping outputs. The relay shall be suitable for 19″ rack-mounting.

Reference

Buyer's Guide	No.
Auxiliary current transformer type:	
SLCE 12	B03-9280E
SLCE 16	B03-9281E
SLXE 4	B03-9282E
Test system COMBITEST	B03-9510E
Mounting and connection	B03-9301E
Dimensions	B03-9382E

Information	No.
Description of RADSS	RK 637-300E
Checking of operating and restraint characteristics	RK 637-104E
Commissioning:	
single bus system	RK 637-101E
double bus system	RK 637-105E
Maintenance test	
double bus system	RK 637-105E
Bus coupler CT's disconnection	RK 637-301E
Auxiliary CT's	RK 637-302E
Schematic diagram for 2-zones	RF 637 359

Switching schemes

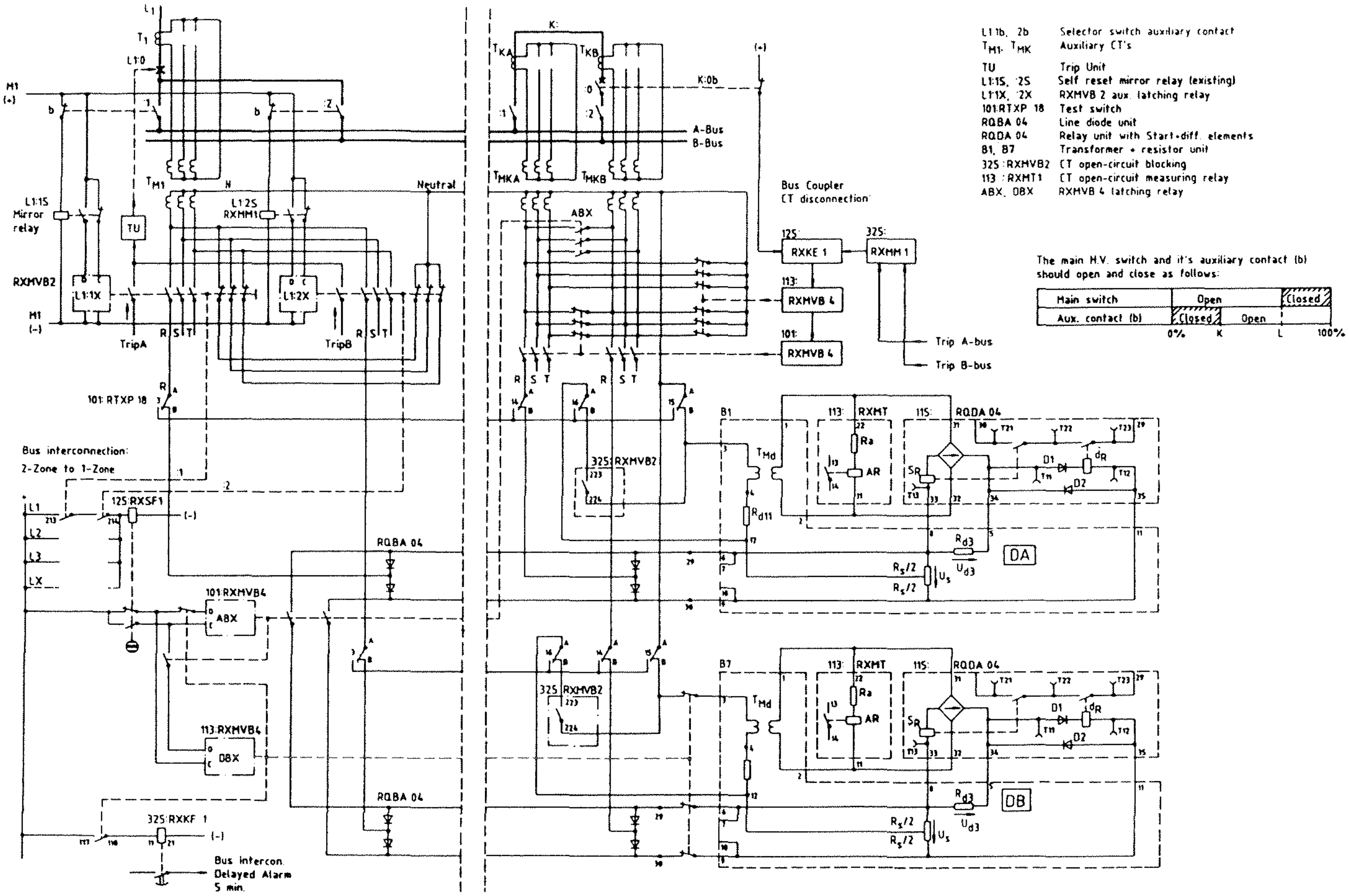


Fig. 9 Bus diff relay for 11-Lines, 1-Bus coupler 3-ph, 2 zones

The line CT's (T1) may be switched to the DA or DB diff relays. In most stations a mirror relay (L1:1S) is available and arranged to be enrgized when the (L1:1) selector switch is open. The auxiliary contact (L1:1b) must open and close as shown in fig. 9.

When both selector switches (L1:1 and :2) are closed simultaneously it is an advantage to interconnect the DA- and DB-line diodes and disconnect the DB-measuring circuit.

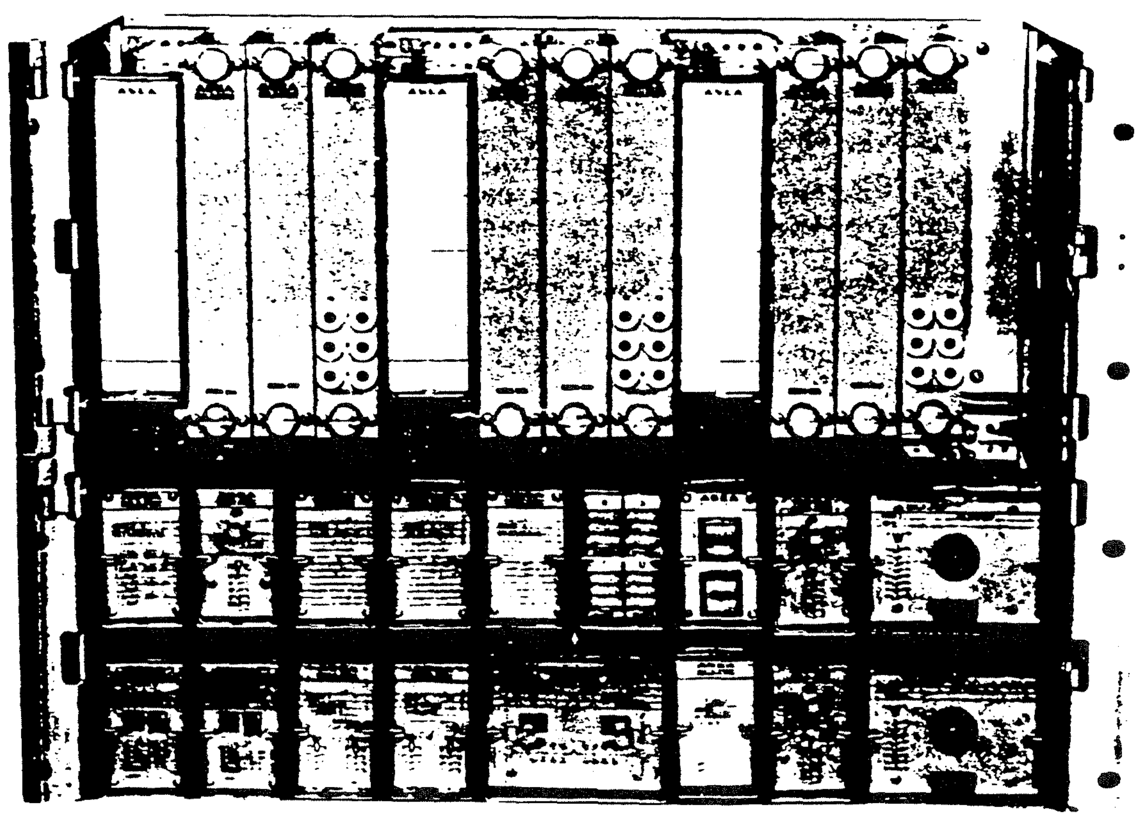
If the dc-supply to a mirror relay should become inadvertently interrupted the two relay zones may be switched to one overall zone. This situation can be supervised by a time-lag relay, sounding an alarm after 5 min. Switching a line from one bus to the other normally takes less than 5 min. and no alarm will then be obtained.

The bus-coupler (BC) CT-disconnection scheme serves the following purposes:

1) When the BC breaker K:O is open a fault which occurs between the CT's and the breaker will be disconnected instantaneously by the correct bus diff relay.
2) If this fault occurs when K:O is closed the wrong bus will be tripped instantaneously and the faulty bus, say 150 ms later.
3) If the K:O fails to open for a proper bus fault the adjacent bus will be tripped, say 150 ms later.

BASIC THEORY OF BUS DIFFERENTIAL RELAY TYPE RADSS

- Percentage restraint bus differential relay for line to line and earth faults.
- High speed operation, about 8-13 ms to energize circuit breaker trip coil.
- Full stability in the event of through faults, with infinite fault MVA and complete saturation of line CT's.
- Low differential relay pick-up setting, within 20-60 per cent of the current rating of the heaviest loaded feeder.
- The sensitivity is basically unaffected by the number of circuits included in the differential scheme.
- Line CT's may be of standard design with relatively poor characteristics and with different turns ratios.
- Standard CT pilot wires with a large loop resistance may be used.
- Other relays may be included within the same CT circuits.



INTRODUCTION

Internal bus faults occur less frequently than line faults. On the other hand, a bus fault tends to be appreciably more severe, both with respect to the safety of personnel, system stability and the damage at the point of fault. The fact that bus faults occur relatively seldom is therefore of little comfort to the engineer-in-charge subsequent to a major system shut-down caused by the lack of adequate bus relay.

When an internal bus fault occurs the magnitude of the fault current and its d.c. component may be so large that the line CT's (current transformers) saturate within 2-3 ms. In such cases it is essential that the bus differential relay operates and seals in within 2 ms, i.e. prior to the saturation of the line CT's. This high speed is necessary because when a line CT saturates its output e.m.f. tends to drop to zero.

In the event of an external fault, just outside the line CT's of a relatively small feeder, the fault current may in an extreme case be as large as 500 times the rating of the feeder. The line CT's of the faulty feeder are then likely to saturate at an even higher speed, particularly so if the remanence left in the core from a previous fault has an unfavourable polarity. The response of the restraint circuit of the differential relay must therefore be at least the same high speed as that of the operating circuit, if mal-operation is to be avoided.

The RADSS bus differential relay has been designed to cope with the above mentioned requirements. Its restraint and operating circuits consist basically of two resistors, across which are developed a restraint voltage and an operating voltage respectively. The actual time constants (L/R) of these two circuits are for all practical purposes zero.

The operating and restraint voltages can therefore be regarded as being developed instantaneously, or at basically the same speed as the primary current variation in the case of a fault.

The combined operating and restraint circuit of the RADSS may be denoted the <u>differential relay comparator circuit</u>, because a comparison is here made between two voltages with respect to both amplitude and phase relation. The output relay (d_R) of the comparator circuit is of the high speed (1 ms) dry-reed type, which ensures that decisive operation will always, be achieved under internal fault conditions.

The RADSS relay is based on the following two fundamental principles:

1. For <u>external faults</u>, the secondary circuit of a fully saturated line CT can be represented by its total d.c. loop resistance only, i.e., with negligible reactance.

2. For <u>internal faults</u>, the secondary circuit of an unloaded line CT can be represented by a relatively large magnetizing impedance, mainly reactive with a large (L/R) time constant.

A simplified schematic diagram of the RADSS relay is shown in Fig. 1, which represents one phase of a single bus-zone arrangement with the feeder circuits L_A, $L_B \ldots L_X$. The current distribution is shown for an assumed positive reference half-cycle. The RADSS relay is normally arranged as three separate single-phase units and a common trip unit.

