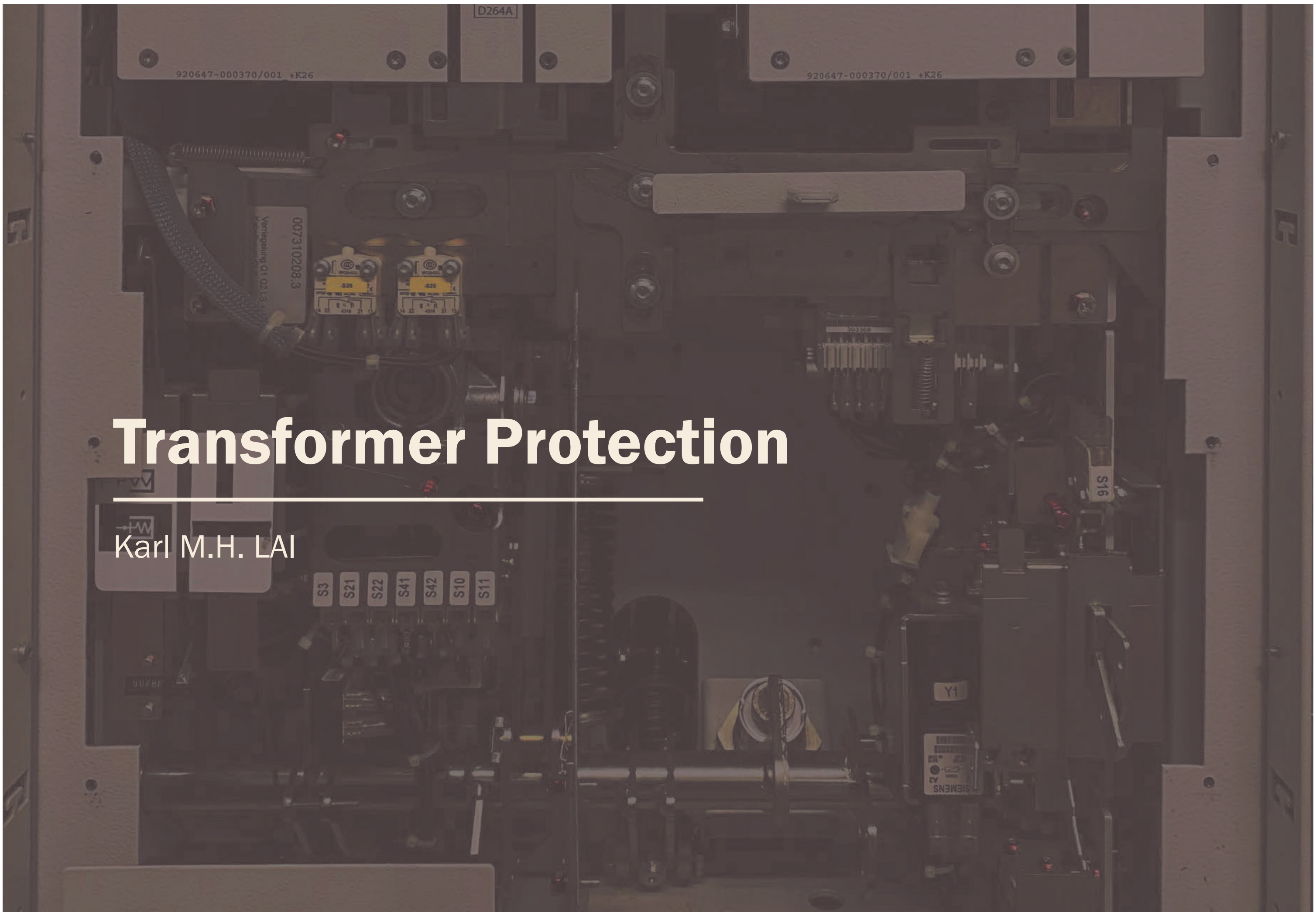


Transformer Protection

Karl M.H. LAI

Transformers in CLP

Standard

- 400/132kV 240MVA EHV Auto Tx
- 132/11kV 50MVA Tx (Ynyn0, current standard, oil & gas type)
- 132/11kV 35MVA Tx (Ynyn0, old)
- 11kV/380V Tx/Dx (Dyn11, 0.5 / 0.75 / 1.0 / 1.5 / 2.0 MVA)

Special

- 500/400kV 900MVA Auto Tx (eg. SZE & NPS)
- 132/110kV 120MVA Tx (eg. MLN, BAL)

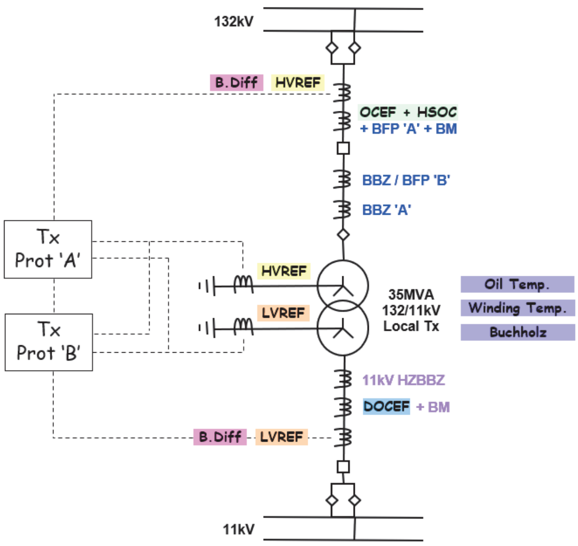
- 18kV/400kV 420MVA Gen.Tx (eg. CPK ‘A’ 16%)
- 18kV/11kV 35MVA Unit Tx (eg. CPK ‘A’ 11.34%)
- 23.5kV/400kV 800MVA Gen. Tx (eg. CPK ‘B’ Ynd7)
- 23.5kV/11kV 60MVA Unit Tx (eg. CPK ‘B’ Dyn5)

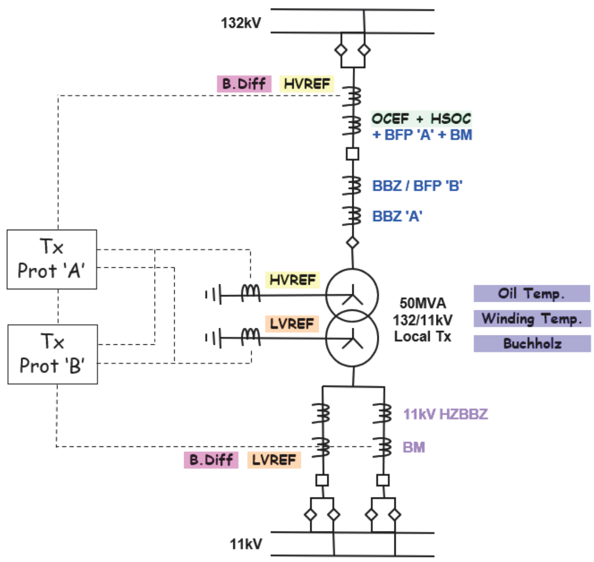
- 132/33kV 80MVA Tx (eg. TTS, KCM, TKM, SWN)
- 132/25kV 38&26.5MVA Tx (eg. TWK, WUK,KWF, 2winding)
- 33/11kV 35MVA Tx (eg. MUK, TPD)
- 132/6.6kV 25MVA Tx (eg. CCM)
- 33/6.6kV 16MVA Tx (eg. ATB)
- 33/3.3kV 8MVA Tx (eg. MWC, TTD, ATA, ATB)

132/11kV Transformer Protection

- Main Protection
  - 2 x Biased Differential protection (BD)
  - 1 x HV Restricted Earth Fault (HVREF) + 1 x LV Restricted Earth Fault (LVREF)
  - High Voltage Winding – High Set Overcurrent (HSOC)
  - Buchholz gas surge protection (Buchholz)
  - Winding and oil temperature protection (WT/OT)

- Backup protection
  - OCEF at 132kV source + DOCEF at LV side (if 35MVA Tx in parallel)

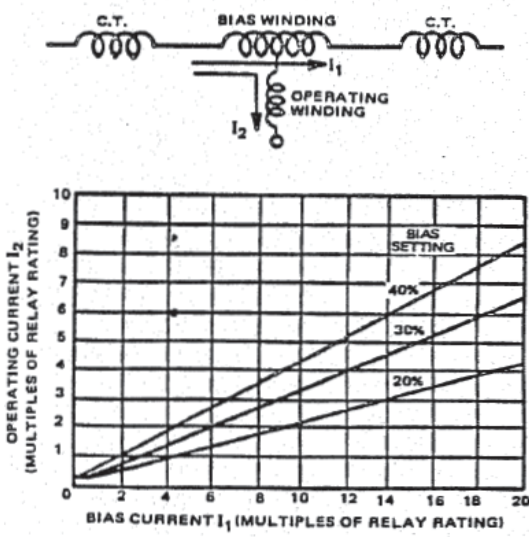




Biased Differential of Tx Protection

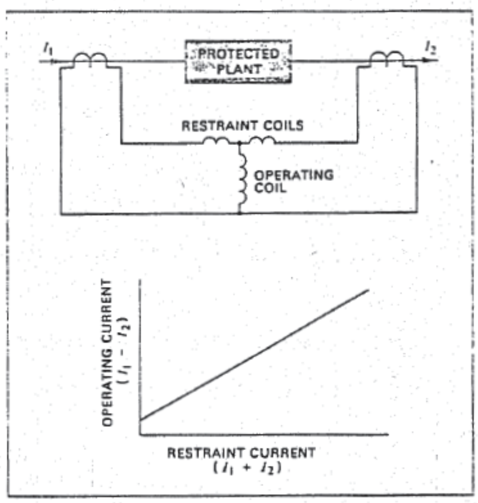
1. Percentage Bias

Percentage Differential:
- Tap charging
- CT mismatch
- CT saturation when through fault



NOTE: The bias current I_1 is the component of current which circulates around the balancing loop between the current transformers.

The operating current I_2 is the out-of balance component which flows in the operating winding.



Percentage biased differential protection.

Operating quantity $= K_1(I_1 - I_2)$

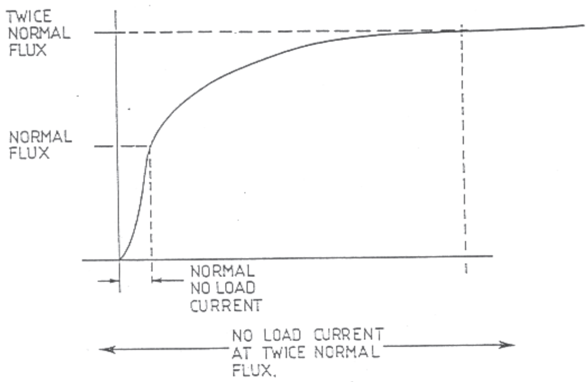
Biasing quantity $= K_2(I_1 + I_2)$

Biased Differential of Tx Protection

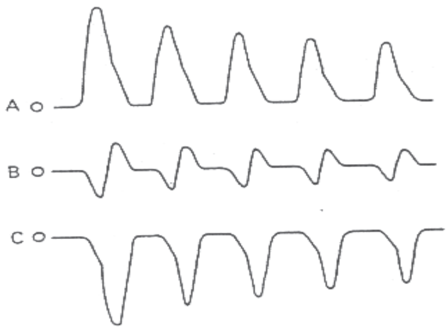
2. Harmonic Bias

- **Magnetisation characteristic**
  - Large transient current flow into the energising winding with a possible peak value of 8-30x full load current
  - The inrush current contains both even and odd harmonics
    - Presence of pre-dominantly / mainly 2^{nd} harmonic component
    - Presence of zero-current gaps in the current waveform of a time duration of at least ¼ cycle (5ms)

Magnetizing characteristic



Transformer magnetizing inrush current waveform



Biased Differential of Tx Protection

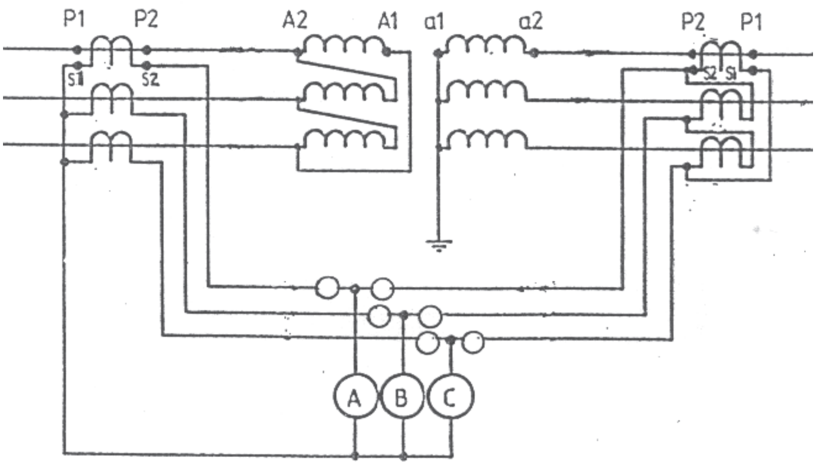
Percentage Bias - Mismatch of currents
- Use of interposing current transformers to produce balanced current flows into the relay
- The interposing current transformers provide:
  - Phase shift compensation
  - Ratio correction
  - Zero phase sequence current compensation

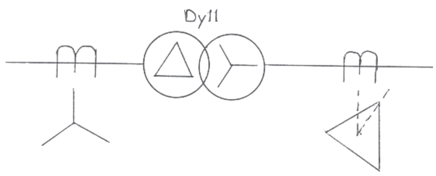
Harmonic Bias - Magnetising inrush current
- Appears on one side of transformer only and is therefore seen as a fault by differential relay
- Normal magnetising current is less than relay setting but transient magnetising inrush could cause relay to operate
- Solution 1:
  - Time delay
    Magnetising current dies away before relay operates (e.g. induction disc relay). However, relay is slow for genuine faults
- Solution 2:
  - Make relays immune to magnetising inrush
    - Using 2^{nd} (& 5^{th}) harmonic restraint.
      This can be slow if CT's saturate during faults
    - Using 'gap' measurement technique in the inrush waveform

Biased Differential of Tx Protection - ICT

Phase shift between HV and LV currents

- Use current transformer (ICT) connection to introduce phase shift of secondary currents to counter the phase shift introduced by the power transformer
- Generally, current transformers on
  - Star-winding side of power transformer
    - Delta connection ICT
  - Delta-winding side of power transformers
    - Star connection ICT
- Current transformer connections must be of the correct polarities





Biased Differential of Tx Protection

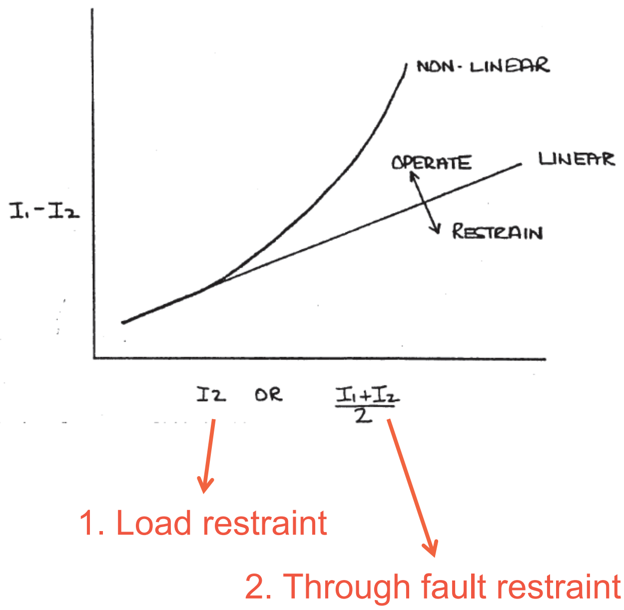
- allow more sensitive setting for internal fault
- greater stability for external through fault
  (larger op current need if larger through fault)

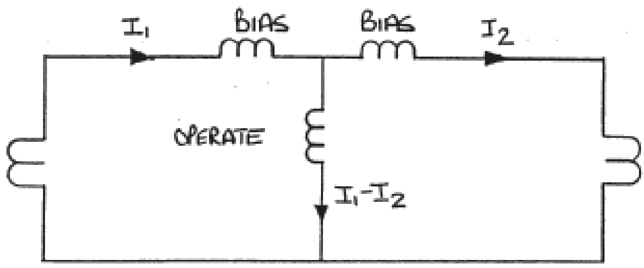
1. Load restraint

$$\frac{I_{operate}}{I_{load}} \times 100 \qquad \text{i.e. } \frac{I_1 - I_2}{I_2} \times 100$$

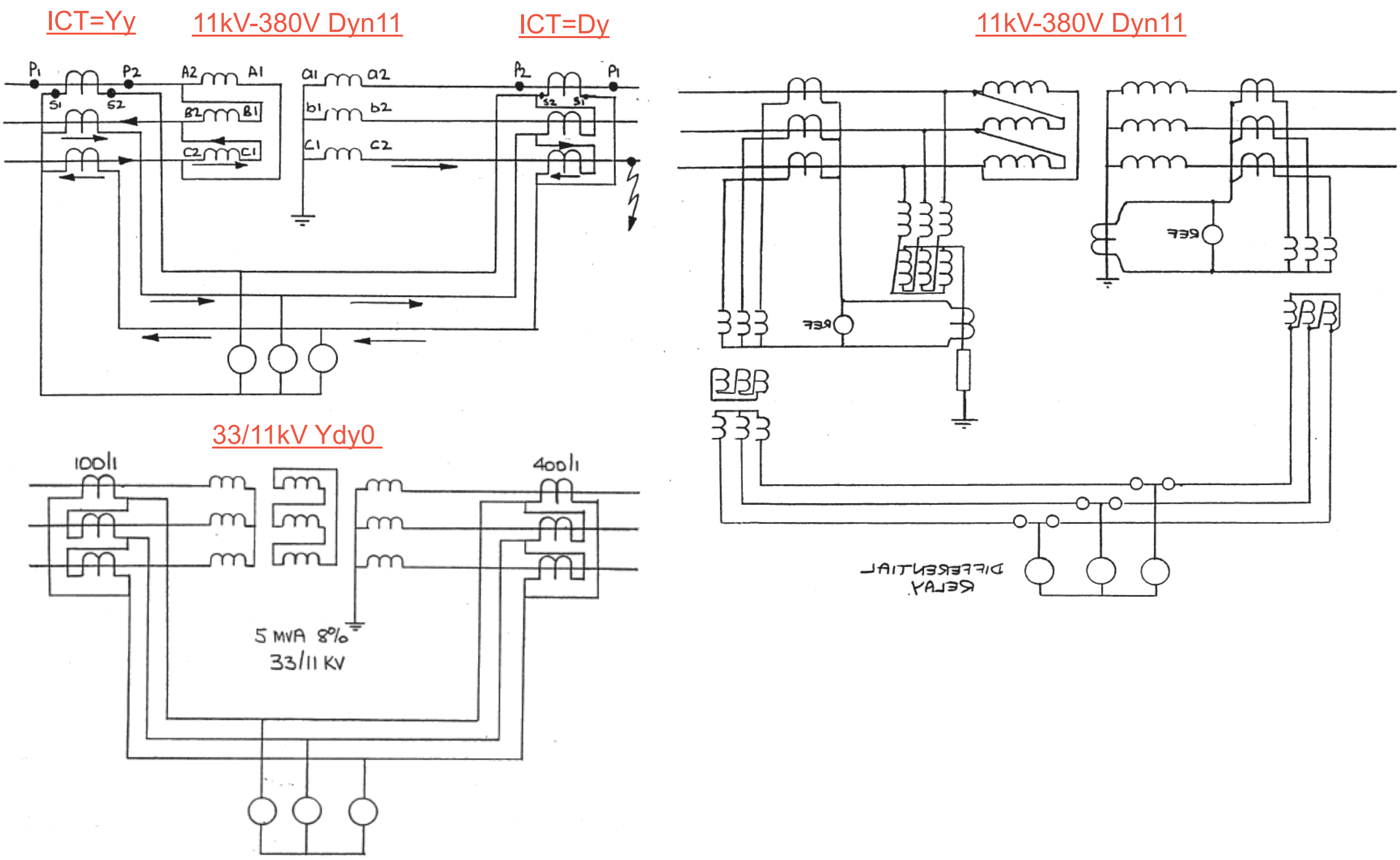
2. Through fault restraint

$$\frac{I_{operate}}{\text{Average restraint}} \qquad \text{i.e. } \frac{I_1 - I_2}{\frac{(I_1 + I_2)}{2}}$$