Symbols

A	Alarm relay, RXMT 1
S_R	Starting relay
d_R	Differential relay
U_S	Restraint voltage
U_{d3}	Operating voltage
I_{R2}	Blocking current through diode D_2
T_{MA}	Auxiliary CT (ratio correction, $n_{MA} = I_{A2}/I_{A3}$)
n_0 =	Overall CT ratio
n_0 =	$I_{A1}/I_{A3} = I_{X1}/I_{X3}$
n_0 =	$n_A\, n_{MA} = n_X\, n_{MX}$
R_S, R_{d3}	Restraint and differntial circuit resistances
R_{d1} =	$U_{d1}/I_{d1} = n_d^2\, R_{d3}$ resistance referred to T_{Md} primary side
R_{d11}	Variable differential circuit resistor
n_d =	U_{d1}/U_{d2}, ratio of T_{Md} ($n_d = 10$)
U_{dT}	Total voltage of differential circuit
I_{d1}	Differential current
R_{dT} =	$R_{d1} + R_{d11} = U_{dT}/I_{d1}$ total resistance of differential circuit
I_{T3}	Total incoming relay current
I_L	Current leaving at terminal L
I_{R1}	Current through d_R-relay

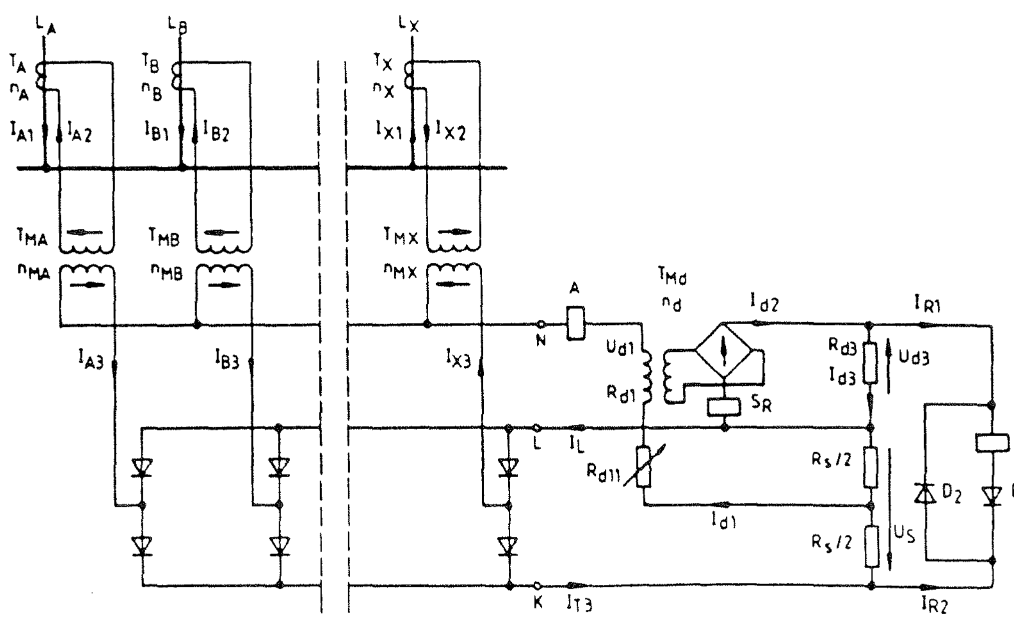


Fig. 1. Schematic diagram for one phase of a single-zone bus differential relay with feeders. If feeder L_A has the largest primary rating, a secondary rating with $I_{A3} = 1$ A is normally selected.

Normal service

The total incoming current I_{T3} enters the relay at terminal K, and the total outgoing current leaves at terminal L. During normal service these currents are equal and the differential current I_{d1} is therefore zero.

A restraint voltage U_s is obtained across the terminals K and L and this drives a certain current I_{R2} through the diode D_2 and the resistor R_{d3} towards the output terminal L. The differential relay (d_R) is then blocked and cannot operate.

During the subsequent negative half-cycle all the line currents will be reversed, i.e. I_{X3} will enter the relay at terminal K and the total outgoing current $I_{A3} + I_{B3}$ will leave the relay at terminal L.

The differential current will still remain zero and the restraint voltage U_S will be identical to that obtained during the positive reference half-cycle.

It should be noticed that the diode D_2 puts R_{d3} in parallel with R_S. The <u>effective burden</u> (R_{se}) of the restraint circuit during normal service can therefore be reduced by making R_{d3} as small as possible.

External faults

The positive reference directions of the currents shown in Fig. 1 still apply. The outgoing current I_{X1} may be assumed to increase owing to an external fault on the feeder L_X.

The mechanism of CT saturation and relay response may briefly be explained as follows:

During the initial rise of the fault current no saturation will occur for the first few milliseconds (see Fig. 9 on page 20).

The relay current I_{T3} will be proportional to the total incoming primary current ($I_{T1} = I_{A1} + I_{B1}$) and the restraint voltage U_S will increase causing a larger blocking current I_{R2} to pass through diode D_2. Also, the voltages U_{d3} and U_S will be basically equal. The differential current I_{d1} remains practically zero as long as no saturation occurs. This condition is shown in a simplified way in Figs. 2a and 2b.

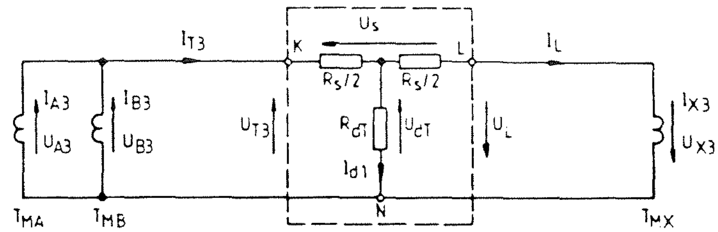


Fig 2 a. Basic relay circuit during the initial rise of external fault current, prior to CT saturation i.e. $U_{T3} = U_L$ and $I_{T3} = I_L$.

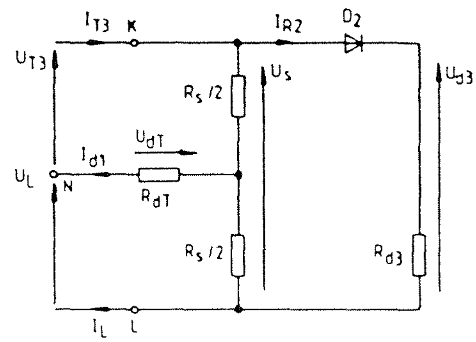


Fig 2 b. Voltage distribution for conditions shown in Fig 2 a. $U_{dT} = 0$ and $I_{dl} = 0$. Also $U_{A3} = U_{B3} = U_{T3}$ and $U_{X3} = U_L$.

Finally, saturation starts in the most exposed line CT (T_X) and U_L is reduced whereas U_{T3} still increases without any saturation. In Fig. 2c it is seen that U_{dT} becomes larger as the unbalance between U_{T3} and U_L increases. It would appear that the current I_{dl} is free to flow as soon as U_{dT} exceeds zero. This, however, is not the case.

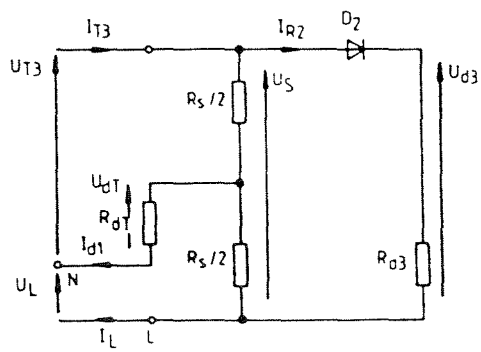
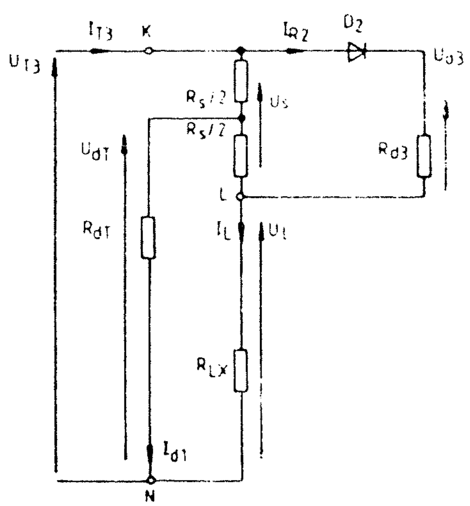


Fig 2 c. Voltage distribution when line CT (T_X) has started to saturated. U_{dT} and hence U_{dl} are each much less than n_d U_S, (where $n_d = 10$). Hence, I_{dl} remains at zero.

In order that I_{d1} shall flow a secondary current I_{d2} must also flow (see Fig. 1), i.e. the driving e.m.f. (U_{d2}) of the T_{Md} secondary winding must exceed the voltage U_{d3}. The T_{Md} primary voltage U_{d1}, obtained owing to the unbalance between the incoming and outgoing line CT's, must therefore exceed a certain voltage value before the differential current can flow. This voltage is given by: $n_d\ U_{d3}$ or $n_d\ U_S$; where the ratio of T_{Md} may be selected $n_d = 10$. Hence, in the case of a through fault, if $U_S = 10$ V it is necessary that the total differential voltage exceeds 10 x 10 = 100 V in order to produce a differential current. This restraint or blocking action, imposed on the flow of differential spill-currents is of minor importance for the stability of the RADSS relay. On the other hand, it enables a very sensitive earth fault relay to be inserted in the differential circuit in the case of resistance earthed networks, where the earth fault current may be limited to 10-20 per cent of the largest line CT rating.



As an example consider:

Total incoming current $I_{T3} = 10$ A

Effective restraint circuit resistance

$$R_{Se} = \frac{R_{d3}\ R_s}{R_{d3} + R_s} = 1 \text{ ohms}$$

$$R_{d11} = 0$$

$$U_s = U_{d3} = I_{T3}\ R_{Se} = 10 \text{ V}$$

$I_{d1} = 0$ and

$$U_{d1} = U_{dT} = n_d\ U_{d3} = 100 \text{ V}$$

$$R_{LX} = \frac{U_L}{I_L} = \frac{100 - 5}{10} = 9.5 \text{ ohms}$$

Also, $U_{T3} = U_{d1} + \frac{1}{2}\ U_s = 105$ V

Fig 2 d. Approximate voltage distribution required to make $I_{d1} > 0$. Line CT (T_X) is fully saturated

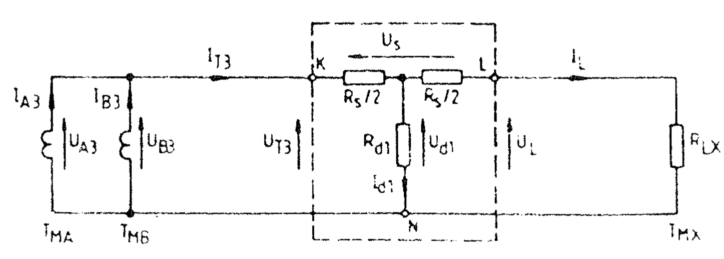


Fig 2 e. Simplified schematic diagram for external fault on feeder I...

In the case of Fig. 2d and 2e the e.m.f. of the T_X CT has been fully reduced to zero owing to saturation and the effects of the total loop resistance R_{LX}, as seen at the L terminal towards the line L_X, must be taken into account. The value of R_{LX} has in Fig. 2d been increased to such an extent that I_{d1} will just start to flow.

It can be shown that the current I_{R1} flowing towards the output relay (d_R) is just zero when:

$$I_{d1} = S\, I_{T3} \qquad \text{(Eq. 3)}$$

where S is the stability constant, which depends on the selected setting of the comparator circuit.

Equation 3 is also called the stability equation (see Fig. 4b on page 12).

It indicates that the operating and restraint voltages will just balance when I_{d1} is equal to a certain fixed percentage of the total incoming current I_{T3}. Also, it can be deduced that increasing I_{d1} above this percentage makes U_{d3} exceed U_S. Similarly, reducing I_{d1} makes U_{d3} smaller than U_S.

In a co-ordinate system with I_{d1} vs. I_{T3}, equation 3 represents a straight line through origin with the slope S. This line is denoted the stability line, and the value of S may be varied between 0.50-0.85 depending on the stability requirements of the installation. Hence, with the maximum restraint setting the differential spill-current must exceed 85 per cent of the total incoming current in order to cause maloperation.

Referring to Fig. 2e it is seen that the percentage current distribution in the I_{d1} and I_L circuits is dependent only on the R_{dT} and R_{LX} resistance values. The influence of $R_S/2$ is in this respect so small that it may be ignored. For the conditions corresponding to the stability line, we have:

$$R_{LX} = \frac{S}{1 - S}\; R_{dT} \qquad \text{(Eq. 5)}$$

Example: If R_{dT} = 301 ohms and S = 0.8
then R_{LX} = 4 x 301 = 1204 ohms

In this example therefore, the relay will, remain stable if the total loop resistance seen at the L terminal towards the L_X circuit varies between 0-1204 ohms. If, in the case of an actual installation, R_{LX} should exceed 1204 ohms, the relay can still be made stable by further increasing the slope. However, increasing the slope decreases the sensitivity of the relay.

With $S = 0.8$ the maximum permissible loop resistance for the line CT secondary circuits can be found from:

$$R_{A2} = \frac{1204}{(n_{MA})^2} \text{ ohms and}$$

$$R_{X2} = \frac{1204}{(n_{MX})^2} \text{ ohms}$$

where R_{A2} and R_{X2} represent the total secondary burden of the T_A and T_X line CT circuits.

This burden includes: the secondary winding resistance, the pilot-wire loop resistance and the resistance of any additional apparatus. The burden of the auxiliary CT's can normally be disregarded.

In practice, the RADSS relay is designed to include two variable resistors R_S and R_{d11}. The R_S is used primarily for setting the slope S, and the R_{d11} is used simply for increasing the total resistance of the differential circuit. The R_{d3} is fixed (not variable) and equal to about 1.10 ohms.

A closer examination of Fig. 2e and Equations 3 and 5 shows that the stability of the relay is independent of the actual magnitude of I_{T3}, i.e. even if U_{T3} increases to an infinitely large transient voltage the relay remains stable provided the value of R_{LX} does not exceed that given by Equation 5. The stability of the RADSS relay is, therefore, independent of the magnitude of the system fault level and the system d.c. time constant.

It should also be noticed that no requirement whatsoever has been established with respect to the characteristics of the various line CT's, for example their individual matching, accuracy, winding distribution, saturation level, remanence, time constant, etc. The reason is that these factors do not in any way affect the through fault stability of the RADSS.

In the above discussions the positive reference half-cycle only has been considered. It can, however, be shown that the differential relay comparator circuit works in exactly the same way during the negative half-cycle.

Internal faults

In the case of an internal bus fault, the fault current may be considered to enter the bus via the feeders L_A and L_B. All the other feeders, L_C... L_X, may be assumed to be disconnected or carrying no primary current (idle CT's).

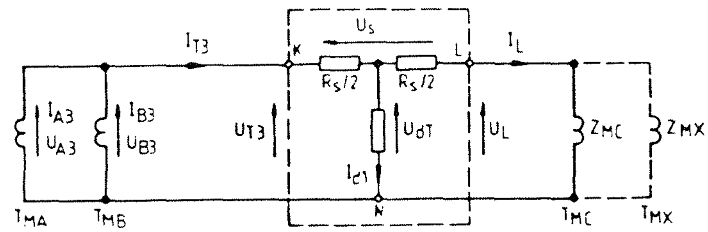


Fig 3. Basic circuit under internal fault conditions $Z_L = U_L/I_L = Z_{LM}$, total magnetizing impedance.

The schematic diagram in Fig. 3 may be used to represent this situation. At the L terminal of the relay the impedance:

$$Z_L = U_L/I_L = Z_{LM}$$

is obtained, which corresponds to the total magnetizing impedance of all the unloaded line CT's. This impedance however, is normally quite large and highly reactive, with a relatively large time constant, about 200 ms. In the case of an internal fault, the differential current is therefore larger than the magnetizing current. Also, the time constant of the differential circuit is practically zero and the rate-of-rise of the operating voltage will therefore exceed the rate-of-rise of the restraint voltage. Finally, the inductive nature of the magnetizing circuit causes a certain phase displacement between the operating and restraint voltages.

All of these features will assist to ensure decisive operation in the event of internal bus faults, irrespective of the number of circuits connected to the RADSS relay.

The minimum operating current of the differential relay (d_R) is given by:

$$I_{d1\,min} = \frac{K}{1 - S}$$

where K and S are constants depending on the selected settings of the comparator circuit.

The following approximate values apply to standard settings:

Slope (S)	0.50	0.66	0.80	0.85
I_{d1} min. (A)	0.20	0.30	0.46	0.61

It is seen that increasing the slope from 0.50 to 0.85 increases the minimum pick-up current from 0.20 to 0.61 A.

The speed of operation of the d_R-relay is about 1-3 ms for fault currents of more than 2 times the rating of the largest line CT. To ensure relay operation even when the line CT's saturate quickly, the d_R-relay together with the S_R-relay are arranged to energise an impulse storing (capacitor plus resistor) unit and a selfsealing high speed, 3.5 ms, auxiliary relay (RXMS 1).

CHARACTERISTICS OF RADSS

The operating and restraint characteristics of the RADSS can easily be determined by using the test circuit in Fig. 4a. The injection test voltage U_{T3} and the external test circuit impedance Z_L are varied to give the required I_{d1} and I_{T3} current distribution values.

The test circuit impedance Z_L is varied to represent a pure resistance in the case of an external fault, and to represent the total magnetizing impedance of all the idle line CT's in the case of an internal fault. When Z_L is infinite, i.e. open-circuited, all the incoming current must pass through the differential circuit. This is represented by the straight line $I_{d1} = I_{T3}$. It should be noted that the area above this line is of no significance, because I_{d1} can never exceed I_{T3}.

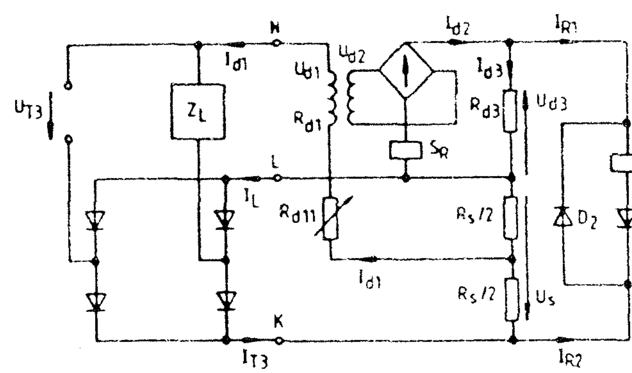


Fig 4 a. Test circuit used to determine the restraint and operating areas on external and internal faults.

U_{T3} = Test supply voltage; Z_L = Test circuit impedance.

The small narrow area between the stability line and the operating line if Fig. 4b is a dispersion area caused by the operating VA requirement of the d_R-relay. The relay current I_{R1} is here larger than zero, but less than the pick-up value.

The characteristics shown in Fig. 4b and 4c apply to a relay with the following typical setting:

R_{d3} = 1.10 ohms; $R_S/2$ = 7.30 ohms;

n_d = 10 which gives the constant K = 0.092 and the slope:

$$S = \frac{R_S}{n_d R_{d3} + R_S/2} = \frac{2 \times 7.30}{10 \times 1.10 + 7.30} = 0.8$$

and a minimum operating current:

$$I_{d1 min} = \frac{0.092}{1 - 0.8} = 0.46 \text{ A}$$

The stability line in Fig. 4b can be made to correspond to a test circuit where:

$$Z_L = R_{LX} = \frac{S}{1 - S} \times R_{dT} = \frac{0.8}{1 - 0.8} \times 301 = 1204 \text{ ohms}$$

by setting the value of the total differential circuit resistance (R_{dT}) equal to 301 ohms.

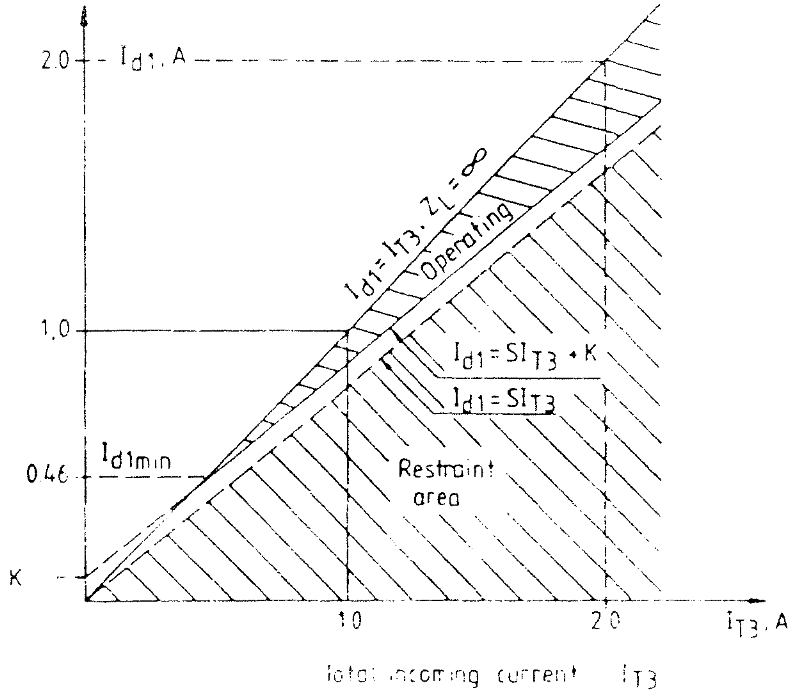


Fig. 4b. Restraint characteristic on external fault with relay slope S = 0.8 and with the test circuit impedance Z_L in fig. 4a given by:

$Z_L = R_{LX}$ = Linear resistance

The restraint area is limited by the equation:

$I_{d1} = S\, I_{T3}$ = stability line

The operating area starts by the equation:

$I_{d1} = S\, I_{T3} + K$ = operating line

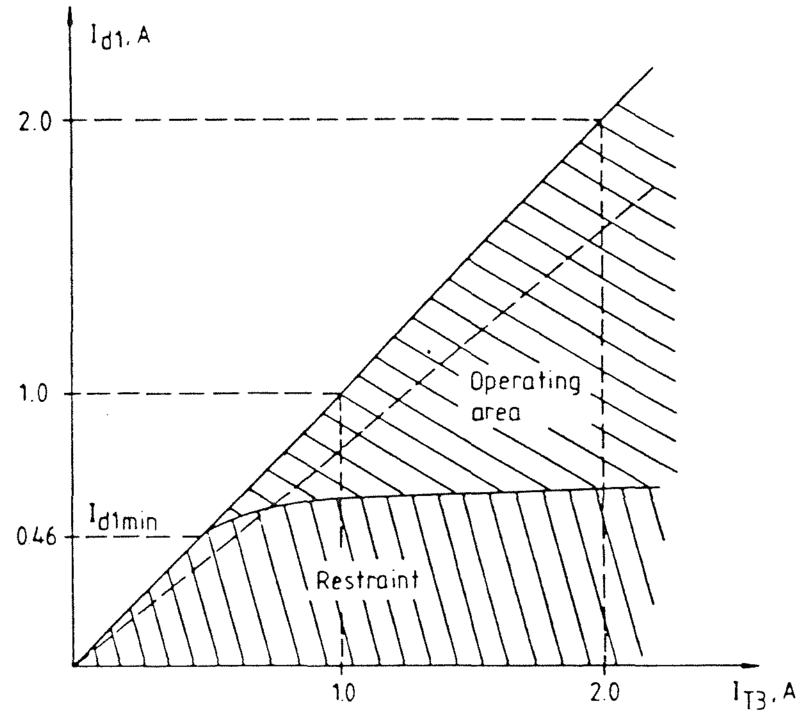


Fig 4 c. Operating characteristic on internal faults, with slope S = 0.8.