Duo-Bias in Different Transformer Windings



Biased Differential of Tx Protection - Summary

Requirement

- Mismatch of currents → Percentage bias
  - ✓ CT ratios
  - ✓ Tap changer
- Magnetising inrush current → Harmonic bias
- Phase shift between HV and LV currents → ICT
  - ✓ Transformer vector group
  - ✓ CT polarities
- Flow of zero phase sequence current → ICT
  - ✓ CT connections to block the flow of zero phase sequence current
  - ✓ In zone earthing transformer

Duo-Bias Protection

(1) Harmonic Bias – prevent relay operation due to flow of pulses of magnetizing inrush current into one winding when the transformer is first energized

(2) Percentage Bias - make the relay stable for external (out of zone) through faults as it increases the differential current required for operation as the current measured increases

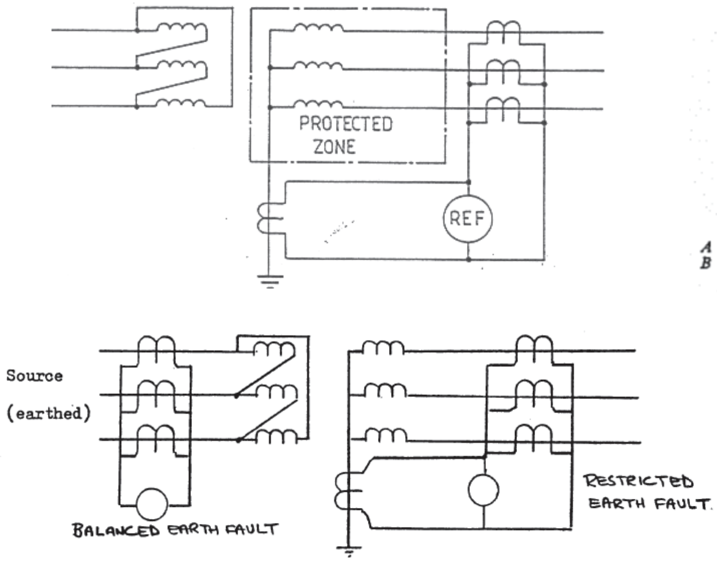
- **To ensure stability for external faults while allowing sensitive settings to pick up internal faults**
- **Line CT/ICT ratios and correction factors set to achieve current balance at nominal tap** = mid tap

→ **An off nominal tap may be seen by the differential protection as an internal fault!**

→ **Mal-operation due to this cause is avoided by selecting the minimum bias to be greater than sum of the maximum tap of the transformer and possible CT errors**

Restricted Earth Fault (REF) of Transformer Protection

- Restricted EF schemes
- Star winding of a transformer
  - Relay only operates for earth faults within "restricted" zone enclosed by the CT's (Unit Protn.) Uses high impedance principle
  - Stability level: Usually maximum through fault level of transformer
  - Sensitivity: Less than 30% of the minimum (internal) earth fault level



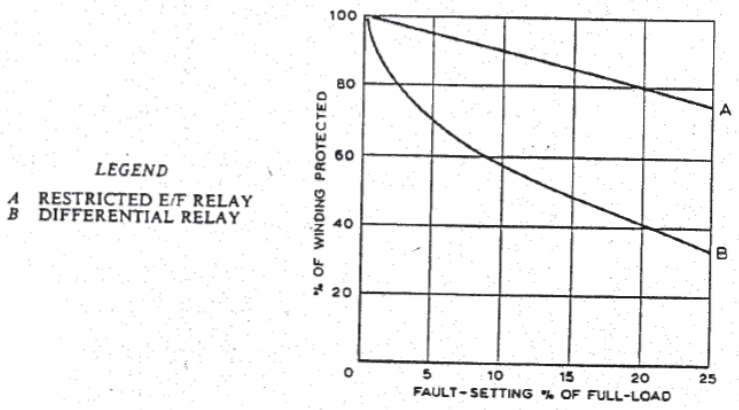
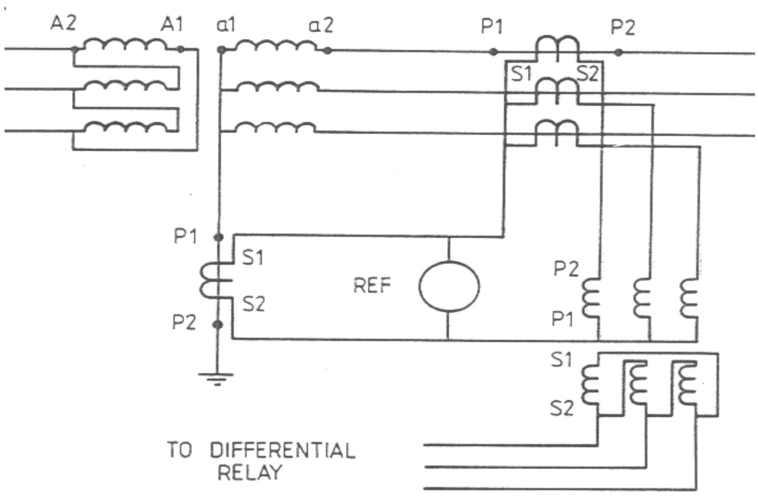


Figure 11.57. Percentage of transformer winding protected against earth faults

Combining BD and REF

Requirement

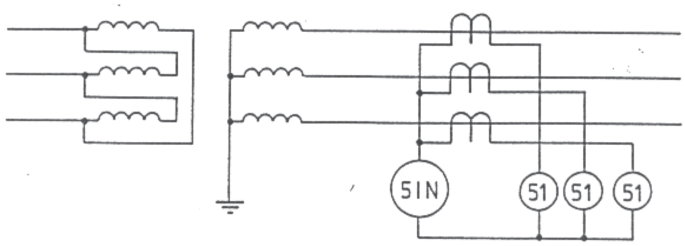
- The line and transformer neutral CT's must be of equal ratio
- The main line and transformer neutral CT requirements are determined by the higher of the differential and restricted earth fault protection functions
- The differential protection relay side of the interposing CT's must have output meeting the requirements of the differential protection relay



Unrestricted Scheme

Unrestricted – OCEF as backup

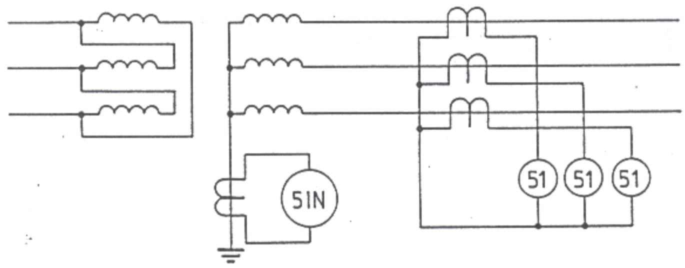
- Provides back-up protection for system
- Time delay required for co-ordination



Standby Earth Fault (SBEF) with EF CT at Neutral

- Can provide better sensitivity,
- CT ratio not related to full load current with improved "effective" setting
- Provides back-up protection for transformer and system

ALTERNATIVELY:



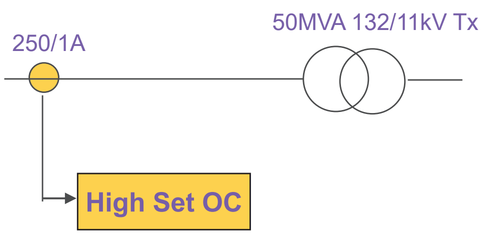
132/11kV Transformer Protection - HSOC

SETTING Criteria:

- a suitable margin above worst 11kV through fault to ensure stability.
- high enough to ensure stability for worst case inrush current during transformer energisation
- sensitive enough to ensure fault detection for the min. fault level condition on 132kV side

Example

- Max. through fault = 185.2MVA
- Max. through fault current = 810A
- 132kV max fault level =6000MVA
- CT current =810/250 =3.24A
- HSOC safety factor is 2.2
- HSOC setting = 3.24 x 2.2 =7.12A



Safety factor x IF ≤ HSOC setting < Fault current at min. system fault level

In general, safety factor = 1.3 ~ 1.5 for MHJ, CAG39, KCGG & DCD

= 2 ~ 2.2 for CAG37
(To prevent mal-operation under relay transient overreaching)

132/11kV Transformer Protection Summary

Fault Detection:

Fault Type	Protection Used
Pri. winding ph-ph fault	Differential, OC, HSOC
Pri. winding ph-E fault	Differential, OC, HSOC, HVREF, EF
Sec. winding ph-ph fault	Differential, OC
Sec. winding ph-E fault	Differential, OC, LVREF, EF
Interturn/Core/Tank fault	Buchholz
Overheating	Oil & winding temp.
Reverse current	DOCEF (35MVA Only)

Tx Fault Trip Relay / Tx Master Trip Relay (For local Tx)

Tx Fault

Initiated by:

a) HSOC
b) HV REF
c) LV REF
d) Transformer Biased Differential Protection
e) Main Tank & Tap changer Buchholz surge Protection

Actions taken:

- Trip LV CB & HV CB
- 11kV Auto-Switching Initialization (ASI)
- For RMU fed Tx
  - If HV CB is present → Trip HV CB
  - If HV CB is absent → High Speed Inter-trip (HSI)

132/11kV Transformer Protection Summary

Tx LV Trip Relay

Tx Overload

Unclear 11kV Fault

Initiated by
a) OCEF
b) Oil Temperature Trip
c) Winding Temperature Trip

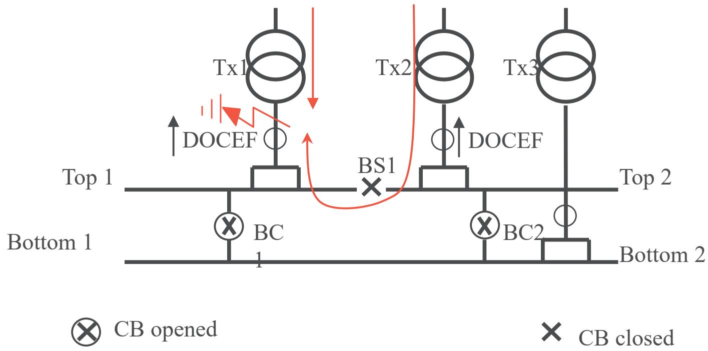
Actions Taken:

- Trip LV CB
- For RMU fed Tx
  - If HV CB is present → Trip HV CB + HV CB BFP
  - If HV CB is absent → Remote Trip Initiation (RTI)
- Auto-Switching is initiated by OTT, WTT (directly to NAS Panel)

Remote Trip Initiation (RTI)

- Initiated by
  - 11kV Busbar Protection
  - Transformer LV Trip
- Operation
  - Current check (same CT for OCEF/HSOC)
  - Timer (0.3s)
  - Auxiliary contact (Tx-RMU LBS)
- Action Taken
  - Trip 132kV source CB and other tee transformer

Other Components in 132/11kV Transformer Protection



NAS Scheme

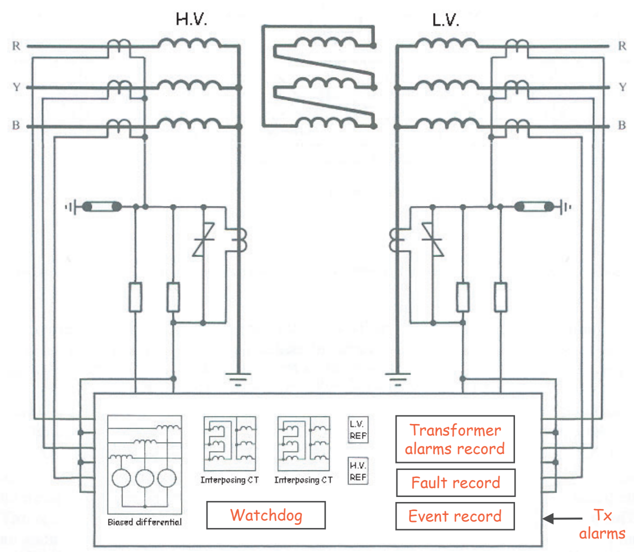
- Tx 1 Tripped - BS 1 closed
- Tx 2 Tripped - BS 1 Closed
- Tx 3 Tripped - BS2 opened → BC1 & BC2 closed
- Initiate when Tx is tripped (except tripped by OCEF)
- Inhibit when BBP operate / One or more Tx is out of service

DOCEF

- 35MVA transformers are operating in parallel
- DOCEF provides backup for unclear fault at upstream
- Operate by back-feed current (directional)

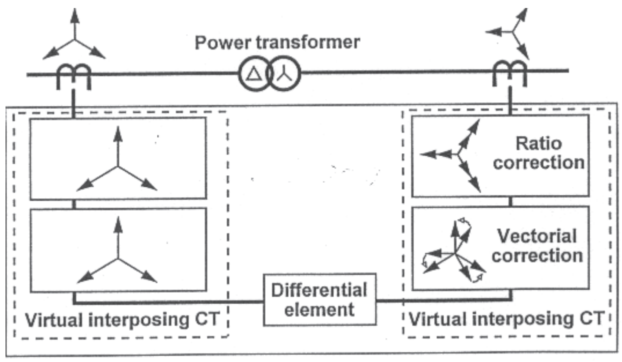
Transformer Protection in Digital Relay

- Differential protection
  - ✓ Vectorial and ratio compensation
- Built-in integral protection functions
  - ✓ Restricted earthfault
  - ✓ Back-up overcurrent
  - ✓ Overfluxing

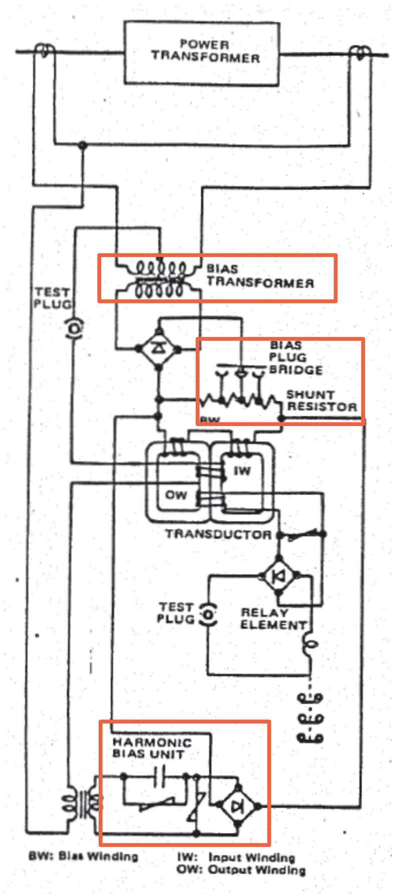


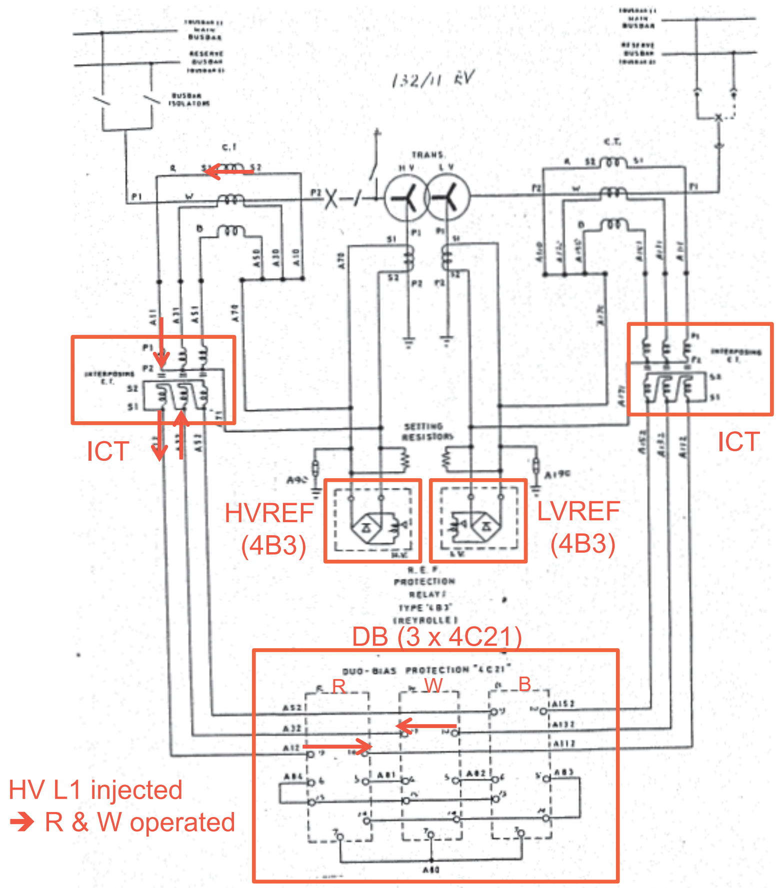
Transformer differential protection

C.T. circuit diagram for combined biased differential and restricted earth-fault protection



Transformer Protection in EM Relay (4C21)



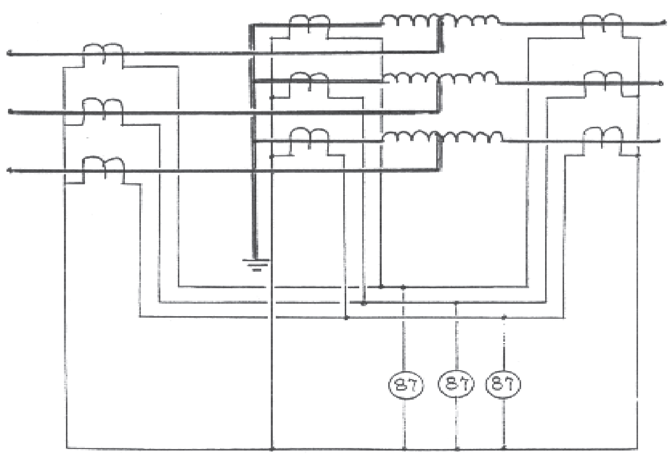


400/132kV Auto-Transformer Protection

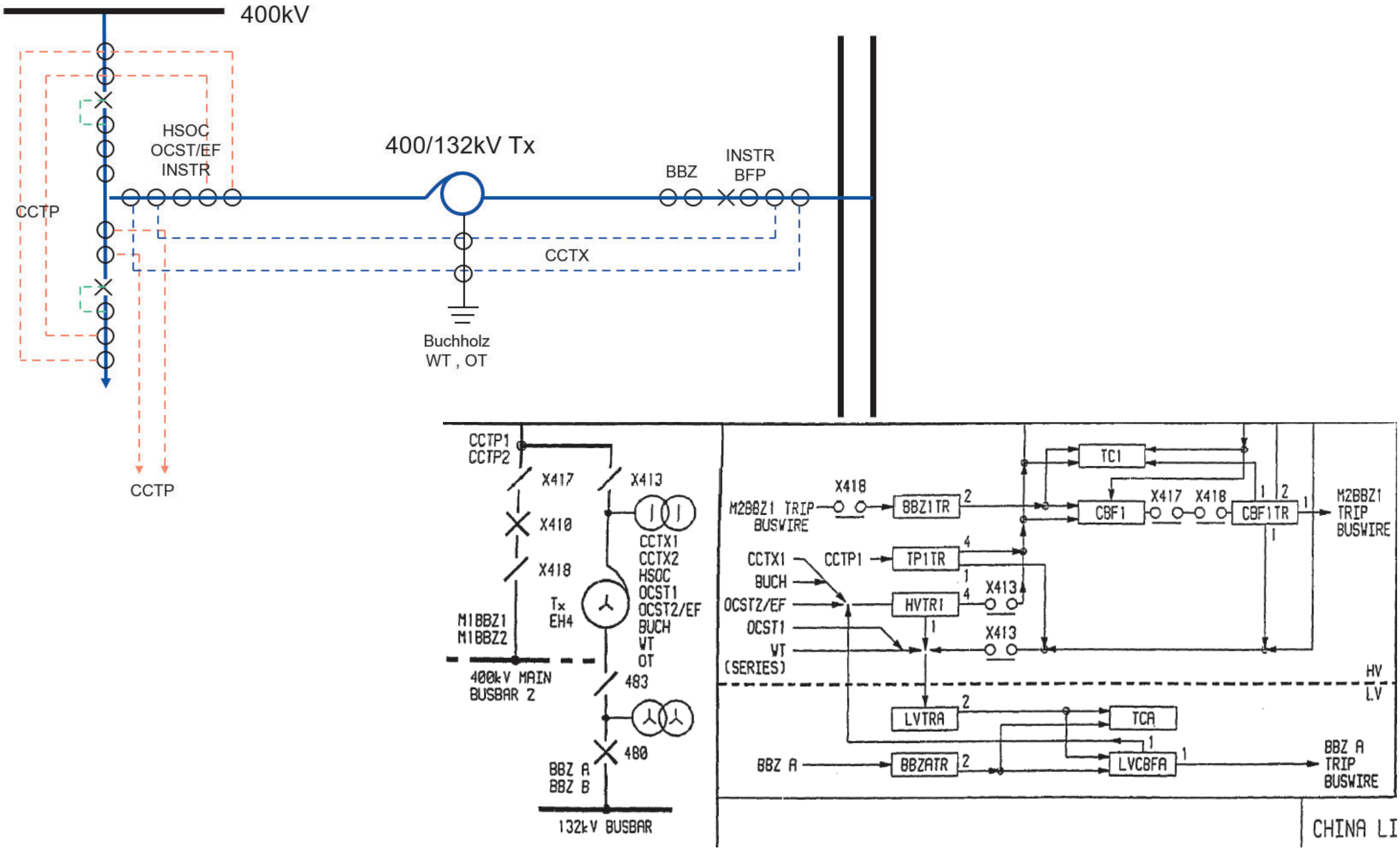
- **Main Protection**
  - 2 x Unbiased Transformer Circulating Current Protection (CCTX)
    - Current Principle
    - Voltage Principle
  - High voltage winding instantaneous high set over-current (HSOC)
  - Buchholz gas surge protection (Buchholz)

- **Backup protection**
  - 2-Stage Over-current & Earth Fault Protection (OCST & EF)
  - Winding temperature protection (WT Series & WT Common)
  - Oil temperature protection (OT)

Circulating Current Protection :
High impedance differential scheme
for auto-transformers
- Equal CT ratios
- CT in neutral ends of windings

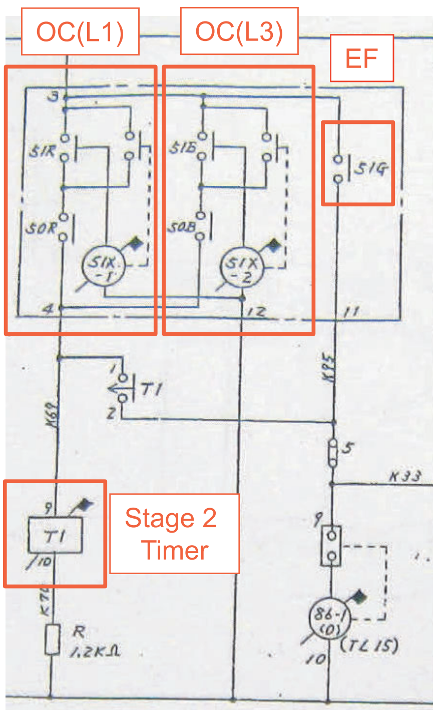


400/132kV Auto-Transformer Protection

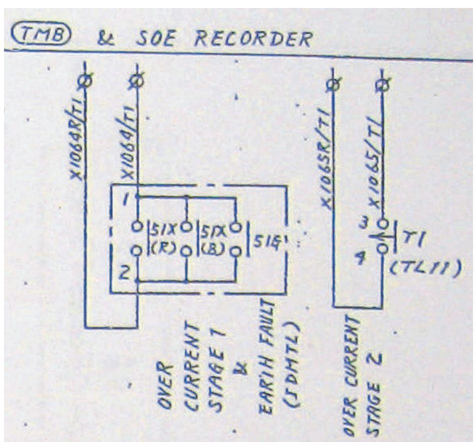


2 Stage OC

- Stage 1 OC: IDMTL, 125%, 0.8 - Detect Overload & Trip LV CB
- Stage 2 OC: DTL, 140%, 0.3s (INST + Timer) - Trip also HV CB
- EF: IDMTL, 40%, 0.6 - Must be fault – trip HV & LV CB



Stage 1 OC ➔ Trip LV
Stage 2 OC ➔ Trip HV & LV
EF ➔ Trip HV & LV



Buchholz Relay

1. Buchholz Gas

The generation of gas in an oil filled transformer is a clear indication of a problem.

The gas may be a result of the following:

- Decomposition/degrading of solid or liquid insulation inside the transformer due to the overheating, or arcing.
- From the outside towards the pipeline.
- From the oil itself due to unsatisfactory de-gassing prior filling.

If sufficient gas is found to displace the upper float, the alarm (BGA) should be activated.

The small valve at the top left is to bleed the gas off and reset the relay.

2. Buchholz Surge

- Rapid oil movement in the pipeline towards the conservator is caused by an internal arc short circuit, or hot spot which must be correctly addressed.
- Oil leaks from the transformer are environmentally unacceptable and a fire hazard will lead to transformer failure.

Why need Buchholz?

- Non-electrical detection
- Inter-turn / near-neutral fault may not detect by electrical method

Buchholz Relay

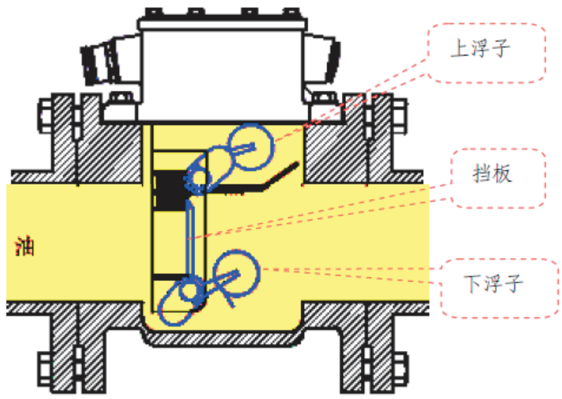


图1-2-1-14 正常情况下，气体继电器状态示意图

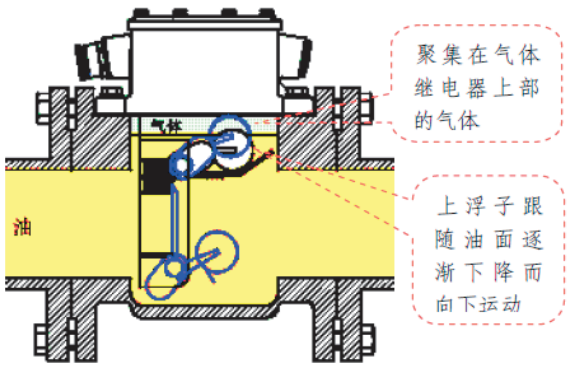


图1-2-1-15 气体继电器内聚集气体示意图

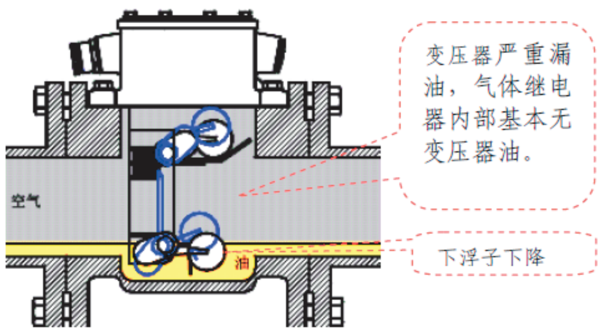


图1-2-1-16 气体继电器内部无油示意图

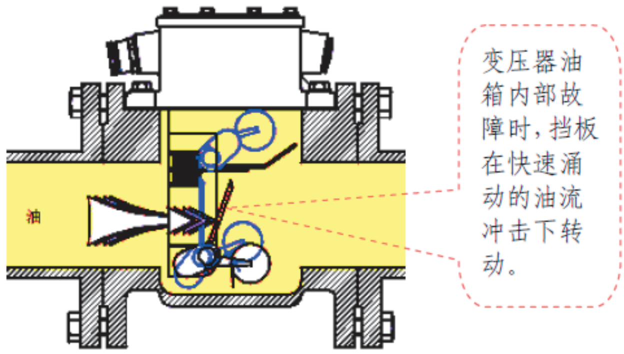


图1-2-1-17 油流冲击气体继电器挡板示意图

Transformer Protection

1. Introduction

Power transformer is one of the most important links in a power system. Its development stems from the early days of electromagnetic induction, when it is was discovered that varying magnetic flux in an iron core linking two coils produces an inducted voltage. From the basic discovery has evolved the power transformer we know today using advanced insulation materials and having complex windings on a laminated core using special magnetic steels cold rolled to ensure grain orientation for low loss and high operating density.

With transformers of large capacity, a single transformer fault can cause large interruption to power supplies. If faulted transformer is not isolated quickly, this can cause serious damage and also power system stability problems. Protective systems applied to transformers thus play a vital role in the economics and operation of a power system.

In common with other electrical plants, choice of suitable protection is governed by economic considerations brought more into prominence by the range of size of transformers which is wider than for most items of electrical plant. Transformers used in distribution and transmission range from a few KVA to several hundred MVA.

For transformers of the lower ratings, only the simplest protection such as fuses can be justified and for large rating transformers; comprehensive protection scheme should be applied.

Transformer faults are generally classified into four categories :

(i) Winding and Terminal faults

(ii) Core faults

(iii) Abnormal operating conditions such as overvoltage, overfluxing and overload

(iv) Sustained or uncleared external faults

2. Transformer Protection

a. Transformer differential protection.

b. Restricted earth fault protection for both HV and LV windings.

c. Buchholz gas protection.

d. IDMTL O/C and E/F Protection.

e. Directional O/C and E/F on LV side.

f. Winding temperature.

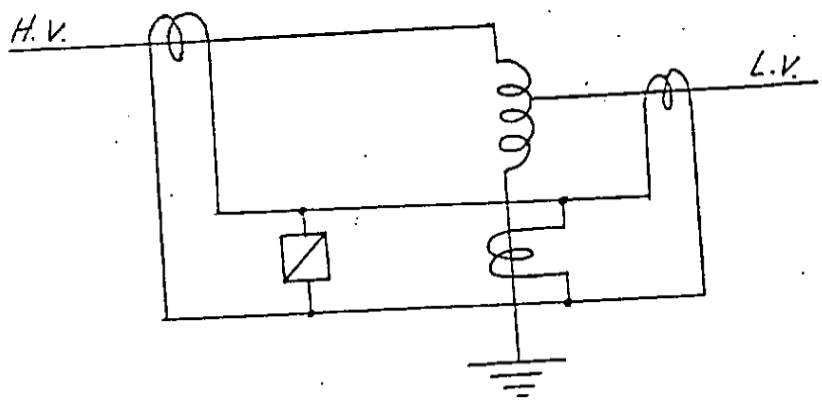
g. Oil temperature.

It is to be noted that intertripping should be provided between HV and LV circuit breakers.

2.1 Transformer Differential Protection

2.1.1 Circulating Current Differential Protection

Auto-transformers can be adequately protected by high impedance differential relays. The setting voltage is calculated assuming the worst through fault conditions and therefore bias is not necessary. Current transformers are required on the HV, LV and neutral connections and all must be the same ratio. The CT ratio should be based on the LV full load current for the nearest standard ratio. For simplicity, the protection scheme can be depicted in the following single phase arrangement.



The above scheme is being employed for the 400/132kV 240MVH transformers in CLP.

2.1.2 Biased Differential Protection

For power transformers equipped with on load tap changers the overall differential protection must incorporate a bias feature, if a low fault setting and high operating speed are to be obtained. For small transformers the percentage differential (biased) induction - disc relay can be used, such as for the KCRC 132/25kV single phase transformers.

A high speed biased differential relay incorporating a harmonic-restraint feature will prevent relay operation under magnetising inrush current conditions of which the maximum peak values equal to 6 - 8 times the rated current of the transformer can occur. Reyrolle type "Duobias" biased differential relays which have the essential percentage bias and the harmonic bias characteristics, are widely used for the power transformers in CLP's system.

2.2 Earth Fault Protection

It is usual to provide instantaneous earth fault protection to transformers since it is relatively easy to restrict the operation of the protection to transformer faults only i.e. the protection remains stable for external faults. This protection is called balanced or restricted earth fault and the high impedance principle is utilised.

Balanced earth fault for a delta (or unearthed star) winding can be provided by connecting three line CT's in parallel (residual connection). The relay will only operate for internal earth faults since the transformer itself cannot supply zero sequence current to the system. The transformer must obviously be connected to an earth source.

For an earthed star winding, the residual connection of the line CT's are further connected in parallel with a CT located in the transformer neutral. Under external earth fault conditions the current in the line CT's is balanced by the current in the neutral CT. Under internal fault conditions, current only flows in the neutral CT and since there is no balancing current from the line CT's, the relay will operate.

2.3 Combined Differential and Restricted Earth Fault Protection

Although it is preferable to use separate CT's for restricted earth fault protection, it can be combined with differential protection using the same current transformers, together with interposing current transformers. A CT is required in the neutral connection and should be the same ratio as the line current transformers.

2.4 Buchholz Protection

All types of fault within a transformer will produce heat which will cause decomposition of the transformer oil. The resulting gases that are formed rise to the top of the tank and then to the conservator. A buchholz relay connected between the tank and conservator collects the gas and gives an alarm when a certain volume of gas has been collected. A severe fault causes so much gas to be produced that pressure is built up in the tank and causes a surge of oil. The buchholz relay will also detect these oil surges and under these conditions is arranged to trip the transformer circuit breakers.

The main advantage of the buchholz relay is that it will detect incipient faults which would not otherwise be detected by conventional protection arrangements. The relay is often the only way of detecting interturn faults which cause a large current to flow in the shorted turns but due to the large ratio between the shorted turns and the rest of the winding, the change in terminal currents is very small.

2.5 Overcurrent Protection

Overcurrent relays are often the only form of protection applied to small transformers. They are used for backup protection for larger transformers, and both instantaneous and time delayed overcurrent can be applied.

Inverse time relays on the HV side of a transformer must grade with those on the LV side which in turn must grade with the LV outgoing circuits. Due to this, the HV overcurrent relays could have operating times which might cause operation of distance relays at other substations unless the second zone time settings of the distance relays are made unacceptably high. To overcome this problem, high set instantaneous overcurrent relays with low transient overreach are sometimes used. The settings of these relays should be 130 -160% of the through fault level of the transformer to ensure that the relays are stable for through faults. Care must also be taken to ensure that the relays do not operate under magnetising inrush conditions.

It is usual to provide 2 pole overcurrent and 1 pole earth fault relays, but it may be necessary to use 3 pole overcurrent where the current distribution can be 1:2:1 as is the case for a phase fault on the delta side of a star/delta transformer.

2.6 Protection for Overloads

Since overloads cause heating of the transformer above the normal recommended temperatures, protection against overloads is normally based on winding temperature - which is usually measured by a thermal image technique. The thermal sensing element is placed in the transformer top oil. A small heater, fed from a C.T. is placed near to the sensing element and produces a local temperature rise, similar to that of the main winding, above the general oil temperature.

2.7 Directional OCEF

Directional OCEF protection is also fitted to the LV side of transformers or transformer feeders to detect reverse low of current through the transformer, such as will occur for H.V. feeder faults. It provides a backup function to the intertripping facilities.

132kV SF6 Metalclad Ring Main Unit Protection

1. Introduction

132kV Ring Main Unit (RMU) has given satisfactory service in CLP
system. By using RMUs, one 132kV switchgear can feed more than one
transformers. 132kV RMUs will still be used until one day when the
cost and space of modern 132kV GIS become competitive with RMUs.
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2. RMU Protection

The well known high impedance circulating current protection scheme
is chosen for the RMU protection in CLP system.

The main features of the scheme are as follows :

a. Simplicity
b. Reliability
c. High transient stability for external faults
d. High speed operation for internal faults
e. Ease of maintenance
f. Stability limit and fault settings are easily calculated.

Principle of Operation

High impedance circulating current RMU protection is based on the
differential current-balance principle and its successful
performance is due to the use of high impedance relays. Each relay
has a low current setting and their voltage setting is adjusted to a
value equal to, or greater than the maximum voltage which can occur
under the worst through fault condition.

The current-transformers of the incoming and outgoing circuits are
connected to form a current balance group and a relay is connected
at some convenient point in this group to form a spill circuit. An
internal fault upsets the current balance and so causes the relay to
operate.
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3. Remote Trip Initiation Scheme

This scheme is commonly employed in 132kV multiple-tee transformer protection. To minimize interruptions to the primary circuits, it is desirable that operation of the tripping relay, including winding temperature, oil temperature, OCEF and 11kV Leakage to frame protection shall trip the transformer LV breaker only. In the event of failure of this breaker, intertripping will be initiated by the Remote Trip Initiation (RTI) scheme.