$Z_L = Z_{LM}$ = magnetizing impedance of all line- and aux.-CT's

CHECK FEATURES

The principles and methods of applying additional relays for increasing the reliability of bus differential schemes vary appreciably from one country to another. The inadvertent opening of a CT secondary circuit has been of particular concern, because this may lead to maloperation of a bus relay during normal service conditions.

Some power companies permit tripping of the bus zone relay if a CT secondary is open-circuited, whereas other companies require an alarm only, without tripping. The method which is adopted depends often on past experience, reliability of CT secondary wiring and whether tripping of the relay can be accepted from the system stability point of view.

There is also one relatively well known philosophy, which claims that the very important bus zone relay schemes should not be allowed to trip by the closing of one relay contact only. Two separately actuated relays, with their contacts connected in series. are then required to operate simultaneously in order to achieve tripping.

For the purpose of satisfying most requirements a simple overcurrent starting relay S_R has therefore been included as a standard check feature in the RADSS design. This relay is of the same high speed (1 ms) dry-reed type as the comparator circuit output relay d_R. The S_R-relay has a fixed (non-variable) setting, normally arranged to coincide with the largest line CT primary current rating. When a sensitive bus relay is particularly requested, the starting relay setting will be reduced to coincide with the d_R-relay setting. If considered unnecessary, the starting relay contact may be short-circuit.

A typical S_R-relay setting is given by:

$$I_{d1\ (SR)} = 0.88\ A$$

The corresponding primary operating current value must also include the magnetizing currents to all the line and auxiliary CT's. In a typical station with 12-lines the magnetizing current increases the operating value by about 20 per cent, hence:

$$I_{prim\ (SR)} = n_0\ (0.88)\ 1.2\ A$$

When VT's (voltage transformers) are installed on the bus, within the bus zone relay, the high-speed 1-8 ms, three-phase undervoltage relay RXOTB 2 can be used as a check feature, i.e. its contact may be connected in series with the differential relay contact so that both relays must operate to give tripping.

CT OPEN-CIRCUIT ALARM

A dry-reed alarm relay (type RXMT 1) is included in the differential circuit, set to operate at about 30 mA. The actual sensitivity of this alarm relay will depend on the total magnetizing current of all the line and auxiliary CT's. A primary setting of about 10-20 per cent of the largest line CT rating is normally obtained.

Since maloperation of a bus differential relay may lead to a complete system shut-down, the alarm relay is normally arranged to disconnect the trip circuit after a time delay of about 5 seconds and to short out the differential circuit resistors. The continuous thermal rating of the differential circuit is $I_{d1\ th} = 0.5$ A.

AUXILIARY CT'S RATIOS

Auxiliary CT's are required when the line CT's have a secondary rating of 5 A, and also when they have different turns ratios. The overall line and auxiliary CT ratio n_0, is given by:

$$n_0 = n_A\, n_{MA} = n_X\, n_{MX} =$$

$$\frac{I_{A1}}{I_{A2}} \times \frac{I_{A2}}{I_{A3}} = \frac{I_{X1}}{I_{X2}} \times \frac{I_{X2}}{I_{X3}} = \frac{I_{A1}}{I_{A3}} = \frac{I_{X1}}{I_{X3}}$$

The total through going load current of the bus may be donoted:

Max. bus transfer current, i.e.

$$I_{T1n} = I_{A1n} + I_{B1n} + \dots$$

This normally corresponds to the rated current carrying capacity of the bus conductors.

In order to prevent unnecessary heating of the comparator circuit resistors, relay current during normal full load conditions should be limited to 4 A. It should be checked therefore, that:

$$I_{T3n} = \frac{I_{T1n}}{n_0}$$

does not exceed 4 A.

The auxiliary CT's may be omitted altogether if all the line CT's have the same turns ratio, if their secondary rating is 1 A and the maximum permissible circulating relay current is not exceeded. Also, the maximum CT secondary knee-point voltage should be limited to about 500 V rms.

As an example, consider that for a particular bus installation:

Max. bus transfer current I_{T1n} = 4000 A, and that for the line L_A:

n_A = 1000/5 A, and

n_{MA} = 5/1 A

i.e. $n_0 = \frac{1000}{5} \times \frac{5}{1} = 1000$

and $I_{T3n} = \frac{4000}{1000} = 4$ A

Also, it may be assumed that for this station the operating characteristic of Fig. 4c will apply. The primary fault setting (I_{FS}) then becomes (approx):

$I_{FS} = n_0 \times I_{d1\,min} = 1000 \times 0.46 = 460$ A

If separate line CT cores are available for the bus relay, it is recommended that the auxiliary CT's be installed near the line CT's. In this way the auxiliary CT primary winding can be regarded as being securely connected to the line CT secondary winding. If an open-circuit should occur within the wiring up to the differential relay the auxiliary CT becomes damaged but it will protect the line CT from being open-circuited.

LINE CT REQUIREMENTS

The line CT's need not be matched nor must they be of the same type, for example wound or bar type. In the majority of installations it is found that standard line CT's have a knee-point (saturation) voltage and a secondary winding resistance lying well within the requirements of the relay.
In the case of internal bus faults it is normally required that a differential relay current of about 1.3 x the operating current shall be produced before the line CT's start to saturate.

The total resistance (R_{dT}) of the differential circuit may be varied between 165-301 ohm. The required relay operating voltage (U_{T3}) may vary between 86 V and 310 V depending on the selected settings for the installation. In the case of line CT's with a secondary rating of 1 A, their required knee-point voltages are often found to lie in the region of 100-500 V. For 5 A line CT's these requirements are normally reduced to 20-100 V.

It should be noted that these minimum knee-poing voltage requirements are related only to the operating ability of the relay during internal faults. The stability of the relay during external faults is not in any way affected by the saturation levels of line or auxiliry CT's.

FULL SCALE HEAVY CURRENT TESTING

The basic formulae for stability and operation of the RADSS relay have been thoroughly tested under the most severe fault conditions. Such tests have been carried out both at the Central Development Department of ASEA and at the independent, heavy current testing laboratories of KEMA, Arnhem, Holland.

Altogether, some hundred heavy current test shots have been carried out representing both internal and external faults of varying magnitudes. In none of these tests did the relay maloperate, or refuse to operate when required. The stability of the relay, under the most unfavourable through fault conditions, was checked with fault current equal to 600 times the rating of the faulty feeder circuit.

The ability of the relay to operate prior to saturation i.e. on the initial rise of the internal fault current, was checked by using fault currents equal to 375 times the rating of the incoming feeder. The line and auxiliary CT's were premagnetised in the worst direction. In these tests the incoming line CT saturated in less than 2 ms. The starting and differential relays, however, operated in less than 1 ms, causing an immedite seal-in action by means of an impulse storing capacitor unit and a self-sealing auxiliary relay RXMS 1.

BRIEF REPORT OF TEST NO. 6868 A

A brief review of the main test circuits and of two typical oscillograms will be given in the following:

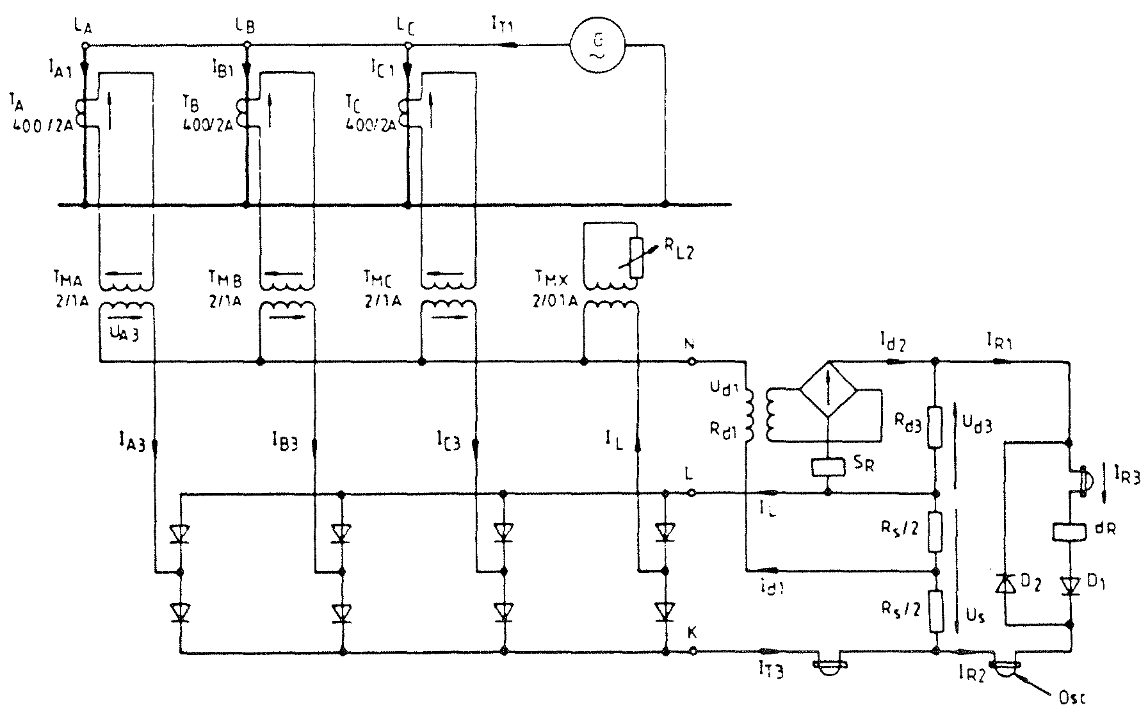


Fig 5. Internal fault with max I_{T1} = 24 kA r.m.s (first peak 62 kA). The oscillograph loops were arranged to record the current at relay terminal K and the current I_{R1}/I_{R2}.

The test circuit of Fig. 5 was used to check the operating characteristic of the relay during internal faults. The primary current I_{T1} is directed towards the bus, and at the same time the secondary current I_{T3} enters the relay at terminal K. The outgoing relay current I_L is relatively small and limited by the value of R_{L2}, which initially was very large. The differential current I_{d1} is therefore large and causes a current I_{d2} to pass through the relay S_R and a current i_{R1} through the relay d_R.
By reducing R_{L2} some of the mathematieally derived equations for stability could be verified.

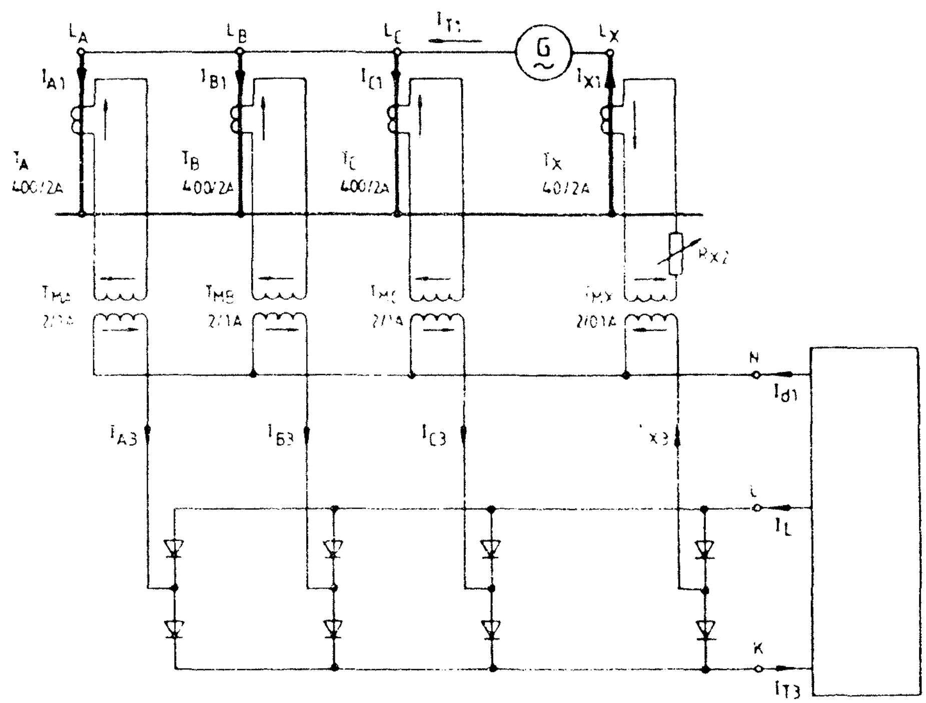


Fig 6. External fault with I_{T1} = 24 kA r.m.s

$$\therefore I_{X1} = \frac{24000}{40} = 600 \text{ times rating.}$$

The test circuit of Fig. 6 was used to check the stability of the relay during external faults. Varying the value of the resistance R_{X2}, in the secondary circuit of the line current transformer T_X, made it possible to determine the limiting condition for stability. It was found that R_{X2} could be increased by about 10 per cent above the calculated value without any risk of maloperation.