The equipment shall normally, comprise a current check relay and a time delay relay.

The attached single line diagrams show the typical protection schemes for transformers and RMU connected transformers.

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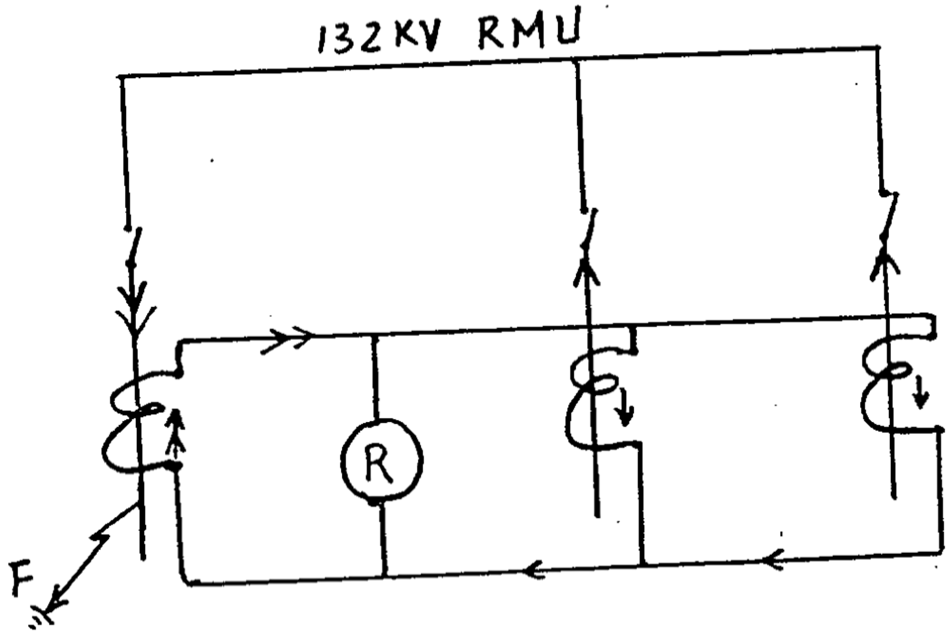
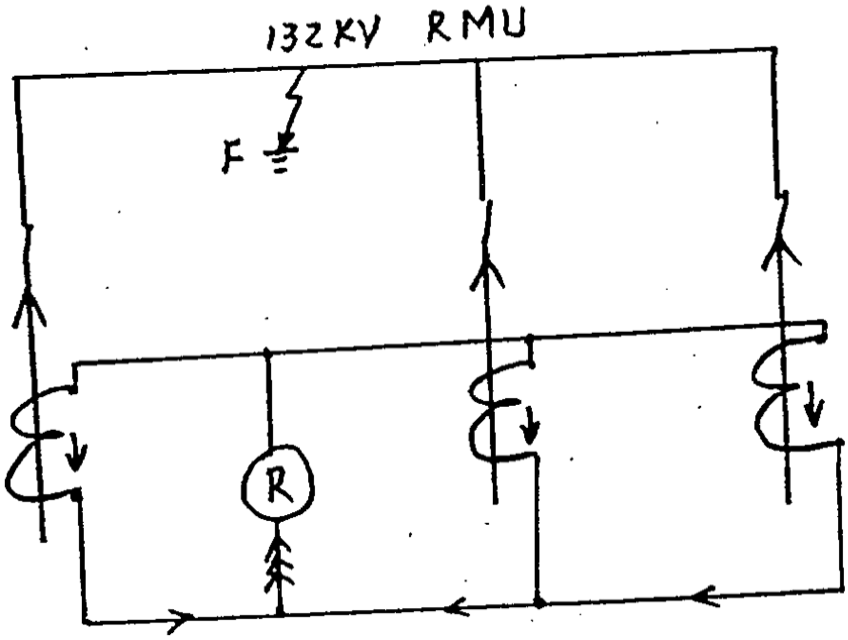
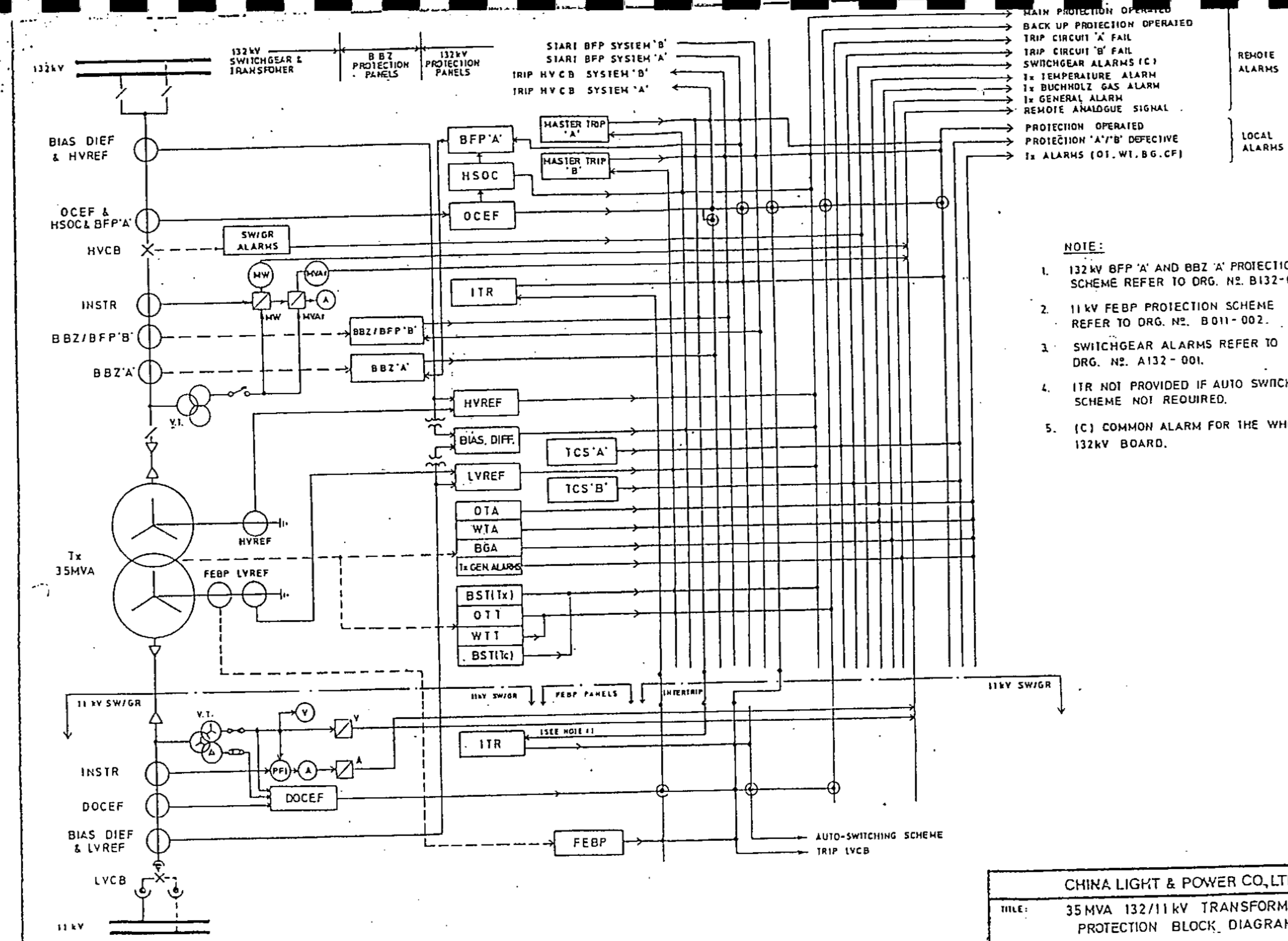


EXTERNAL FAULT



INTERNAL FAULT

BASIC CIRCULATING CURRENT SCHEME

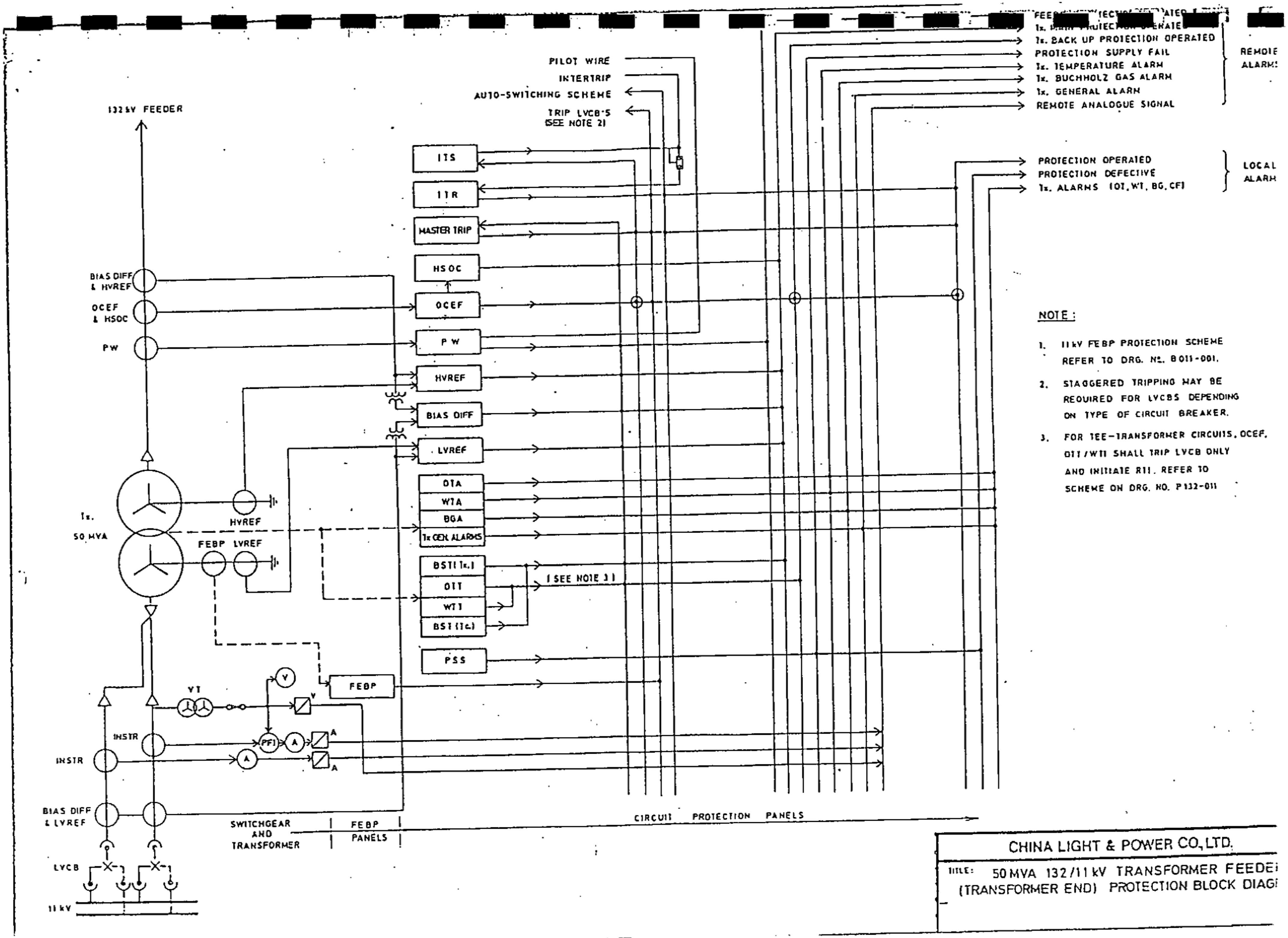


NOTE:

1. 132kV BFP 'A' AND BBZ 'A' PROTECTION SCHEME REFER TO DRG. No. B132-001.
2. 11kV FEBP PROTECTION SCHEME REFER TO DRG. No. B011-002.
3. SWITCHGEAR ALARMS REFER TO DRG. No. A132-001.
4. ITR NOT PROVIDED IF AUTO SWITCHING SCHEME NOT REQUIRED.
5. (C) COMMON ALARM FOR THE WHOLE 132kV BOARD.

CHINA LIGHT & POWER CO., LTD.

TITLE: 35MVA 132/11kV TRANSFORMER PROTECTION BLOCK DIAGRAM

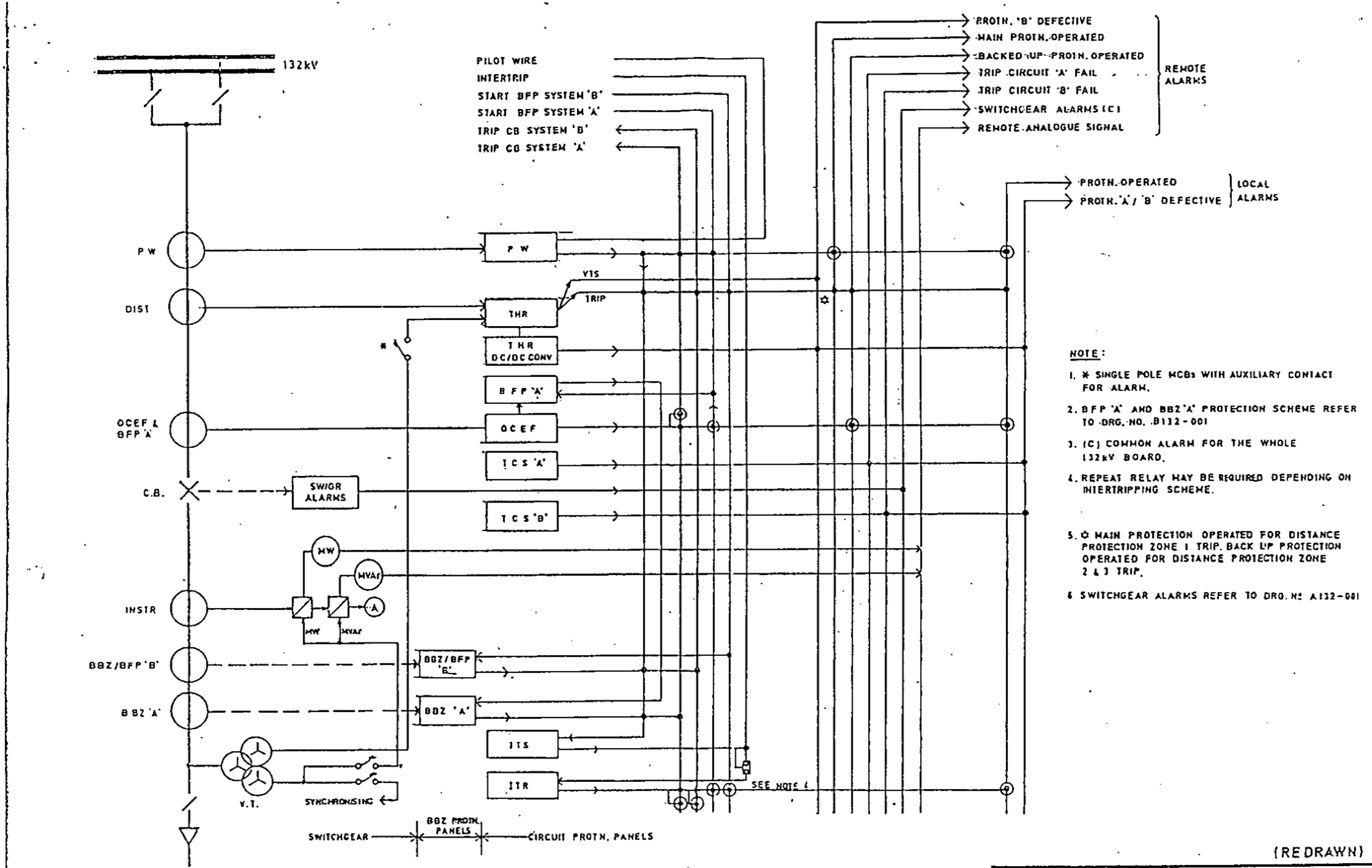


NOTE :

1. 11 kV FEBP PROTECTION SCHEME REFER TO DRG. No. B011-001.
2. STAGGERED TRIPPING MAY BE REQUIRED FOR LVCBS DEPENDING ON TYPE OF CIRCUIT BREAKER.
3. FOR TEE-TRANSFORMER CIRCUITS, OCEF, OTT/WTT SHALL TRIP LVCB ONLY AND INITIATE RTI. REFER TO SCHEME ON DRG. NO. P132-011

CHINA LIGHT & POWER CO., LTD.

TITLE: 50 MVA 132/11 kV TRANSFORMER FEEDE[R] (TRANSFORMER END) PROTECTION BLOCK DIAG[RAM]



NOTE:

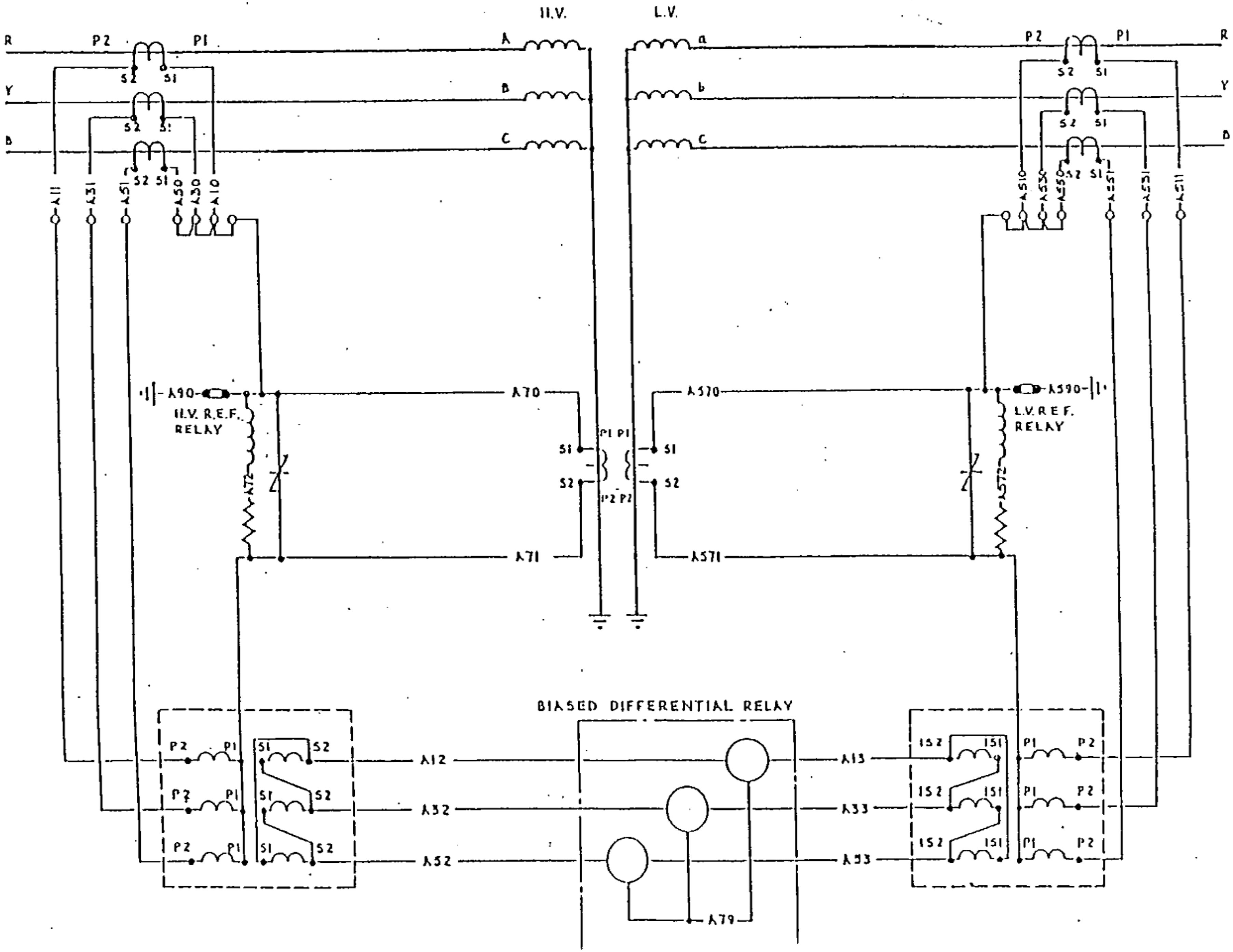
1. ✱ SINGLE POLE MCBs WITH AUXILIARY CONTACT FOR ALARM.
2. BFP 'A' AND BBZ 'A' PROTECTION SCHEME REFER TO DRG. NO. B132-001
3. (C) COMMON ALARM FOR THE WHOLE 132kV BOARD.
4. REPEAT RELAY MAY BE REQUIRED DEPENDING ON INTERTRIPPING SCHEME.
5. ✡ MAIN PROTECTION OPERATED FOR DISTANCE PROTECTION ZONE 1 TRIP. BACK UP PROTECTION OPERATED FOR DISTANCE PROTECTION ZONE 2 & 3 TRIP.
6. SWITCHGEAR ALARMS REFER TO DRG. No. A132-001

(REDRAWN)

CHINA LIGHT & POWER CO., LTD.