The measuring loops of a high-speed multi-channel oscillograph were arranged to provide traces of:

I_{T1} Primary fault current. This always starts in a positive reference direction.

I_{R1}/I_{R2}

The positive trace, above the zero line, represents I_{R1} through the differential relay d_R. The negative trace below the zero line, represents the blocking current I_{R2} through the diode D_2 (blocks operation of d_R).

I_{T3}, I_L
This trace represents I_{T3} when I_{T1} flows in the positive reference direction. When I_{T1} is negative, the current I_L from the auxiliary current transformer T_{MX} enters the relay at terminal K.

t_d Operating time of differential relay d_R.

t_s Operating time of starting relay S_R.

t_T Total operating time (measured on auxiliary self-sealing relay RXMS 1), see Fig. 7.

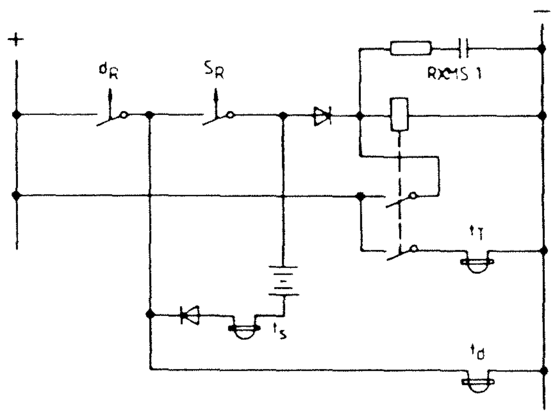


Fig 7. The relays d_R and S_R have only one make contact each. The arrangements shown here were made to permit individual recording of the opening and closing of these contacts.

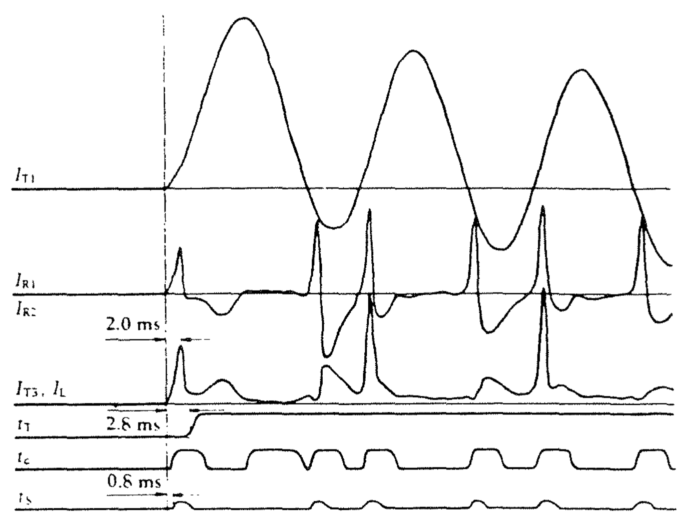


Fig 8. Oscillogram No. 16, I_{T1} = 24 kA r.m.s. Internal fault t_d = t_s = 0.8 ms, t_T = 2.8 ms.

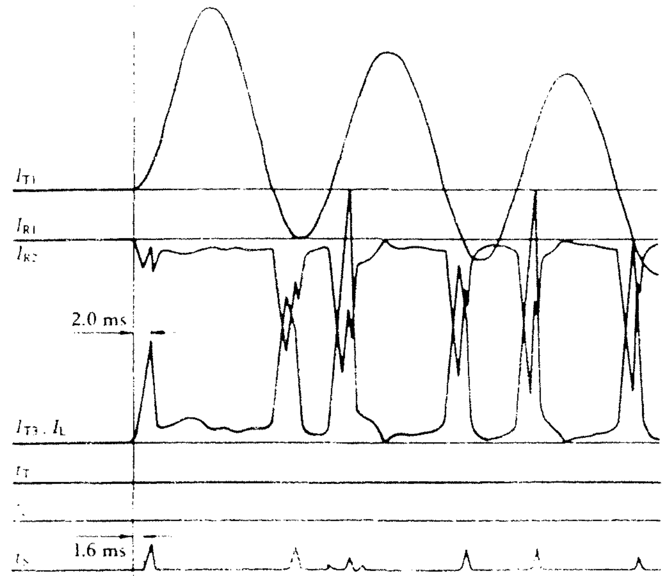


Fig 9. Oscillogram No. 48, i_{T1} = 24 kA r.m.s. External fault. No operation of differential relay (trace t_d) and the relay remains fully stable

RADSS THREE-PHASE DESIGNS

The RADSS components are designed to suit the COMBIFLEX modular mounting and wiring system. A standard relay for 3 phases and 1 zone is shown on drawing 7451 298-HA.

APPENDIX

Derivation of comparator circuit operating and restraint characteristics

The d_R-relay just operates when (see Fig. 1):

$$U_{d3} - U_S = VD1 + I_{R1} \cdot R_{dR} \qquad \text{(Eq. 1)}$$

where

$$U_{d3} = (n_d I_{d1} - I_{R1}) R_{d3}$$

$$U_S = I_{T3} \frac{R_S}{2} + (I_{T3} - I_{d1}) \frac{R_S}{2} + I_{R1} R_S$$

$VD1$ = Forward voltage drop of diode D1

I_{R1} = Pick-up current of d_R-relay

R_{dR} = Resistance of d_R-relay

n_d = Turns ratio of T_{Md} = 10

By inserting these values in equation (1) and also including the constants given by:

$$S = \frac{R_S}{n_d R_{d3} + R_S/2}$$

$$K = I_{R1} \frac{R_{d3} + R_S + R_{dR}}{n_d R_{d3} + R_S/2} + \frac{VD1}{n_d R_{d3} + R_S/2}$$

the operating equation for the d_R-relay becomes a straight line with the slope S, i.e.

$$I_{dl} = SI_{T3} + K \qquad \text{(Eq. 2)}$$

This implies that the differential current must exceed a certain percentage (S) of the total incoming current I_{T3} plus a certain fixed amount (K) in order to cause operation of d_R-relay.

Full stability can be guaranteed when the output current $I_{R1} = 0$ and $K = 0$, giving the stability line:

$$I_{dl} = SI_{T3} \qquad \text{(Eq. 3)}$$

The minimum operating current is obtained when all the incoming current goes through the differential circuit, i.e.

$I_{dl} = I_{T3} = I_{dl\,min}$ inserted in Equation 2 gives:

$I_{dl\,min} = S\,I_{dl\,min} + K$

$$\text{Hence, } I_{dlmin} = \frac{K}{1-S} \qquad \text{(Eq. 4)}$$

Maximum permissible loop resistance R_{LX}

Referring to Fig. 2d and 2e, the maximum value of R_{LX} required to bring the relay to its stability limit, is determined by:

$I_{dl} = SI_{T3}$, and $I_L = (1 - S)\, I_{T3}$

Also, neglecting the influence of $R_S/2$ and assuming $U_{dT} = U_L$, gives:

$$U_{dT} = SI_{T3}\, R_{dT} = (1 - S)\, I_{T3}\, R_{LX} = U_L$$

$$\text{Hence, } R_{LX} = \frac{S}{1-S}\, R_{dT} \qquad \text{(Eq. 5)}$$

where, the total differential circuit resistance:

$$R_{dT} = n_d^2\, R_{d3} + R_{Md} + R_A + R_{d11} \qquad \text{(Eq. 6)}$$

and, where the differential circuit components are given by:

$n_d^2\, R_{d3} = R_{dl}$ = Resistance referred to T_{Md} primary side.

R_{Md} = Resistance of T_{Md} primary winding.

R_A = Resistance of alarm relay RXMT 1.

R_{d11} = Variable resistor max. range: 0-136 ohms.

Typical settings:

$R_{dT} = 10^2 \times 1.10 + 35 + 20 + R_{d11} = 165 + R_{d11}$

max. setting

$R_{dT} = 165 + 136 = 301$ ohms

Hence, with $S = 0.8$

$R_{LX} = \frac{0.8}{0.2}\ 301 = 1204$ ohms

CT knee-point voltage requirements

The line and auxiliary CT's must have output voltages capable of driving a differential current (I_{d1}) through RADSS, so that the d_R- and S_R-relay elements operate on internal faults.

The output voltage from the auxiliary CT required to cause operation of the d_R-relay is given by approx.:

$U_{T3\ (dR)} = I_{d1\,min} (R_{dT} + 28) + n_d\ VD3$

where: 28 ohms is the secondary winding resistance of T_{Md}, referred to the primary side, and

$VD3 = 2.0$ Volts, is the forward voltage drop of the full wave rectifier on T_{Md} secondary side.

As an example, consider standard settings:

$S = 0.8$, $I_{d1\,min} = 0.46$ A, $R_{dT} = 301$ ohms, $n_d = 10$

the operating voltage of the d_R-relay becomes approximately:

$U_{T3\ (dR)} = 0.46\ (329) + 20 = 171$ V

Similarly, the voltage required to cause operation of the S_R-relay is given by:

$U_{T3\ (SR)} = I_{d1\ (SR)} (R_{dT} + 28) + n_d\ VD3$

hence, with standard S_R-relay setting we have:

$U_{T3\ (SR)} = 0.88\ (329) + 10 \times 2 = 310$ V

When a sensitive relay is required, or when the line CT's are relatively weak, i.e. with small knee-point voltage, the S_R-relay should be particularly ordered to operate at the same, or at a smaller value than the d_R-relay. In that case the various operating currents can be written:

$$I_{d1\,(SR)} = I_{d1\,(dR)} = I_{d1\,min}$$

which is determined by the selected slope setting (i.e. between 0.20-0.61 A).

The line CT's should have a relatively high knee-point voltage, so that sufficient current can be fed through the RADSS diff. circuit. It is considered adequate if the relay input voltage (U_{T3}) and the diff. current (I_{d1}) become at least 1.3 x the pick-up values before the line CT's start to saturate.

The auxiliary CT secondary knee-point voltage should therefore, in this example, be at least

$$U_{T3\,K} = 1.3 \times 310 \approx 400\ \text{V}$$

Referred to the aux. CT primary sides:

$$U_{A2} = \frac{U_{T3\,K}}{n_{MA}}\ ,\quad U_{X2} = \frac{U_{T3\,K}}{n_{MX}}$$

i.e. if $n_{MA} = 5$ and $n_{MX} = 50$

$U_{A2} = 80$ V and $U_{X2} = 8$ V

If line L_A can feed fault current towards the bus, the required knee-point voltage of the T_A CT becomes:

$$U_{A2\,K} = I_{A2\,(SR)}\,R_{A2} + \frac{U_{T3\,K}}{n_{MA}}$$

where:

$I_{A2\,(SR)}$ = Current required to cause operation of S_R-relay (say 5A)

R_{A2} = Total loop resistance of T_A secondary circuit (say 2 ohms)

As a typical example we may have, for a 5A CT secondary rating:

$$U_{A2\,K} \approx 5 \times 2 + 80 = 90\ \text{V}$$

The knee-point voltage requirement for the other <u>feeding</u> lines can be calculated similary.

If line L_X is connected to a load only, this line cannot feed a fault current towards the bus and the T_X CT knee-point voltage requirement is only

$$U_{X2\,K} = \frac{U_{T3\,K}}{n_{MX}} = 8\ V$$

Calculations for a typical station

Assume that:

n_A = Largest line CT ratio = 2000/5 A

n_X = Smallest line CT ratio = 200/5 A

I_{T1n} = Max. bus transfer current = 4000 A

Minimum primary fault current $\geqslant$ 2000 A

On the basis of these data the following relay settings may be selected:

Overall CT ratio:

$$n_0 = \frac{2000}{5} \times \frac{5}{1} = \frac{200}{5} \times \frac{5}{0.1} = 2000$$

hence $n_{MA} = 5$, $n_{MX} = 50$

The max. circulating relay current then becomes

$I_{T3n} = 2\ A$

Selecting:

$S = 0.8$, $I_{d1\,(SR)} = 0.88\ A$ and

$R_{dT} = 165 + R_{d11} = 165 + 136 = 301$ ohms

gives a minimum operating value for the d_R-relay:

$I_{d1\,min} = 0.46\ A$

and permits a max. loop resistance:

$$R_{LXp} = \frac{S}{1-S} \quad R_{dT} = \frac{0.8}{0.2} \quad 301 = 1204 \text{ ohms}$$

i.e. the actual total loop resistance in the T_X CT secondary circuit must be less than:

$$R_{X2} = \frac{R_{LXp}}{(n_{MX})^2} = \frac{1204}{2500} = 0.48 \text{ ohms}$$

and for the other line CT circuits

$$R_{A2} = \frac{R_{LXp}}{(n_{MA})^2} = \frac{1204}{25} = 48 \text{ ohms}$$

The secondary winding resistance of a 200/5 A CT is normally about 0.2 ohms and by installing the aux. CT close to the line CT the permissible resistance value will not be exceeded. In practice, therefore, a problem may exist only if the ratio between the largest and smallest line CT primary current ratings exceed 10.

The line CT knee-point voltage requirements must be checked as indicate in the section above. It should be remembered that in a station with small knee-point voltages an appreciable reduction in the voltage requirements can be obtained by making the S_R- and d_R-relays operate at the same current value, i.e. $I_{d1\,(SR)} = I_{d1\,(dR)} = I_{d1\,min}$.

Typical settings

The turns ratio of T_{Md} is given by:

$n_d = 1500/150 = 10$

Standard S_R-relay setting:

$I_{d1\ (SR)} = 0.88$ A $\pm$ 5 % (fixed)

Resistance of $R_{d3} = 1.10$ ohms $\pm$ 5 % (fixed)

Table 1. RADSS settings and approximate operating value.

Slope	(S)	0.50	0.66	0.80	0.85
$R_S/2$	(ohms)	3.66	5.50	7.30	8.15
K	(A)	0.10	0.096	0.092	0.091
R_{Se}	(ohms)	0.96	1.0	1.02	1.03
$P_n = I_{T3}^2 R_{Se}$	(W)	16	16	16	16
$I_{d1\,min}$	(A)	0.20	0.30	0.46	0.61
R_{dT}	(ohms)	301	301	301	301
R_{LX}	(ohms)	301	602	1204	1705
$U_{T3(dR)}$	(V)	86	118	171	221
$U_{T3(SR)}$	(V)	310	310	310	310

The effective resistance R_{Se} refers to the resultant resistance of R_{d3} in parallel with R_S, as seen by the circulating relay current (I_{T3}) during normal service.

The calculated value $P_n = (I_{T3n})^2 R_{Se}$ is based on the max. heat developed with $I_{T3n} = 4$ A. If a larger heating effect is required the physical size of the resistors must be increased and, probably, also the ventilation of the relay cubicle.

REFERENCE PUBLICATIONS

Test report 6868 A	Full scale heavy current testing
Test report RKU 40-30 E	Result from tests carried out at KEMA, Arnhem, Holland
Information RF 637 321	RADSS 1 Zone, 12 Lines, 3-phase, circuit
Diagram	7451 298-HA

RADSS: Test circuit for checking the operating and restraint characteristics

1 INTRODUCTION

The operating and restraint characteristics of the RADSS protection can easily be checked by the test circuit indicated in Fig. 1. When the test circuit impedance Z_L is made equal to a variable linear resistor, the restraint characteristic of Fig. 2 can be obtained, and when Z_L is made equal to a variable reactance, the operating characteristic of Fig. 3 will be obtained.

The injection test voltage U_{T3} and the test circuit impedance Z_L is varied to make a certain percentage of I_{T3}, the total incoming current, pass through the differential circuit. The various characteristics of I_{d1} versus I_{T3} will then be obtained (Figures 2 and 3).

2 RESTRAINT CHARACTERISTIC (Fig. 2)

The more detailed test circuit of Fig. 4 should be used.

2.1 Minimum operating currents

In the case of a standard RADSS package, set $R_{LX} = \infty$ (i.e. open circuited) and increase U_{T3} until the current $I_{T3} = I_{d1}$ causes operation of the RXMT 1 alarm relay, d_R relay and S_R relay. Check also that a positive deflection is obtained on the sensitive dc voltmeter U_{R1}.

Record:

Pick-up	U_{T3} (V)	I_{d1} (A)	U_{R1} (mV)
Alarm			
d_R relay			
S_R relay			

2.2 Stability (restraint) test

8 Set the resistor R_{LX} about 50 % higher than the calculated maximum permissible loop-resistance. Increase U_{T3}. Check that U_{R1} gives positive deflection. Reduce R_{LX} and observe that U_{R1} is also reduced. Increase U_{T3} until I_{T3} = 0.5 A and adjust R_{LX} so that U_{R1} remains approximately zero (but still positive), record:

U_{T3} (V)	I_{T3} (A)	I_{d1} (A)	U_{R1} (mV)	U_L (V)	I_L (V)	$R_{LX} = U_L/I_L$

Note: Continuous (thermal) rating of differential circuit $I_{d1} = 0.5$ A.
$I_{d1} = 1$ A can be permitted for 50 seconds.

From these results the slope of stability line is obtained from $S = I_{d1}/I_{T3}$.

The boundary of the restraint area may also be checked for different values of I_{T3}, for example: 0.8 A and 1.0 A. The corresponding values of I_{d1} should be found to coincide fairly well with the straight line:

$I_{d1} = S\ I_{T3}$, which may be denoted the stability line,

or restraint line, because it corresponds to zero output voltage to the d_R relay, i.e. $U_{d3} = U_S$.

2.3
Operating area of Fig. 2

Increase the value of R_{LX} and check that in the case of standard settings, the d_R relay just operates when (approx.) $\underline{I_{d1} = 0.8\ I_{T3} + 0.1}$.

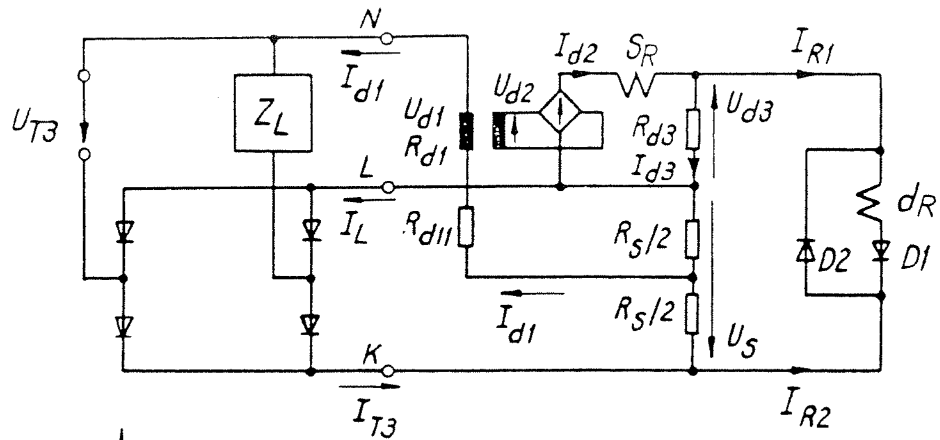
3
OPERATING CHARACTERISTIC (Fig. 3)

The test circuit of Fig. 4 may still be used, but R_{LX} should be replaced by a variable air-gap reactor: 0-500 ohms, 1 A rating. The operating area for the standard protection will be basically as shown in Fig. 3.

Standard RADSS settings:

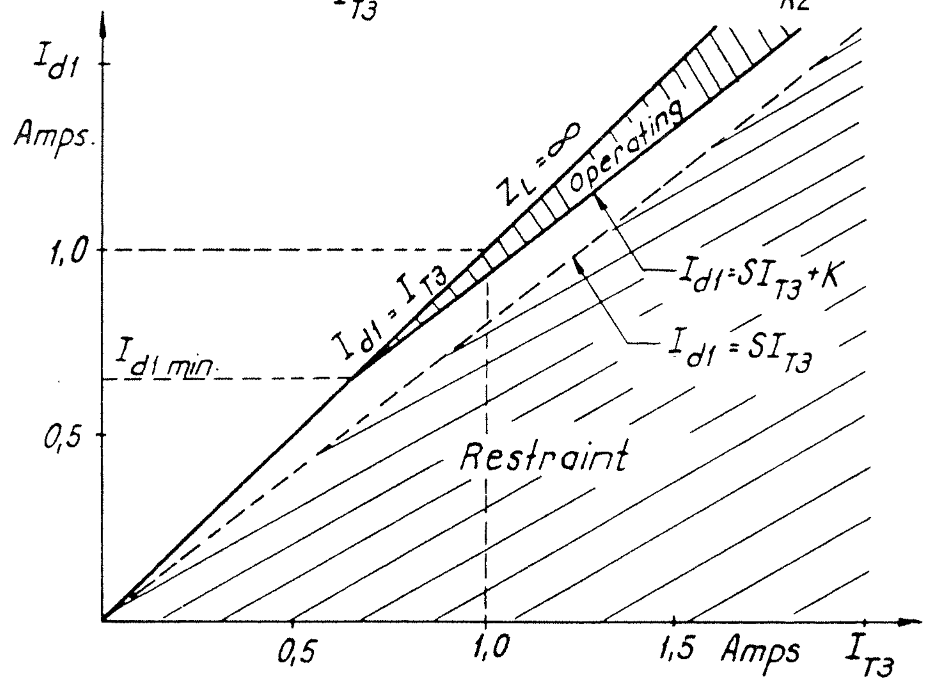
$R_{d3} = 1.1$ ohms; $R_S/2 = 7.3$ ohms

$$n_d = 10 \text{ and } S = \frac{R_S}{n_d\ R_{d3} + R_S/2} = 0.8$$



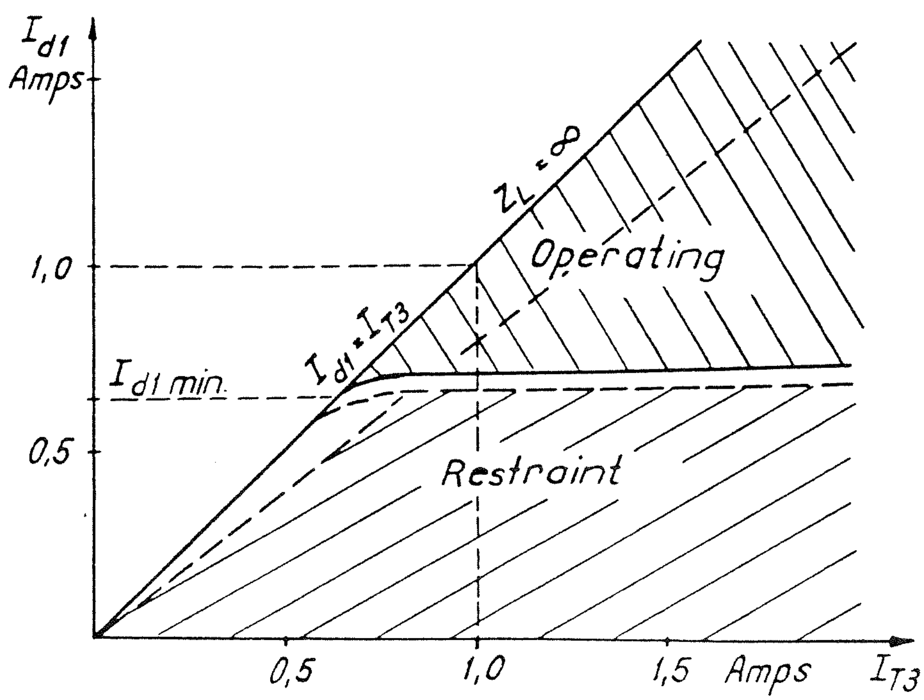
(Fig. 1)