TITLE: 132kV TRANSFORMER-FEEDER PROTECTION BLOCK DIAGRAM

Connection Digram: Transformer Biased Differential And R.E.F. Protection



WINDING POLARITY

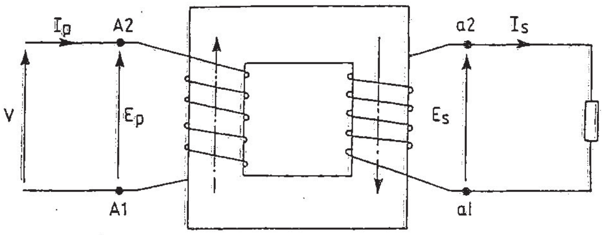


Figure 1

The relative polarity of windings sharing a common magnetic circuit is defined in international standards. If the core flux induces an instantaneous emf from a low numbered terminal to a high numbered terminal (for example) in one winding, then the direction of induced emf in all other windings linked by that flux will also be from a low numbered terminal to a high numbered terminal. Note that for transformer action the current flow in the windings is in opposite directions.

TRANSFORMER CONNECTIONS

- "CLOCK FACE" NUMBERS REFER TO POSITION OF LOW VOLTAGE PHASE-NEUTRAL VECTOR WITH RESPECT TO HIGH VOLTAGE PHASE-NEUTRAL VECTOR
- LINE CONNECTIONS MADE TO HIGHEST NUMBERED WINDING TERMINAL AVAILABLE
- LINE PHASE DESIGNATION IS SAME AS WINDING

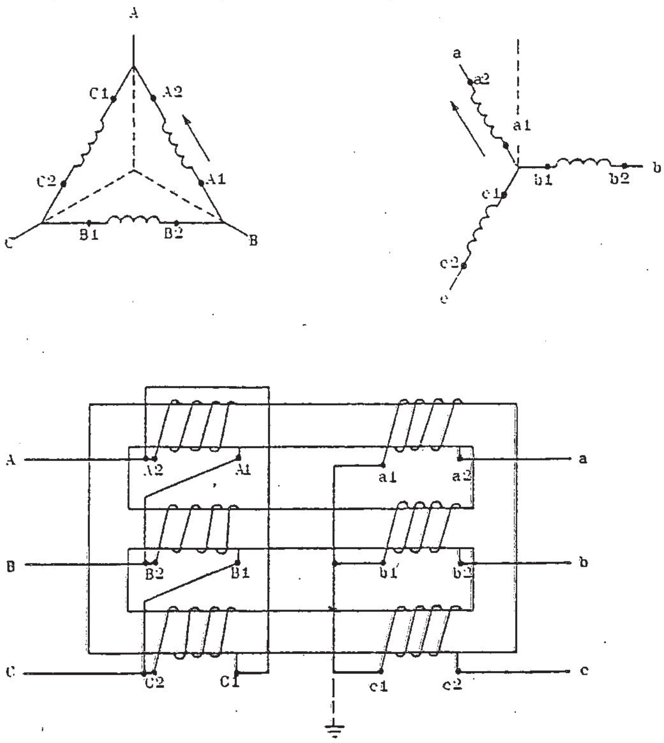


Figure 2

The use of clockface numbers to represent phase shifts always utilises the highest voltage winding as the reference and the phase shift refers to the position of the phase-to-neutral vectors. A knowledge of the relative polarities of the windings then enables straightforward determination of the appropriate three phase connections.

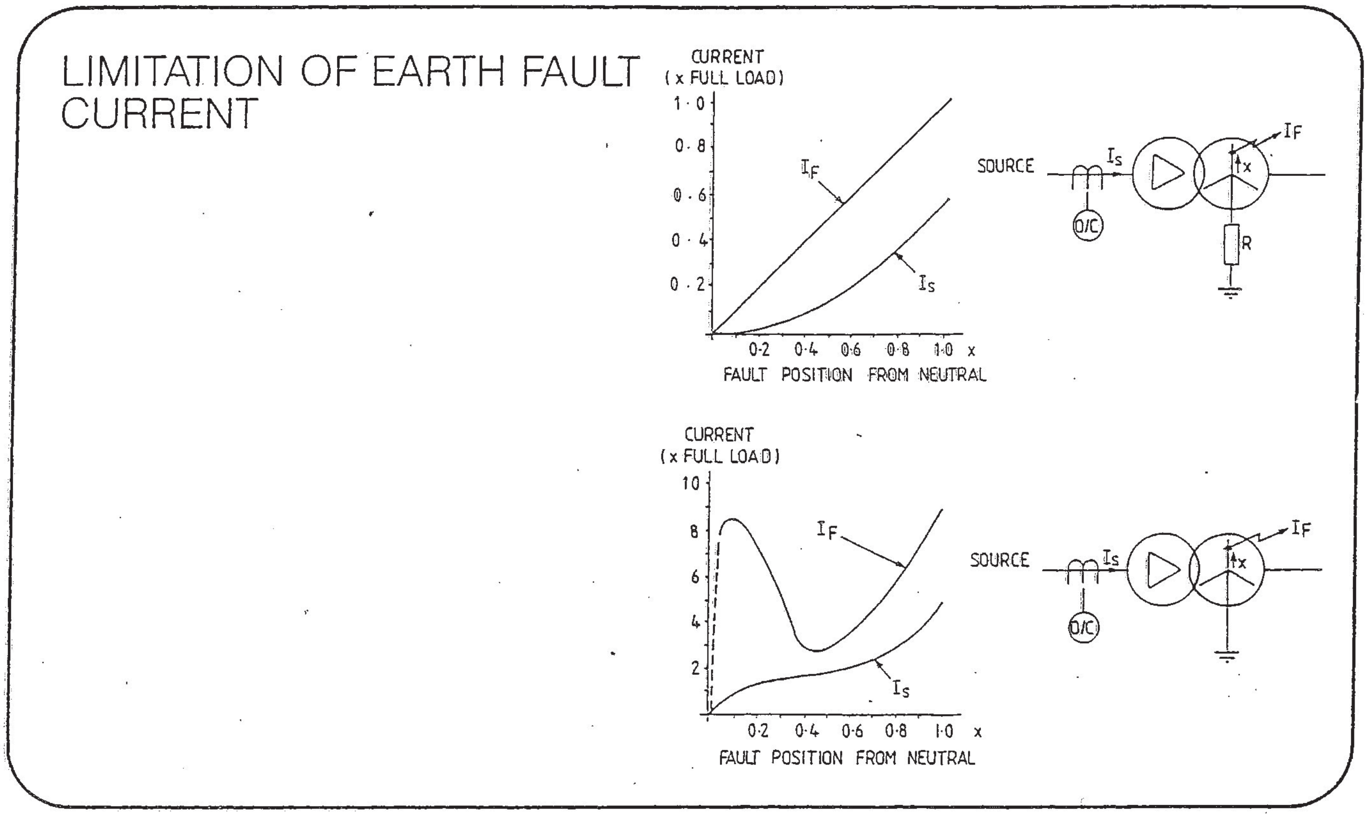


Figure 3

For a resistance earthed star winding the fault current will vary linearly as a function of fault position since the resistor is the dominant impedance and rated to limit the maximum fault current to a full load value. However, when viewed from the delta primary side of the transformer the maximum fault current is limited to approximately 57% of rated current.
Even with a solidly earthed star winding the fault current as viewed from the primary side is limited to 2 — 3 times full load current for fault positions over a substantial part of the star winding.
An overcurrent relay located on the primary side of the transformer clearly will not provide adequate protection for earth faults on the secondary side.

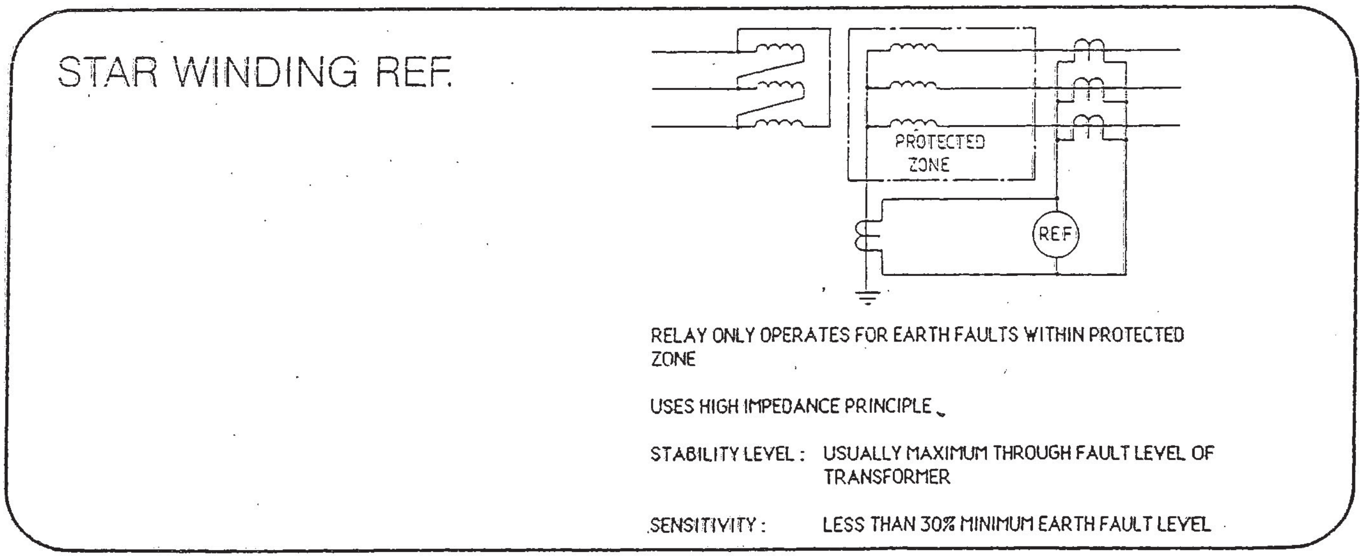
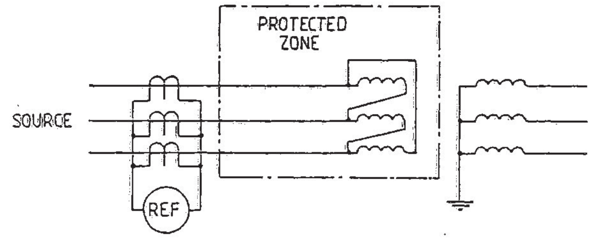


Figure 4

For the reasons given in Figure 3 the use of restricted earth fault protection is strongly recommended. This protection, providing high speed of operation and good sensitivity, utilises the high impedance principle. Current transformers of Class X designation are recommended in order to achieve the desired performance, it being necessary to perform appropriate calculations to determine the actual CT design required.

DELTA WINDING REF



DELTA WINDING CANNOT SUPPLY ZERO SEQUENCE CURRENT TO SYSTEM

STABILITY LEVEL ?

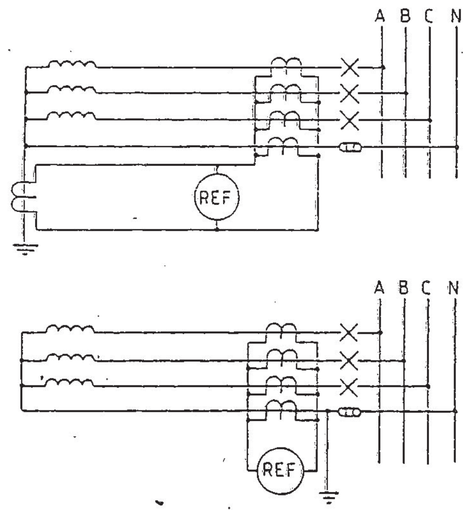
RECOMMENDED SETTING : LESS THAN 30% MINIMUM EARTH FAULT LEVEL

Figure 5

Earth faults occurring on a delta winding may also result in a magnitude of fault current, measured in the line connections, of less than full load and therefore overcurrent relays will not provide adequate protection. A relay connected to monitor residual current will inherently provide restricted earth fault protection since the delta winding cannot supply zero-sequence current to the system. The high impedance principle can again be applied to provide fast, sensitive earth fault protection.

Theoretically, the restricted earth fault protection should not operate for a balanced three phase fault at the transformer terminals and the protection could indeed be stabilised to ensure that this was the case. However, this approach often yields a requirement for very large current transformers since the fault level on the primary side of the transformer is generally high. A more practical approach is to stabilize the protection for faults on the secondary side of the transformer where the fault level will be substantially lower and therefore result in a lower output voltage requirement for the current transformers. The possible instability of the earth fault protection for transformer delta winding faults not involving earth, is acceptable, since the maloperation will not cause incorrect tripping.

RESTRICTED E/F PROTECTION LOW VOLTAGE WINDINGS



LV RESTRICTED EARTH FAULT PROTECTION TRIPS BOTH HV AND LV BREAKERS

RECOMMENDED SETTING : 10% RATED

Figure 6

For low voltage four wire transformer windings it may be necessary to utilise five current transformers to provide restricted earth fault protection — the deciding criterion being the actual location of the neutral to earth connection.
Since even a small amount of fault resistance would severely limit the magnitude of earth fault current on a low voltage system, an effective setting of 10 — 20% of transformer rated current is recommended.

REDUCTION OF VOLTAGE SETTING

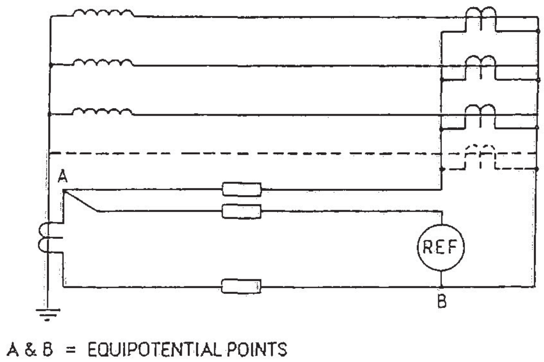
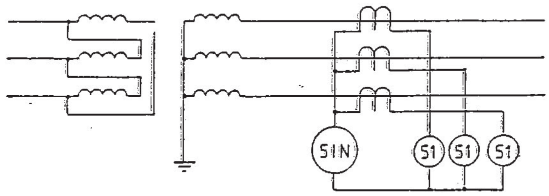


Figure 7

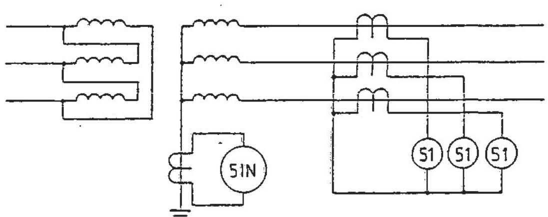
The calculation of setting (stability) voltage for high impedance protection involves a knowledge of the system fault levels and the current transformer/secondary wiring resistance. A reduction in voltage setting, and hence a reduction in CT kneepoint voltage requirement, may be achieved by attempting to connect the relay across approximately equipotential points within the secondary connections.
Since the CT in the earth connection is often remote from the relay location, a useful reduction in setting voltage can be obtained by utilising a third core in the connecting cable to connect the relay across the differential circuit.

UNRESTRICTED EARTHFAULT PROTECTION



- PROVIDES BACK-UP PROTECTION FOR SYSTEM
- TIME DELAY REQUIRED FOR CO-ORDINATION

ALTERNATIVELY:



- CAN PROVIDE BETTER SENSITIVITY
  (CT RATIO NOT RELATED TO FULL LOAD CURRENT)
  (IMPROVED "EFFECTIVE" SETTING)
- PROVIDES BACK-UP PROTECTION FOR TRANSFORMER AND SYSTEM

Figure 8

System back-up earth fault protection can be provided with a time delayed relay located in the residual connection of the line CT's. Alternatively, improved sensitivity and additional transformer back-up protection may be provided by a similar relay connected to a current transformer located in the earth connection.
In either case, co-ordination of the relay with downstream fuses is likely to prove extremely difficult. Nevertheless the provision of a back-up earth fault relay is recommended, particularly on low voltage systems, due to the requirement for sensitivity under earth fault conditions. The relay is given a sensitive setting, but a relatively long time delay (say up to five seconds) to allow every opportunity for other downstream protective devices to operate (it being accepted that, over a limited current range, co-ordination may not be possible).

PARALLEL TRANSFORMERS CT IN EARTH CONNECTION

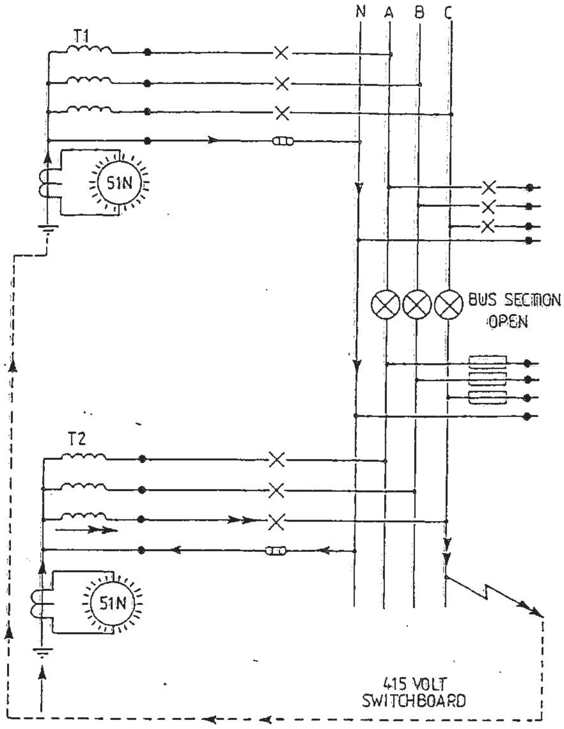


Figure 9

Special attention is required for LV installations with multiple infeeds. Mal-tripping may occur if the CT's are located on the transformer earth connections and the system utilises a solid neutral busbar. The use of a four pole bus section circuit breaker will prevent the maloperation.

PARALLEL TRANSFORMERS CT IN EARTH AND NEUTRAL

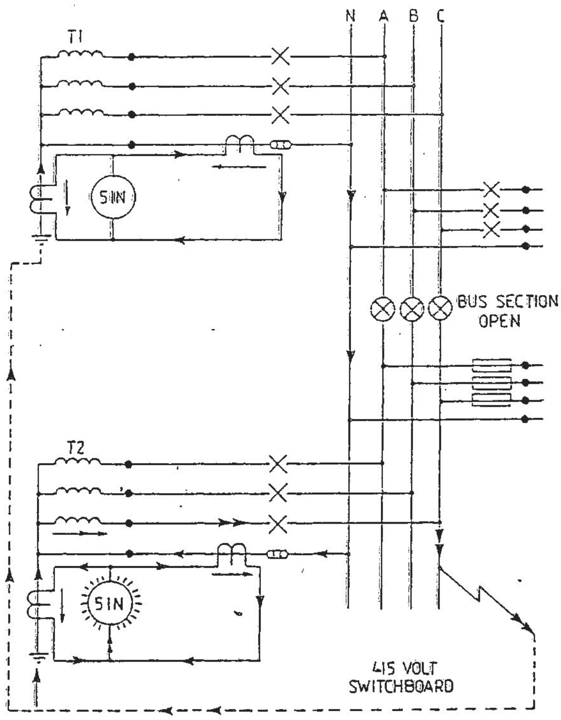


Figure 10

The problems associated with a solid neutral may also be overcome by utilising a combination of two current transformers — one on the earth connection and one on the neutral connection — to provide unrestricted earth fault protection. Clearly it is necessary that both current transformers have the same ratio and, ideally, a similar magnetisation characteristic. Also, the earth fault relay setting must be greater than the anticipated maximum neutral current caused by single phase loads.

PARALLEL TRANSFORMERS RESIDUAL CONNECTIONS

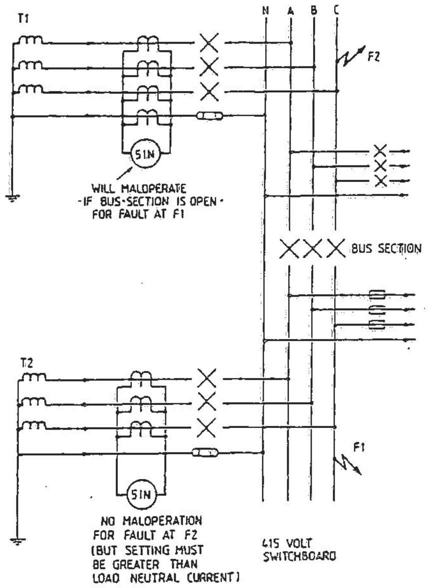


Figure 11

The 'four CT' residual connection can also give problems on solid neutral systems. The 'three CT' connection will prevent any maloperation but it is then necessary to provide the earth fault relay with a setting greater than the normal out-of-balance current caused by single phase loading.

PARALLEL TRANSFORMERS DIRECTIONAL RELAYS

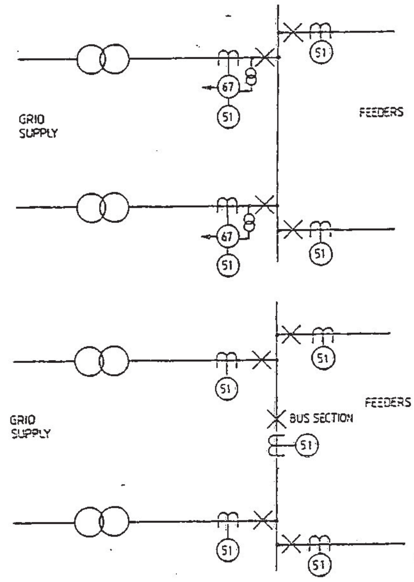


Figure 12

For parallel transformer applications which do not include a bus-section circuit breaker (or do include a non-automatic bus section circuit breaker) it is necessary to provide directional overcurrent and earth fault relays to ensure co-ordination and prevent unnecessary loss of supply. The direction relays are connected to 'look' into the transformers and the overcurrent elements may be set to a value of less than full load current, with due regard to the thermal rating of the relay. Theoretically the directional relays may be instantaneous (assuming no infeeds from the LV feeders) but a short time delay is recommended to improve transient stability. The directional relay is arranged to trip both LV and HV circuit breakers. In order to provide back-up protection for the system, the directional relays should be supplemented with non-directional relays co-ordinated with the directional (and other) relays in the usual manner.

To save costs (of both relays and associated voltage transformers) the directional facilities may be dispensed with if the bus section circuit breaker is fitted with protective devices. However, the loss of one half of the LV busbar, due to tripping of the bus section breaker for a transformer LV winding fault, will have to be accepted.

PARALLEL TRANSFORMERS PARTIAL DIFFERENTIAL SCHEME

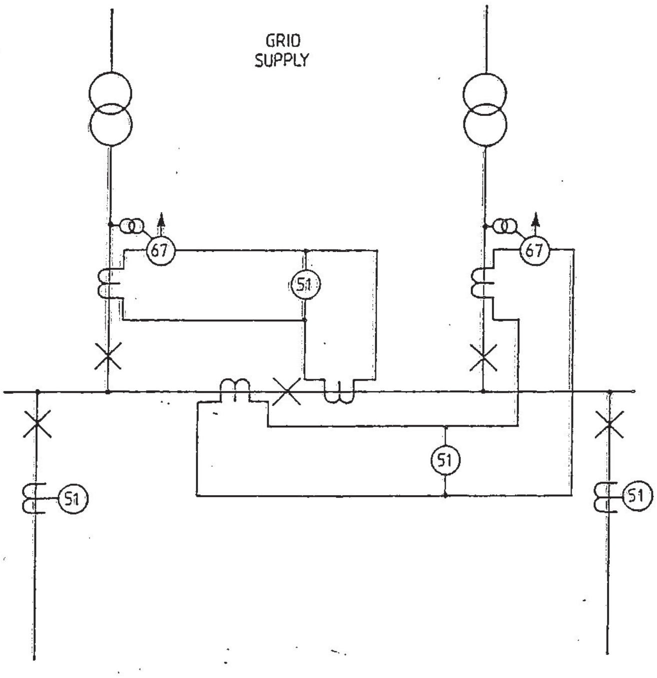


Figure 13

If current transformers are available on the bus-section circuit breaker then it is possible to eliminate a stage of co-ordination (and also a protective relay) by forming a partial differential scheme with a current transformer on the incoming circuit. The differentially connected non-directional relay provides feeder back-up protection for one half of the busbar and is arranged to trip both the bus-section and incoming circuit breakers. The directional relay is set to 'look' into the transformer in the usual manner.

USE OF INSTANTANEOUS OVERCURRENT

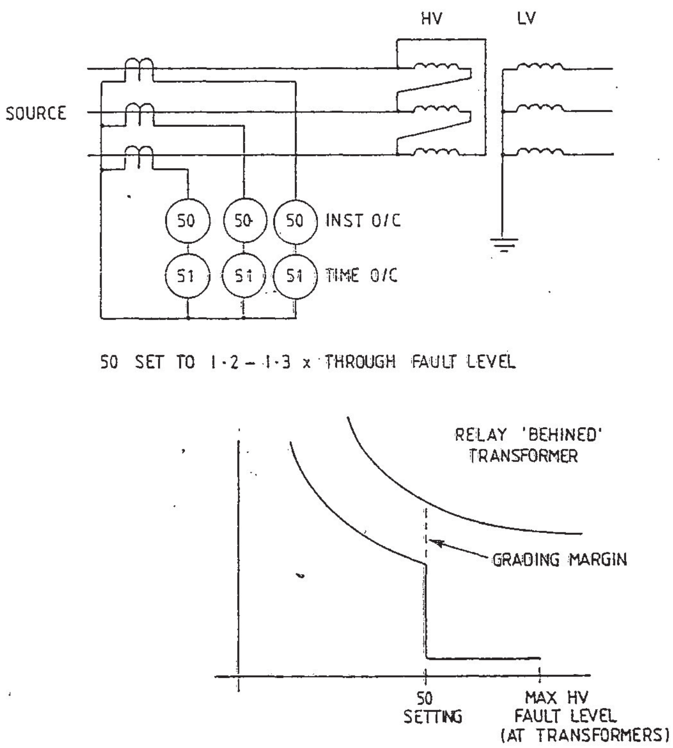


Figure 14

The use of instantaneous relays for the primary side of the transformer is recommended in order to improve fault clearance time and enable a lower time mutiplier setting on relays elsewhere on the system. The relay should have low transient overreach and be set to approximately 125% of the maximum through-fault level of the transformer, in order to prevent operation for faults on the secondary side.

2-1-1 DISTRIBUTION

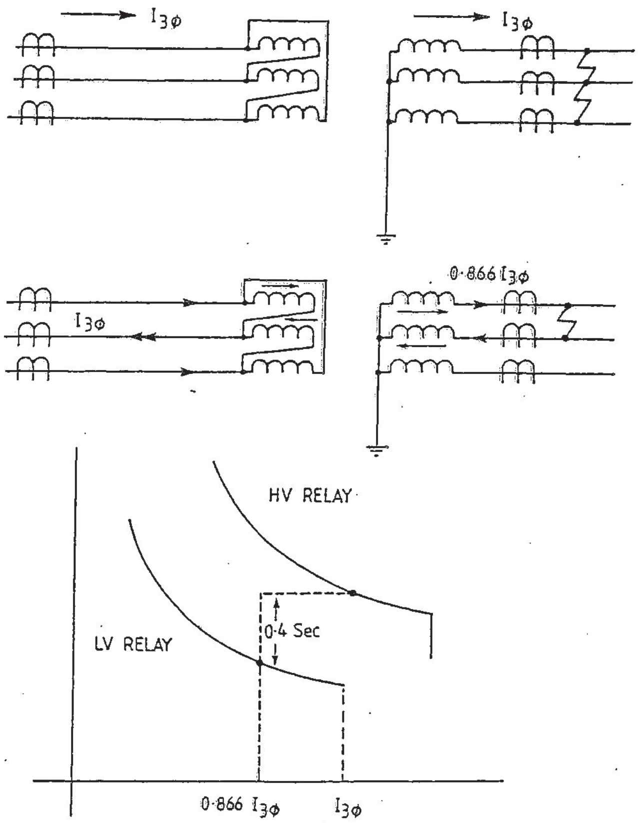
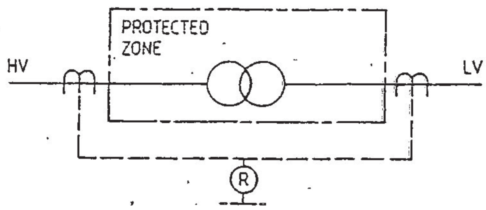


Figure 15

When grading dependent time overcurrent relays across a delta-star transformer it is necessary to establish the grading margin between the operating time of the star side relay at the phase-phase fault level and the operating time of the delta side relay at the three phase fault level. This is due to the fact that, under a star side phase-phase fault condition, which represents a fault level of 86% of the three phase fault level, one phase on the delta side of the transformer will carry a current equivalent to the three phase fault level.

DIFFERENTIAL PROTECTION



REQUIRES : BALANCE HV CT'S WITH LV CT'S

NOTING - (1) DIFFERENCE IN CURRENT MAGNITUDE
(2) PHASE SHIFT (IF ANY)
(3) WINDING CONNECTIONS

CT SECONDARY CONNECTIONS SHOULD BE "REPLICA" OF PRIMARY SYSTEM

Figure 16

Overall differential protection may be justified for larger transformers (greater than 5 MVA) due to the nominally instantaneous operation of the protection for faults on either winding. The CT's require interconnection with due regard to the difference in current magnitude on either side of the transformer, any inherent phase shift, and the possibility or otherwise of transfer of zero sequence current between the line connections.

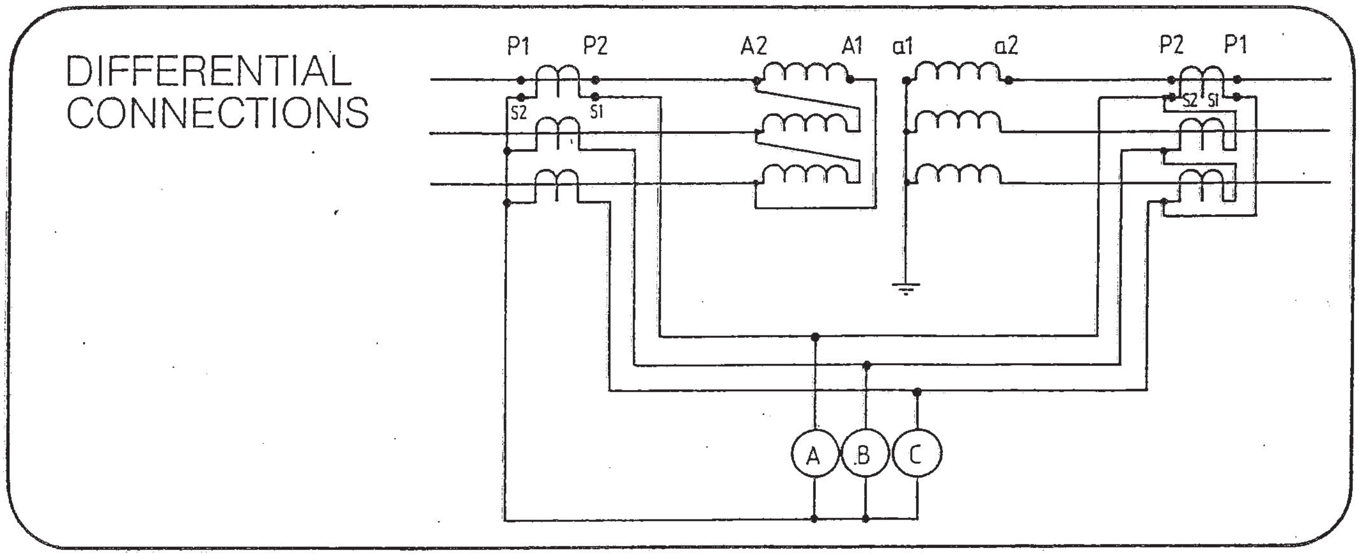


Figure 17

Typical connections for a delta-star transformer involve connecting the delta side CT's in star and the star side CT's in delta. The delta connection of the star side CT's compensates for the phase shift across the transformer and also provides a closed path for zero-sequence current, thereby eliminating zero sequence current from the secondary connections. This is necessary since the flow of zero sequence current in the line connections of the star side of the transformer is not balanced by any equivalent zero sequence current in the line connections on the delta side of the transformer. Note that particular care is required to ensure that the relative polarities of the CT connections are correct.

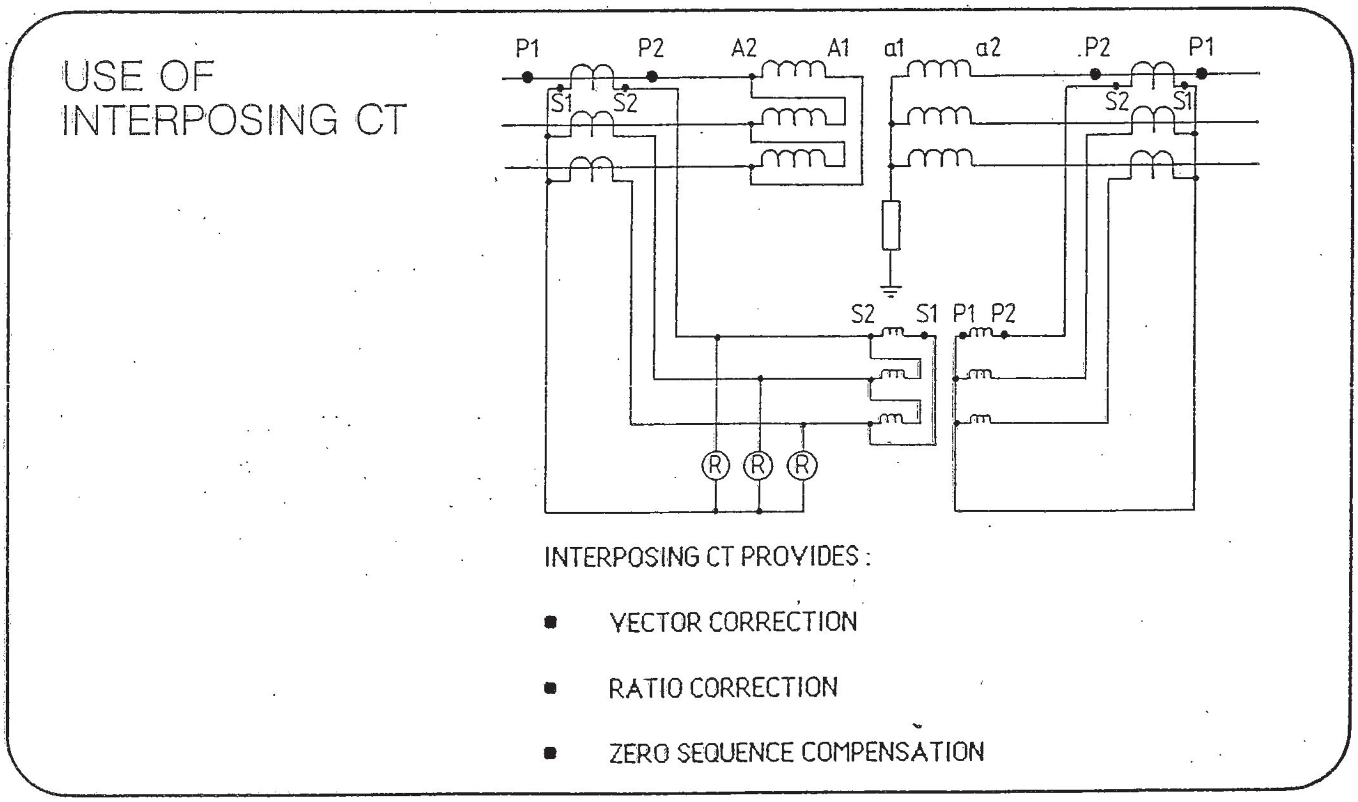


Figure 18

Often a more convenient approach is to utilise a star-delta interposing CT. This has two advantages over the connections shown in Figure 17:

– the lead VA burden on the line CT's is reduced due to the lower secondary current (note however that the interposing CT itself imposes an additional burden)

– it allows a convenient means of providing any necessary ratio correction due to the use of standard ratio line CT's. (Note also that correct balance should be established at the mid-point of the tap-changer range).