Test circuit used to determine the restraint and operating areas on external and internal faults.
U_{T3} = Test supply voltage;
Z_L = Test circuit impedance



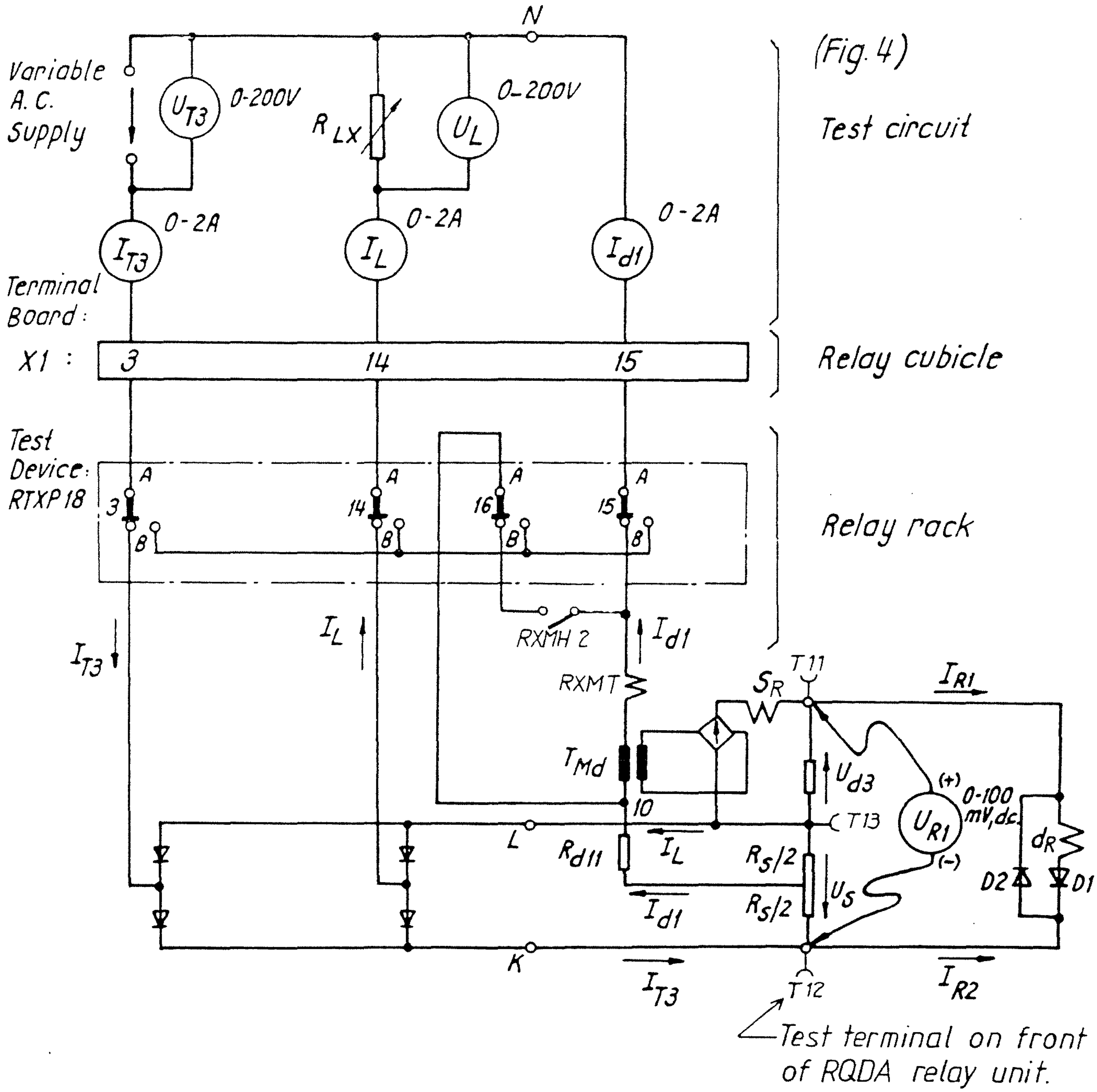
Restraint characteristic on external fault; $Z_L = R_{LX}$ linear resistance
$I_{d1} = SI_{T3}$ stability line
$I_{d1} = SI_{T3} + K$ operating line.

(Fig. 2)



Operating characteristic on internal fault, $Z_L = Z_{LM}$ magnetising impedance

(Fig. 3)



Instruments:

U_{T3}, U_L Voltmeter 0-200V a.c.
I_{T3}, I_L, I_{d1} Ammeter 0-2A a.c.
U_{R1} Sensitive d.c. voltmeter 0-100mVdc

Resistor:

R_{LX} Variable resistor 0-1000Ω, 1A

Auxiliary CT's for RADSS bus protection

The RADSS bus differential protection uses auxiliary CT's for the following reasons:

- Ratio correction, so that the overall turns ratio (n_o) becomes the same for all CT circuits.
- To bring down the main CT secondary current from 5 A to 1 A, or in some special cases from 5 A to 2 A.
- The auxiliary CT's also limit the maximum transient voltage imposed on the RADSS relay. This is achieved by keeping the secondary knee-point voltage less than about 500 V r.m.s.

AUXILIARY CT TYPE SLCE 16 AND SLXE 4

The auxiliary CT's types SLCE 16 and SLXE 4 are available. The auxiliary CT's have strip mounted cores made up of high quality sheet steel with C-shaped stampings. The SLCE 16 and SLXE 4 is normally provided with screw terminal 2 for maximum 10 mm^2 wires (see Fig. 3 and Fig. 4 for dimensions).

Table 1. Typical ratios

Type	Current ratio	Turns ratio	Cu-loss at 20°C and rated current
SLCE 16	5/1	160/800	20 W
	5/0.5	80/800	5 W
	1/1	800/800	20 W
	1/0.1	80/800	0.2 W
SLXE 4	5/2	240/600	25 W
	2/2	600/600	25 W
	1/2	1200/600	25 W

The knee-point voltages for the SLCE 16 resp. SLXE 4 are about 450 resp. 400 V r.m.s. It should be noted that the number of secondary turns is kept constant for both types, 800 resp. 600 turns. Different CT turns ratios are therefore obtained by varying the number of primary turns.

8

The volts/turn at an induction of about 1.6 Tesla is 0.52 V/t for SLCE 16 and 0.66 V/t for SLXE 4.

MULTI-RATIO AUXILIARY CT'S

For a particular bus installation, with several different main CT ratios, it is an advantage to use only one type of auxiliary CT with the required number of taps. The SLCE 16 may be provided with seven terminal taps for the primary winding and two terminals for the secondary winding.

As an example consider a bus installation with the following line CT and aux. CT ratios:

Table 2

Line CT	2000/5	1600/5	1200/5	1000/5	800/5	400/5
Aux. CT	5/1	5/0.8	5/0.6	5/0.5	5/0.4	5/0.2
Aux. turns	160/800	128/800	96/800	80/800	64/800	32/800

The overall ratio is in this example $n_c = 2000$.

One multi-ratio auxiliary CT with the above data may be ordered as follows:

Type SLCE 16, aux. CT with

Current ratio: 5/0.2 - 0.4 - 0.5 - 0.6 - 0.8 - 1 A

Primary terminals/turns:
P1 - P2 - P3 - P4 - P5 - P6 - P7
0 - 32 - 64 - 80 - 96 - 128 - 160

Secondary terminals/turns:

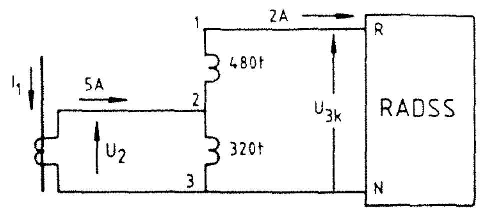
S1 - S2 / 0 - 800 t to be used with RADSS

It should be noted that if more ratios are required these can be obtained by using intermediate terminals, e.g. by using the primary connections P3 - P4 = 16 t and P4 - P6 = 48 t, the ratios 5/0.1 and 5/0.3 A can also be obtained.

AUTO-CONNECTED AUX. CT FOR 2 A SECONDARY RATING

The SLCE 16 may be used for the ratio 5/2 A provided it is permitted to use the auto-connection principle.

This is normally the case if dedicated main CT's are used. On the other hand, if the RADSS plus some other relays are connected to same main CT core, certain wiring and polarity problems may arise. The SLXE 4 must then be used with separately insulated primary and secondary windings.



SLCE 16
5/2 A
Autoconnected with
terminals/turns:
1 - 2 - 3 / 0 - 480 - 800 t

Fig. 1 Possible arrangement of SLCE 16

The knee-point voltage $U_{3k} \approx 450$ V across terminals 1 - 3.

STOCKED MULTI-WINDING AUX. CT

A special reconnectable SLCE 16, suitable for being used with the RADSS protection, will be made available from a small stock at the R-division. Two different ratings will be provided, i.e. with 1 A or 5 A rated primary windings. The secondary winding will always be made with a maximum rating of 1 A.

The two different designs are denoted:

- o Multi-winding SLCE 16
  Ratio 1/0.025 - 1 A
  Ordering No. 4785 040-BCV

- o Multi-winding SLCE 16
  Ratio 5/0.025 - 1 A
  Ordering No. 4785 040-BCZ

In both designs the secondary current can be altered in steps of 25 mA up to 1 A. The primary current is always considered to be fixed, i.e. equal to the rated current of 1 A or 5 A.

As indicated in Fig. 2 there are four primary windings with the relative number of turns: 1 k, 3 k, 9 k and 27 k, where k is a constant. The secondary winding has a fixed number of 800 turns, which provides the typical knee-point voltage of about $U_k = 450$ V r.m.s.

The total relative number of turns in all the primary windings is:
1 k + 3 k + 9 k + 27 k = 40 k.

Hence, in the case of a 1/1 A ratio it follows that:
40 k = 800 t, i.e. k = 20.

Similarly, in the case of a 5/1 A ratio:
40 k = 160 t, i.e. k = 4.

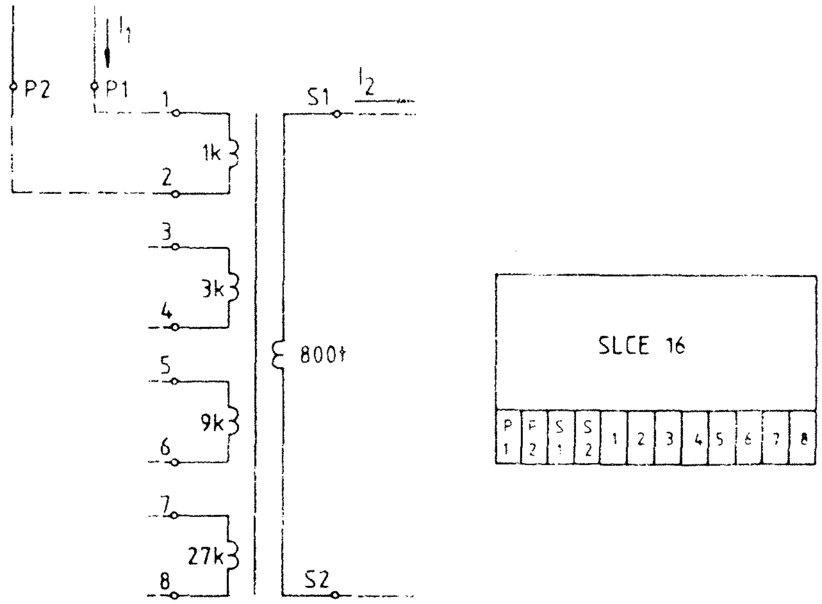


Fig. 2 Multi-winding SLCE 16

From Table 3 it is seen that any relative number of primary turns between k = 1 and k = 40 can be obtained by adding or subtracting the turns in the various windings.

The percentage value between each relative number of turn is

$$\frac{1\ k}{40\ k} \times 100\ \% = 2{,}5\ \%$$

which corresponds to steps of 25 mA when reflected to the output current of the 1 A rated secondary winding.