IN-ZONE EARTHING TRANSFORMER

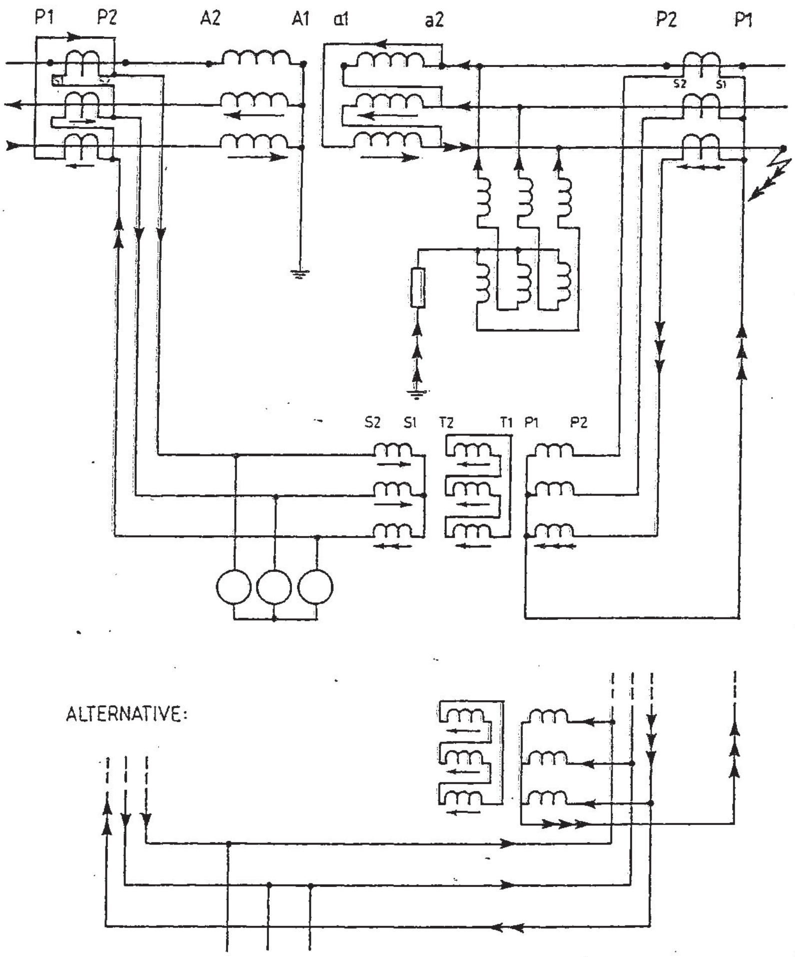


Figure 19

The zero sequence path produced by an in-zone earthing transformer requires compensation in the secondary connections by the use of a star-delta-star interposing CT. Note that the star point of the interposing CT secondary winding should not be connected to the star point of the relay since this would provide a zero sequence circuit in addition to that provided by the delta winding.
An alternative to the star-delta-star interposing CT is to use a shunt connected star-delta interposing CT.

COMBINED DIFFERENTIAL AND RESTRICTED EARTHFAULT PROTECTION

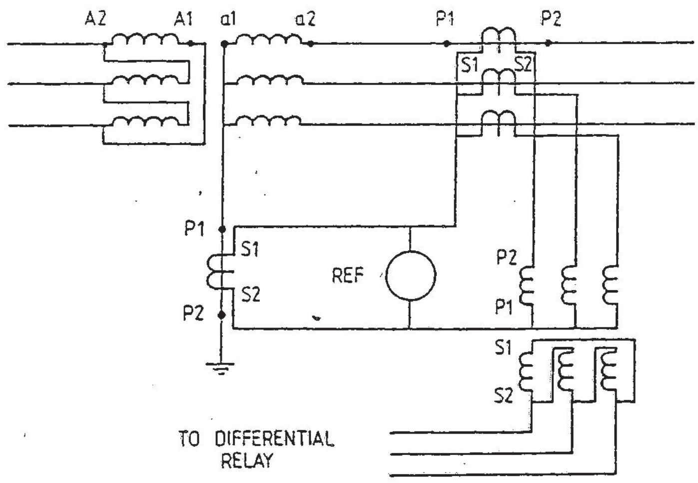


Figure 20

The use of an interposing CT also facilitates the interconnection of restricted earth fault protection utilising a common set of line CT's. Note that setting voltage calculations for the high impedance protection should take into account the effects of the interposing CT and main differential relay.

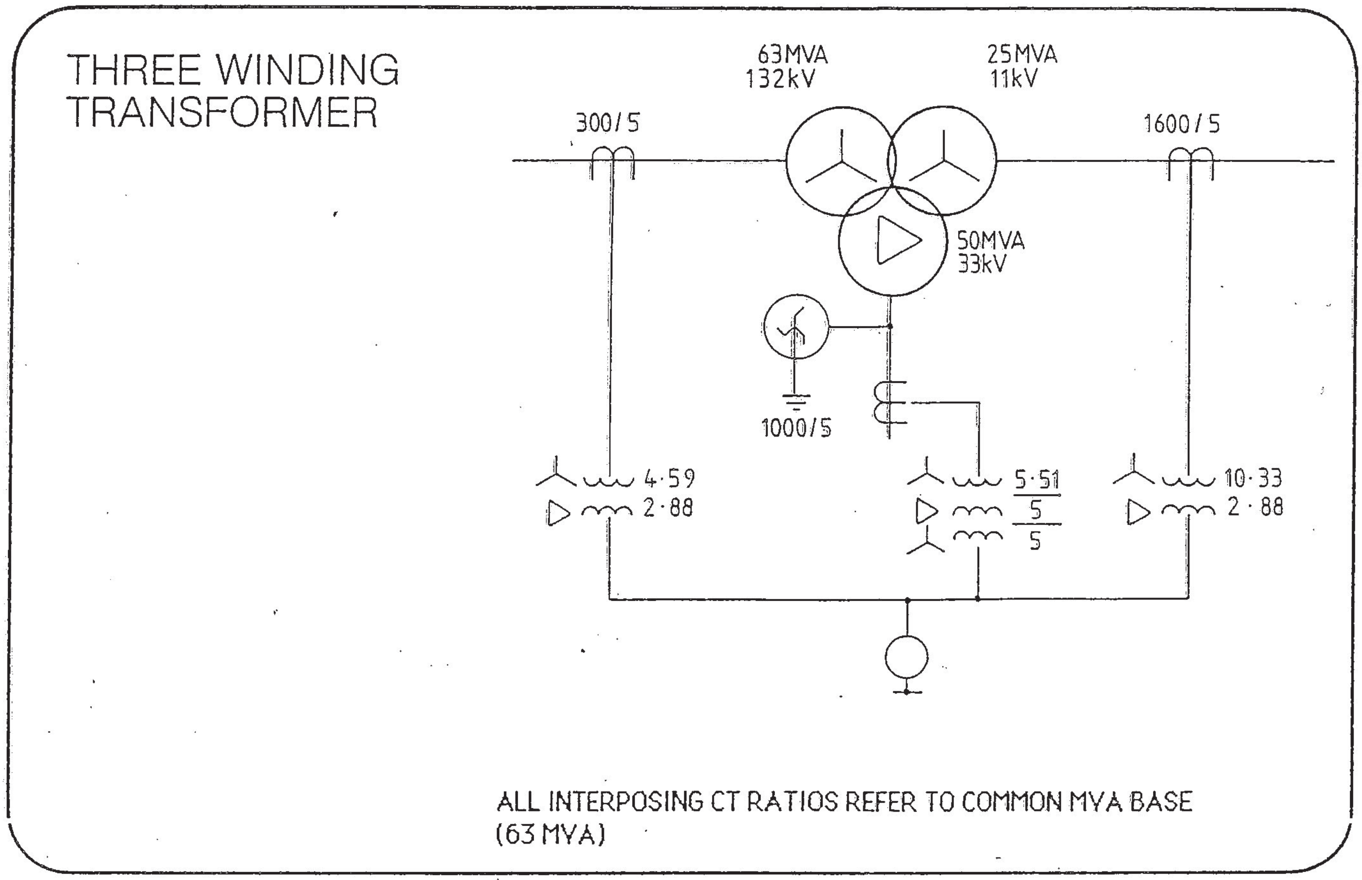


Figure 21

The required interposing CT ratios associated with a three winding transformer must be calculated with regard to a common MVA rating – usually that of the highest rated winding. The procedure is to consider each pair of windings in turn (with the third winding open circuited) and connections established in the usual manner with regard to phase shift etc.

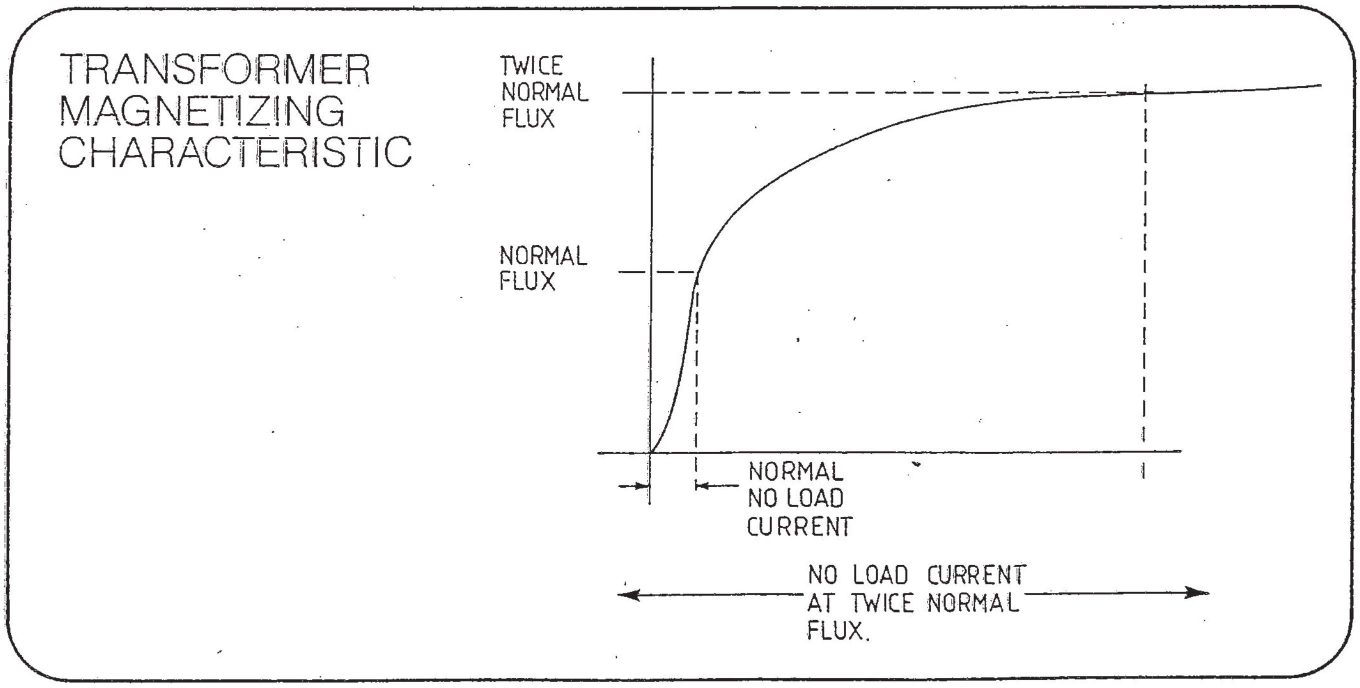


Figure 22

For efficiency reasons transformers are generally operated near to the 'knee point' of the magnetic characteristic. Consequently, any increase above rated terminal voltage tends to cause core saturation and therefore demands an excessive increase in magnetisation current.

IN-RUSH CURRENT

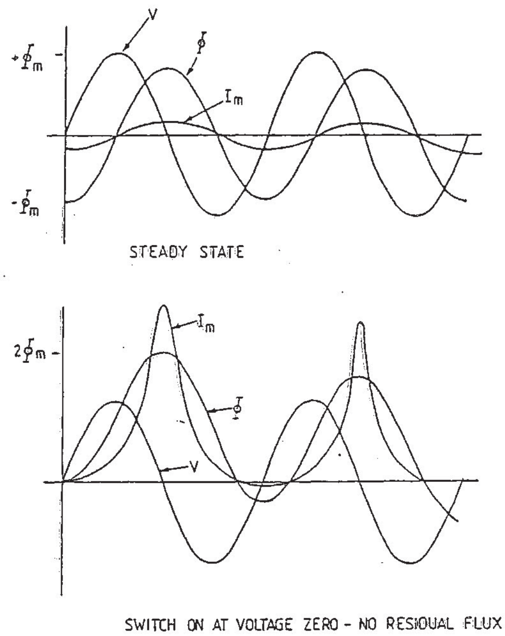


Figure 23

Under steady state (normal) conditions the magnetising current necessary to produce the required flux is relatively small (usually less than 1% rated current). However, if a transformer is energised at a voltage zero then the flux demand during the first half voltage cycle (2 x normal max flux) causes an excessive, essentially uni-directional current to flow. This current is commonly referred to as magnetising inrush current and may persist for several cycles.

MAGNETIZING CURRENT

- APPEARS ON ONE SIDE OF TRANSFORMER ONLY AND IS THERFORE SEEN AS A FAULT BY DIFFERENTIAL RELAY
- NORMAL MAGNETISING CURRENT IS LESS THAN RELAY SETTING BUT TRANSIENT MAGNETISING IN RUSH COULD CAUSE RELAY TO OPERATE

SOLUTION 1 :

- TIME DELAY
  MAGNETISING CURRENT DIES AWAY BEFORE RELAY OPERATES (eg INDUCTION DISC RELAY)

  HOWEVER, RELAY IS SLOW FOR GENUINE FAULTS

SOLUTION 2 :

- MAKE RELAY IMMUNE TO MAGNETISING IN RUSH
  (A) USING 2ND (& 5TH) HARMONIC RESTRAINT

  CAN BE SLOW IF CT SATURATES DURING FAULT

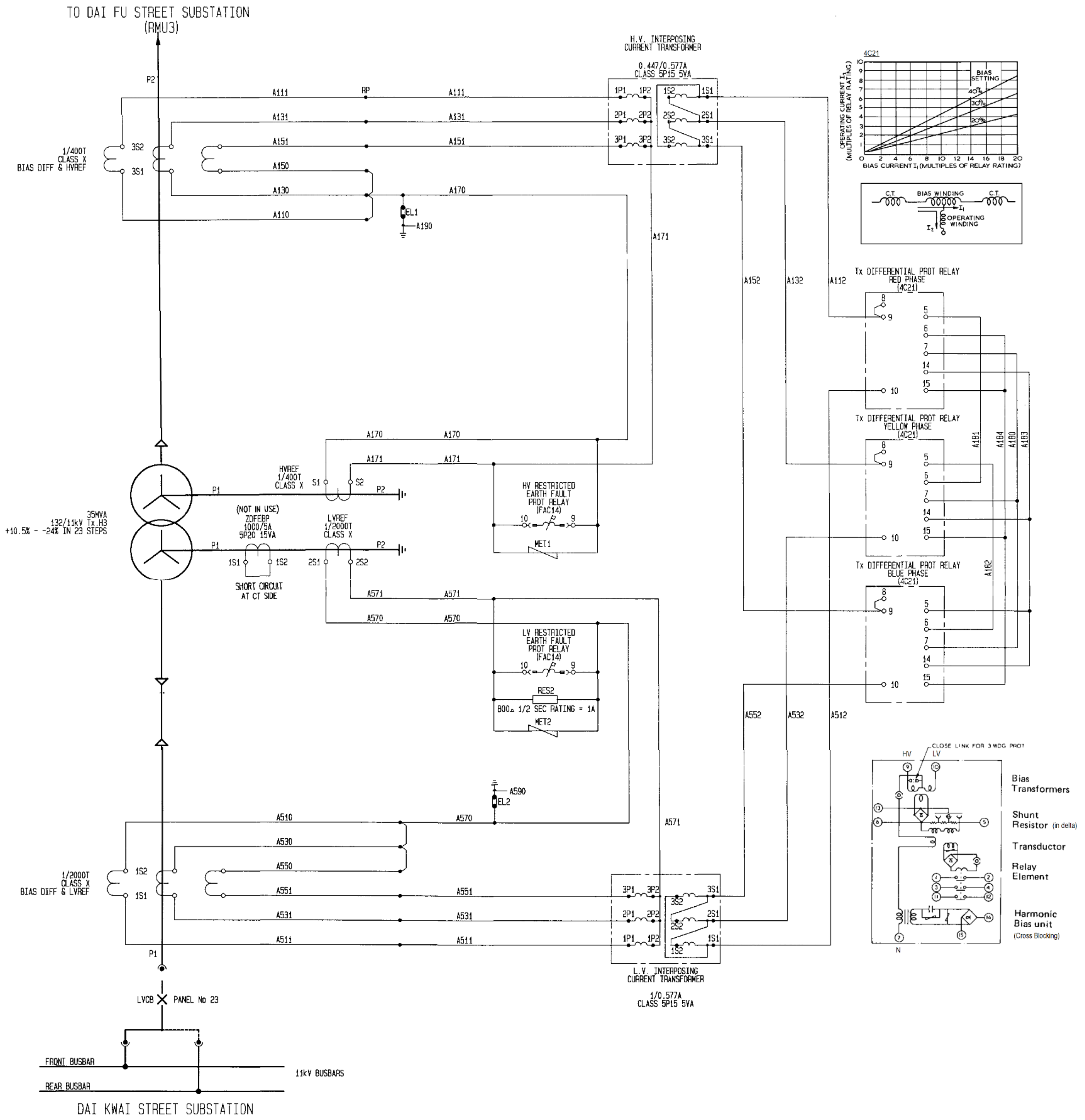
  OR (B) USING 'GAP' MEASUREMENT TECHNIQUE

SOLUTION 2 ALSO PREVENTS PROBLEMS DURING OVERFLUXING CONDITIONS

Figure 24

Since the magnetising inrush phenomenon is associated with one of the transformer windings and demands no equivalent current in the other winding, the current appears as a fault condition to differential protection. Special measures are therefore taken with the relay design to ensure that no maloperation occurs. Analysis of an inrush waveform yields a high proportion of second harmonic and, traditionally, a differential relay utilised filters to extract the second harmonic and use it as a restraining force to prevent operation. However, this technique can result in a slow relay operating time if the current transformers saturate under heavy internal fault conditions since the output waveform of a saturated CT also contains substantial second harmonics.
Modern relay designs utilise waveform recognition techniques to restrain the relay during inrush conditions but allow fast operation for internal faults even with the presence of CT saturation.