The connections shown in Table 3 are valid for both the 1 A- and 5 A-designs, i.e. the ratio 1/0.025 A and 5/0.025 A will be obtained by using the connections for k = 1, i.e. P1 - 1, 2 - P2.

The corresponding actual primary number of turns is 20 t for the 1 A-rating and 4 t for the 5 A-rating. The secondary current I_2 therefore becomes (for k = 1):

$$I_2 = \frac{1\ A \times 20\ t}{800\ t} = 0.025\ A \text{ for the 1 A-rating}$$

$$I_2 = \frac{5\ A \times 4\ t}{800\ t} = 0.025\ A \text{ for the 5 A-rating}$$

Similarly, for all the other k-values, between 2 and 40, the secondary current can be increased in steps of 25 mA up to 1000 mA by using the shown primary connections. The secondary winding is always connected to S1 - S2.

Example

a) Required ratio: 1/0.375 A

Use: SLCE 16, 1/0.025 - 1 A
Reference k-value = 20
Connect: P1 - 4, 3 - 6, 5 - 7, 8 - P2
Ordering No. 4785 040-BCV

b) Required ratio: 5/0.375 A

Use: SLCE 16, 5/0.025 - 1 A
Reference k-value = 4
Connect: P1 - 4, 3 - 6, 5 - 7, 8 - P2
Ordering No. 4785 040-BCZ

It should be remembered that the RADSS protection cannot tolerate too high aux. CT ratios. In practice the ratios 1/0.05 A = 20 and 5/0.125 A = 40 must be regarded as typical maximum values.

REQUIRED AUX. CT SECONDARY SATURATION VOLTAGE

The aux. CT's must be capable of producing a certain secondary voltage in order to ensure that the RADSS relay will operate in the case of an internal bus fault. The secondary knee-point voltage should be at least 1.3 times the RADSS relay operating voltage.

If the operating voltage is about 300 V the aux. CT saturation voltage should be at least 390 V. This is sufficient because in the case of heavy internal bus faults the maximum aux. CT transient voltage can reach 2000 V and since the RADSS relay works within 1 ms decisive operation will still be obtained.

As previously mentioned the aux. CT saturation voltage should not exceed 500 V r.m.s., in order to limit the maximum transient voltage imposed on the RADSS relay.

For the RADSS relay the auxiliary current transformer secondary turns are fixed for SLCE 16 to 800 t and for SLXE 4 to 600 t.

Ordering table: SLCE 16, standard versions with 800t secondary

Fixed ratio	5/1 A	4785 040-AYZ
	1/1 A	4785 040-AZF
	1/0.5 A	4785 040-ANV
Multi ratio	5/0.5-1 A	4785 040-AXP
	1/0.125-0.25-0.5-1 A	4785 040-ANX
	1/0.2-0.4-0.5-1 A	4785 040-ANY
	1/0.3-0.5-0.6-1 A	4785 040-ARF

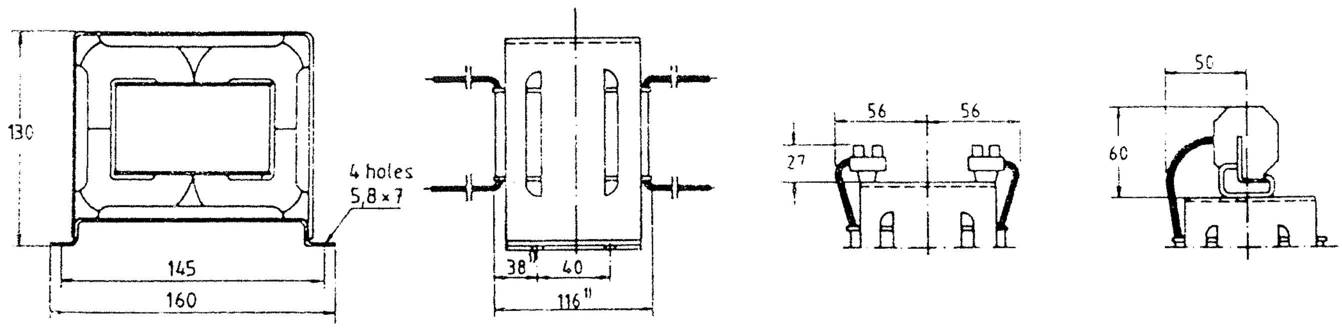


Fig. 3 Type SLCE 16 (Mass: [illegible] kg)

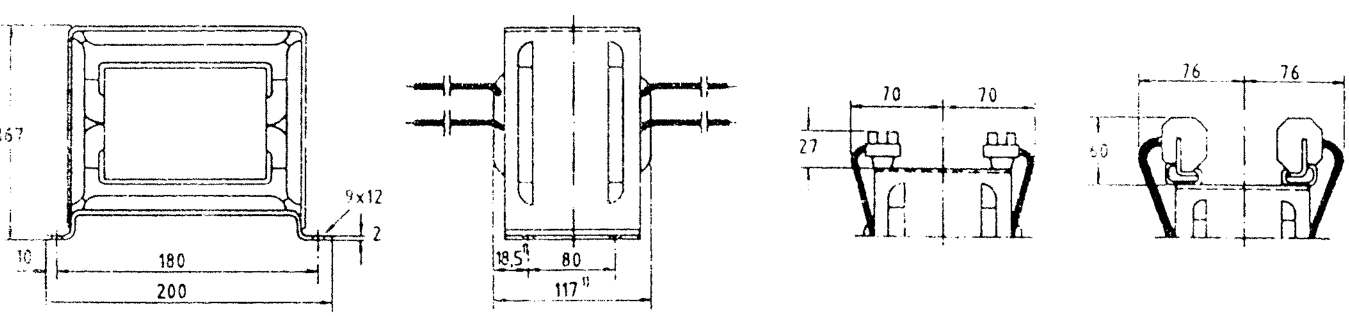


Fig. 4 Type SLXE 4 (Mass: 8 kg)

Multiwinding SLCE 16

Description (own language)

RK 637-302E Ed.2

Accepted by Quality Control | Accepted for production by | Design checked by S.Forsman | Drawing checked by | Drawn by

Reference k-value	I_2 (mA)	P1 1 3 5 7 P2 / 1k 3k 9k 27k / 2 4 6 8	Primary connections
1=1	25		P1-1 2-P2
2=-1+3	50		P1-2, 1-3 4-P2
3=3	75		P1-3 4-P2
4=1+3	100		P1-1, 2-3 4-P2
5=-1-3+9	125		P1-2, 1-4, 3-5 6-P2
6=-3+9	150		P1-4, 3-5 6-P2
7=+1-3+9	175		P1-1, 2-4, 3-5 6-P2
8=-1+9	200		P1-2, 1-5 6-P2
9=9	225		P1-5 6-P2
10= 1+9	250		P1-1, 2-5 6-P2
11=-1+3+9	275		P1-2, 1-3, 4-5 6-P2
12=3+9	300		P1-3, 4-5 6-P2
13=1+3+9	325		P1-1, 2-3, 4-5 6-P2
14=-1-3-9+27	350		P1-2, 1-4, 3-6 5-7, 8-P2
15=-3-9+27	375		P1-4, 3-6 5-7, 8-P2

No | Revision | Appd | Dept | Year Wk

Description (own language)	RK 637-302E Ed.2	Iss. by dept	Year	Week

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		S.Forsman		

Reference k-value	I_2 (mA)	P1 1 3 5 7 P2 / 1k 3k 9k 27k / 2 4 6 8	Primary connections
16=+1-3-9+27	400		P1-1, 2-4, 3-6 5-7, 8-P2
17=-1-9+27	425		P1-2, 1-6 5-7, 8-P2
18=-9+27	450		P1-6, 5-7 8-P2
19=+1-9+27	475		P1-1, 2-6 5-7, 8-P2
20=-1+3-9+27	500		P1-2, 1-3, 4-6 5-7, 8-P2
21=+3-9+27	525		P1-3, 4-6 5-7, 8-P2
22=+1+3-9+27	550		P1-1, 2-3, 4-6 5-7, 8-P2
23=-1-3+27	575		P1-2, 1-4, 3-7 8-P2
24=-3+27	600		P1-4, 3-7 8-P2
25=+1-3+27	625		P1-1, 2-4, 3-7 8-P2
26=-1+27	650		P1-2, 1-7 8-P2
27=27	675		P1-7 8-P2
28=+1+27	700		P1-1, 2-7 8-P2
29=-1+3+27	725		P1-2, 1-3, 4-7 8-P2
30=+3+27	750		P1-3, 4-7 8-P2

No	Revision	Appd	Dept	Year	Wk

Description (own language)

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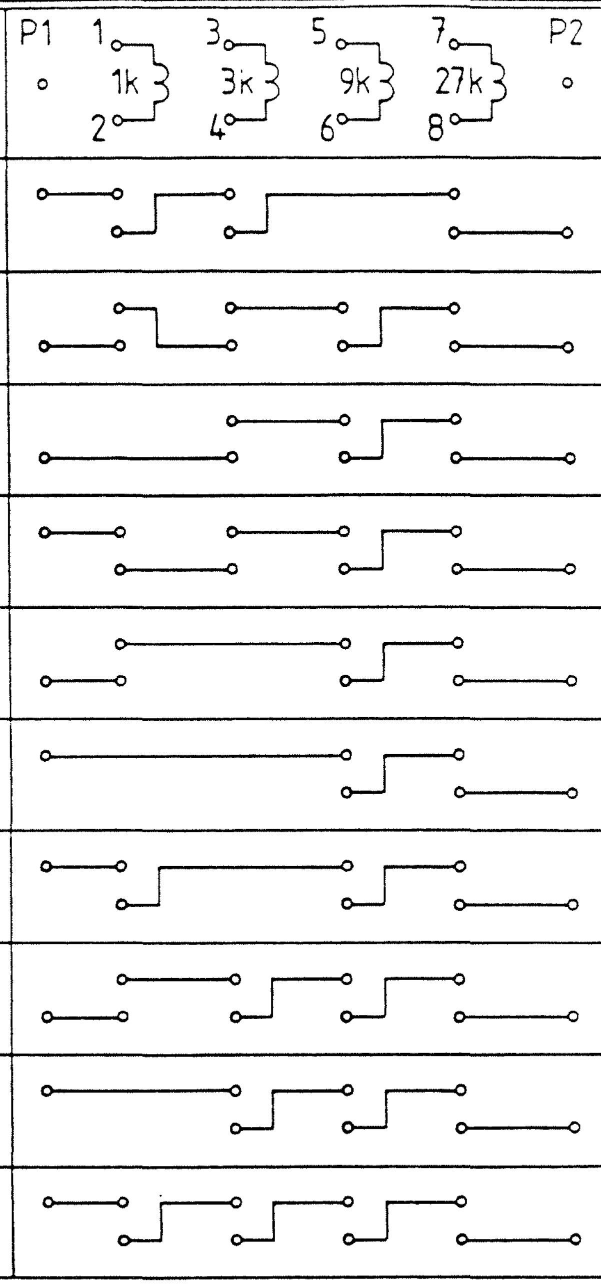
Reference k-value	I_2 (mA)	Connection diagram	Primary connections
			
31=1+3+27	775		P1-1, 2-3, 4-7 8-P2
32=-1-3+9+27	800		P1-2, 1-4, 3-5 6-7, 8-P2
33=-3+9+27	825		P1-4, 3-5, 6-7 8-P2
34=1-3+9+27	850		P1-1, 2-4, 3-5 6-7, 8-P2
35=-1+9+27	875		P1-2, 1-5, 6-7 8-P2
36= 9+27	900		P1-5, 6-7 8-P2
37=1+9+27	925		P1-1, 2-5 6-7, 8-P2
38=-1+3+9+27	950		P1-2, 1-3, 4-5 6-7, 8-P2
39=3+9+27	975		P1-3, 4-5, 6-7 8-P2
40=1+3+9+27	1000		P1-1, 2-3, 4-5 6-7, 8-P2

No	Revision	Appd	Dept	Year Wk