4C21 (BD) + FAC14 (REF)



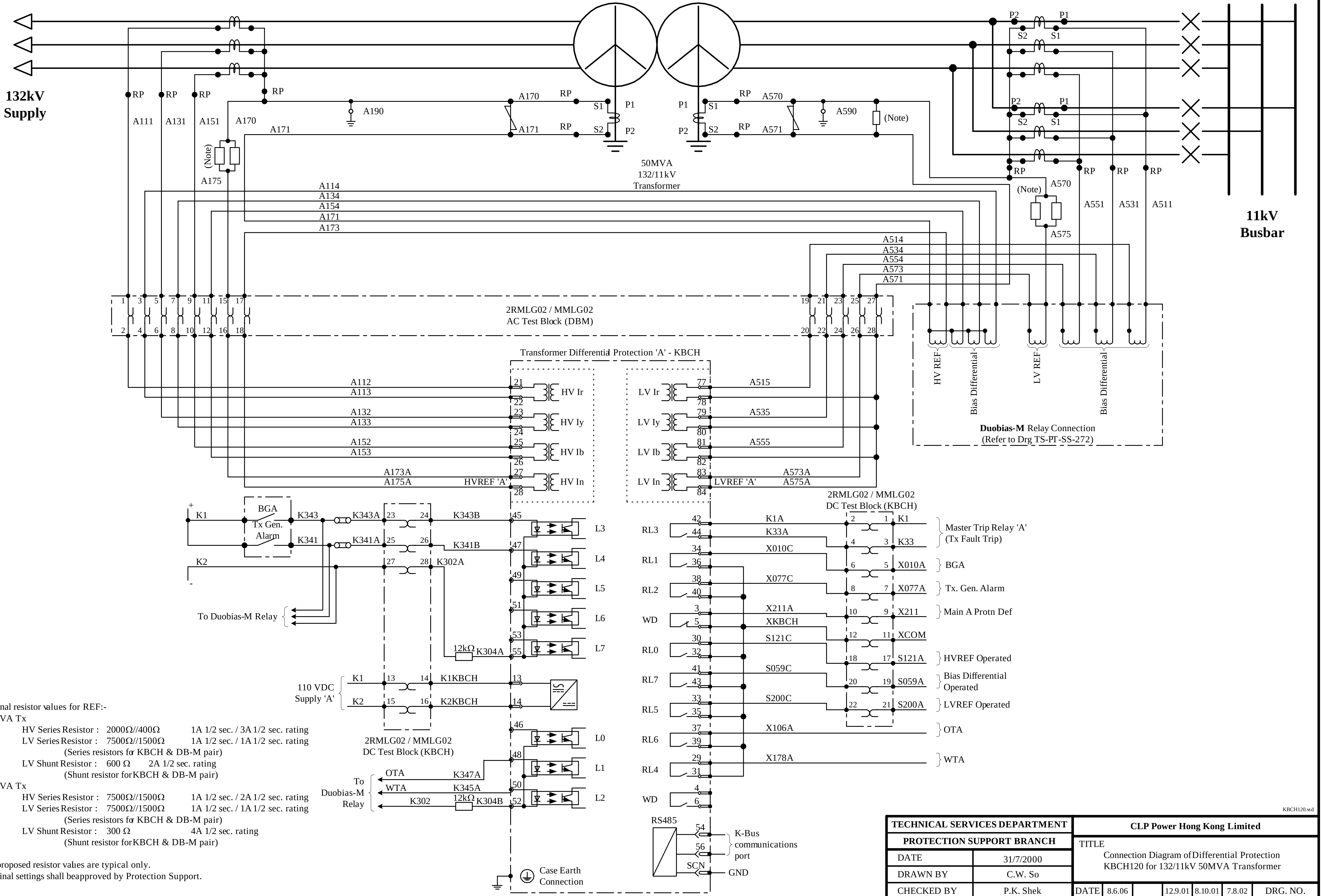
Tx. BIASED DIFFERENTIAL 變壓器差動(繼電)保護

TYPE 種類: SETTING 定值: % RATING 額定值:	PHASE 相位	+ OPERATING CURRENT 操作電流 HV 高壓 (mA)	LV 低壓 (mA)	HARMONIC BIAS CHECK 偏調波檢查 I/P CURRENT 輸入電流 9 & 7	** O/P VOLT 輸出壓 14 & 15
Duo Bias 4C21 1A	RØ 紅	199	195	2 A	15.006
	YØ 黃	202	202	2 A	15.52
	BØ 藍	196	192	2 A	15.86

+TYPICAL OPERATING CURRENT 操作電流之代表值 - 200 mA ± 10 %, ** TYPICAL O/P VOLT 輸出電壓之代表值 - 15 V D.C. ± 1

REF/BEF/CIRCULATING CURRENT 零序/零序對稱/環流(繼電)保護

	TYPE 種類	SETTING 定值 RELAY 繼電器	POC	SETTING RESISTOR 電阻定值 (Ω) SHUNT 並聯(RSH)	SERIES 串聯(RS)	MEASURED SETTING 量度定值 V1 電壓 (V)	I1 電流 (mA)	V2 電壓 (V)	I2 電流 (mA)
HV * BEF / REF 高壓*零序/零序對稱	FAC14	75V	29.72A			76.5	86	75.8	20
LV REF 低壓零序	FAC14	100V	314.67A	800		98.4	155	99.4	19



Note:

External resistor values for REF:-

35 MVA Tx

HV Series Resistor : 2000Ω//400Ω 1A 1/2 sec. / 3A 1/2 sec. rating

LV Series Resistor : 7500Ω//1500Ω 1A 1/2 sec. / 1A 1/2 sec. rating

(Series resistors for KBCH & DB-M pair)

LV Shunt Resistor : 600 Ω 2A 1/2 sec. rating

(Shunt resistor for KBCH & DB-M pair)

50 MVA Tx

HV Series Resistor : 7500Ω//1500Ω 1A 1/2 sec. / 2A 1/2 sec. rating

LV Series Resistor : 7500Ω//1500Ω 1A 1/2 sec. / 1A 1/2 sec. rating

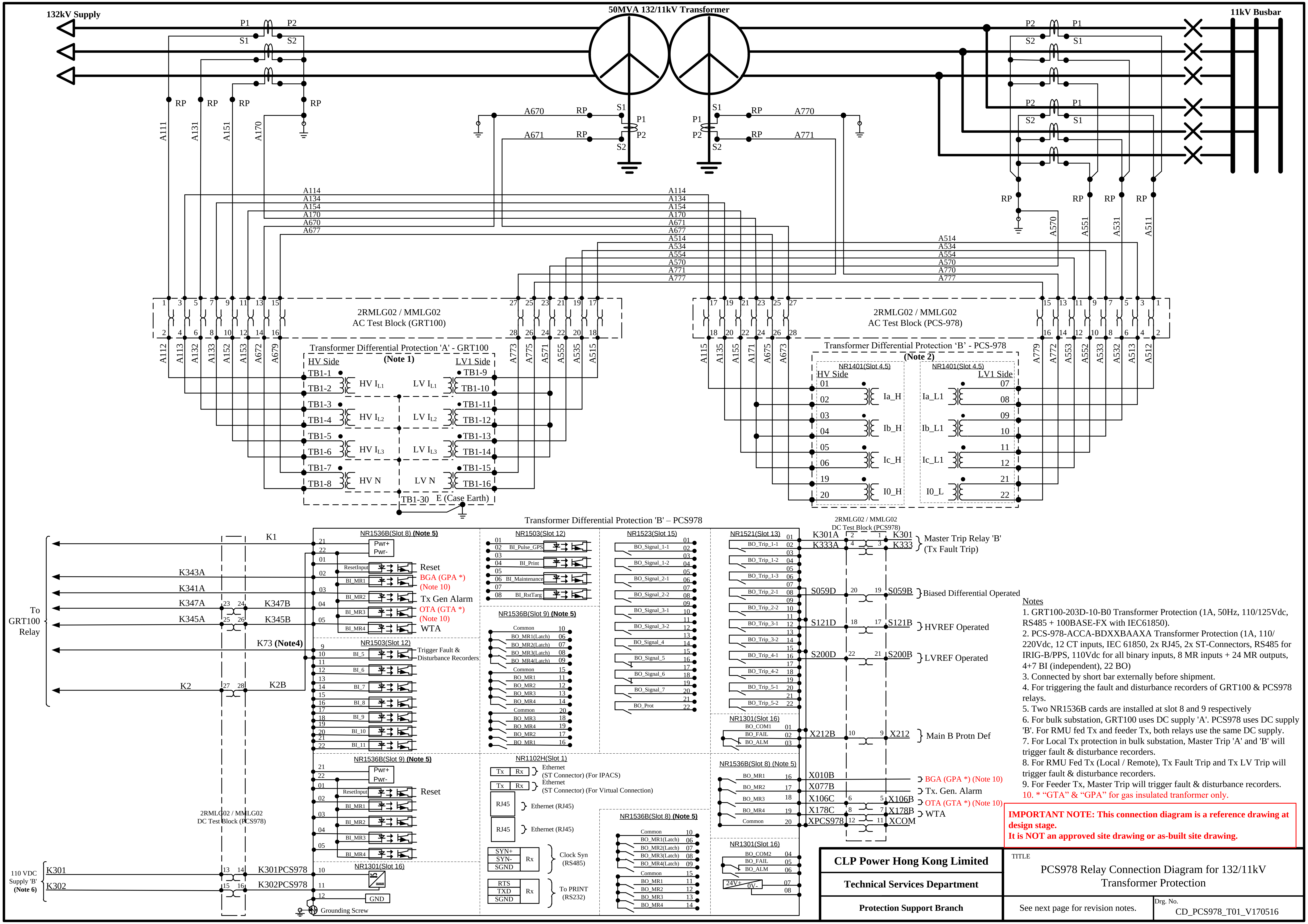
(Series resistors for KBCH & DB-M pair)

LV Shunt Resistor : 300 Ω 4A 1/2 sec. rating

(Shunt resistor for KBCH & DB-M pair)

The proposed resistor values are typical only.
The final settings shall be approved by Protection Support.

TECHNICAL SERVICES DEPARTMENT		CLP Power Hong Kong Limited
PROTECTION SUPPORT BRANCH		TITLE Connection Diagram of Differential Protection KBCH120 for 132/11kV 50MVA Transformer
DATE	31/7/2000	
DRAWN BY	C.W. So	
CHECKED BY	P.K. Shek	DATE 8.6.06 / 12.9.01 / 8.10.01 / 7.8.02 — DRG. NO.
APPROVED BY	K.T. Lai	REV. F / C / D / E — TS-PT-SS-271



Notes

1. GRT100-203D-10-B0 Transformer Protection (1A, 50Hz, 110/125Vdc, RS485 + 100BASE-FX with IEC61850).
2. PCS-978-ACCA-BDXXBAAXA Transformer Protection (1A, 110/220Vdc, 12 CT inputs, IEC 61850, 2x RJ45, 2x ST-Connectors, RS485 for IRIG-B/PPS, 110Vdc for all binary inputs, 8 MR inputs + 24 MR outputs, 4+7 BI (independent), 22 BO)
3. Connected by short bar externally before shipment.
4. For triggering the fault and disturbance recorders of GRT100 & PCS978 relays.
5. Two NR1536B cards are installed at slot 8 and 9 respectively
6. For bulk substation, GRT100 uses DC supply 'A'. PCS978 uses DC supply 'B'. For RMU fed Tx and feeder Tx, both relays use the same DC supply.
7. For Local Tx protection in bulk substation, Master Trip 'A' and 'B' will trigger fault & disturbance recorders.
8. For RMU Fed Tx (Local / Remote), Tx Fault Trip and Tx LV Trip will trigger fault & disturbance recorders.
9. For Feeder Tx, Master Trip will trigger fault & disturbance recorders.
10. * "GTA" & "GPA" for gas insulated tranformer only.

IMPORTANT NOTE: This connection diagram is a reference drawing at design stage.
It is NOT an approved site drawing or as-built site drawing.

CLP Power Hong Kong Limited	TITLE PCS978 Relay Connection Diagram for 132/11kV Transformer Protection	
Technical Services Department		
Protection Support Branch	See next page for revision notes.	Drg. No. CD_PCS978_T01_V170516

PROTECTION OPERATION SUMMARY

REFERENCE NO.
POS394

To: Director – Transmission

SUBSTATION / CIRCUIT

(ST11) San Shek Wan - Tsun Wen Road RMU No.1; San Hui RMU No.1 - Tsun Wen Road RMU No.1; Tsun Wen Road RMU No.1 - Lam Tei 132/11kV Feeder Tx H1; Tsun Wen Road 132/11kV Tx H1

IDR NO.			DATE	TIME	CASE NO.
1365267-1			19 Sep 2023	15:24	N872

FAULT DESCRIPTION

On 19-Sep-2023 at 15:34hr, a genuine OHL fault occurred at the Chi Tin Tsuen Line (TWRL02) and the circuit auto-reclosed successfully (IDR 1365256-1 refers). However, the source end 132/11kV 50MVA Tx H1 at Lam Tei 11kV Substation (LMT011) tripped simultaneously on main protection (Transformer Differential Protection 'B'), while it also inter-tripped the whole 132kV RMU circuit and another 132/11kV 35MVA Tx H1 at TWR011 (Appendix 1). With the supply to LMT011 R1 busbar restored by Numerical Auto-Switching (NAS) Scheme, the supply to TWR011 T1 busbar was maintained by the Tx H2 running in parallel thus no CML was incurred overall.

With the PCS-978 relay defeated and no abnormality observed, LMT011 Tx H1 was re-energized successfully at 00:22hr on 20 Sep 2023.

INVESTIGATION & FINDING

After site investigation, it was revealed that the 11kV Restricted Earth Fault (LVREF) element of Transformer Differential Protection 'B' (NARI PCS-978) operated while Transformer Differential Protection 'A' (Toshiba GRT100) remained stable during the incident. Besides, site investigation suggested that no fault occurred (both primary and secondary) within the protected zone of LVREF. Therefore, it was suspected that the LVREF element of PCS-978 operated incorrectly resulting in this unwanted tripping.

According to the fault records in PCS-978 relay, current measurement (both 3-phase and neutral) of the relay were normal (Appendix 2) and found matching with those from the GRT100 and fault recorder. However, it was observed that the LVREF element of PCS-978 operated twice at very short pulses of 1ms and 4ms respectively, with the first pulse triggered the output contacts. It was then suspected that the LVREF element marginally operated during the 3-phase through fault at 11kV (around 8200A), leading to the mal-operation.

To validate the relay function, simulation tests with recorded waveforms were performed on another healthy PCS-978 and GRT100 relays at test lab, for which the same relay operations could be replicated upon replaying of the fault waveforms thus confirming the defect to be consistent. Therefore, it is concluded that the mal-operation of the PCS-978 relay should be caused by the relay internal logic on LVREF detection upon high level of inrush through fault current.

FOLLOW-UP ACTION / RECOMMENDATION

As an interim measure, it is recommended to add a time delay of 25ms to the HVREF and LVREF element of the PCS-978 so as to ride through the possible intermittent operation upon inrush of through fault current. This time delay setting had been verified with repeated fault simulation tests and was proven to be effective in preventing the mal-operation. Despite the HVREF and LVREF operation time of PCS-978 would be increased, the overall fault clearance time should be still within the 132kV standard (150ms). Besides, with GRT100 maintained at instantaneous operation, the overall fault clearance time should be unchanged for most of the situations. The relevant information had been sent to NARI for further investigation with root cause analysis so as to advise for the permanent solution as well.

DATE OF LAST CORRECT OPERATION IN THE PAST 5 YEARS	LAST MAINTENANCE DATE	SCHEDULED MAINTENANCE DATE
N/A	15^{th} Nov 2022	14^{th} Nov 2026

REMARKS

N/A

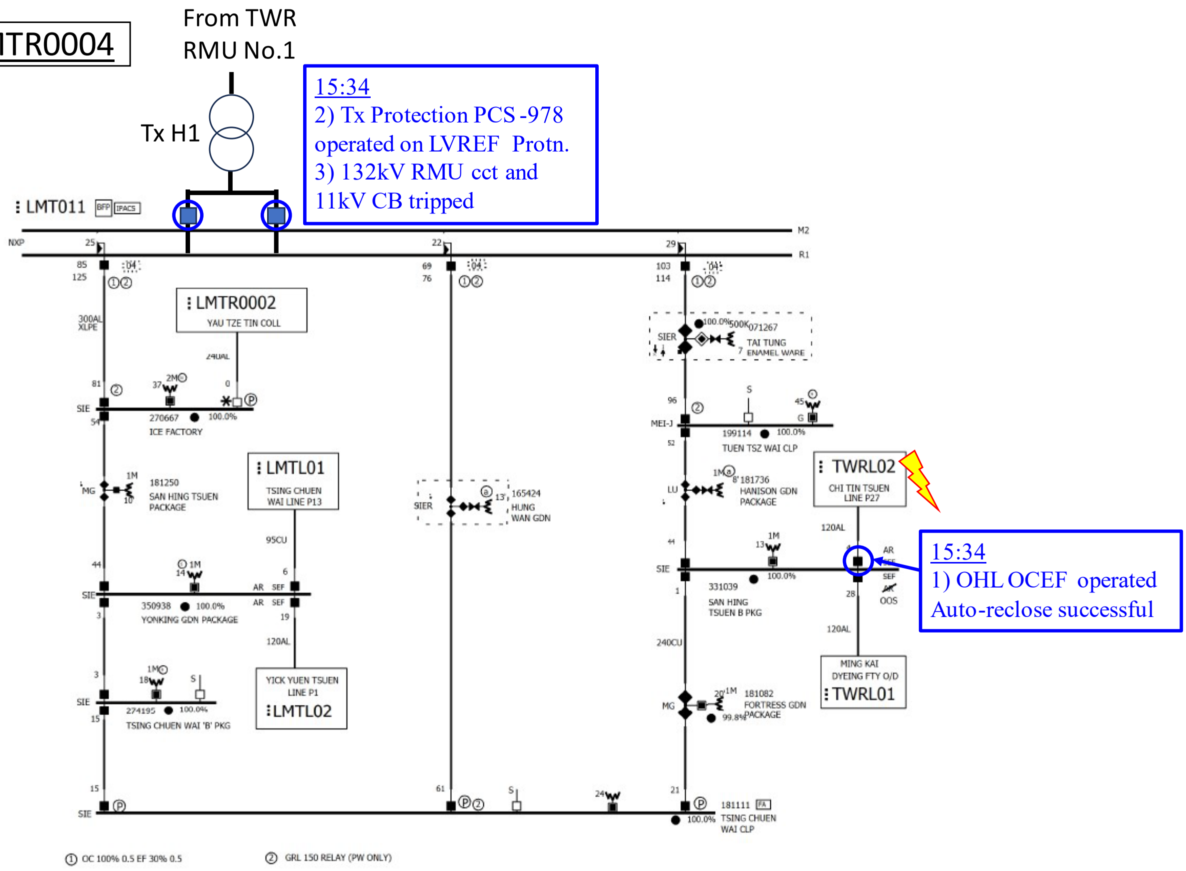
COPY TO

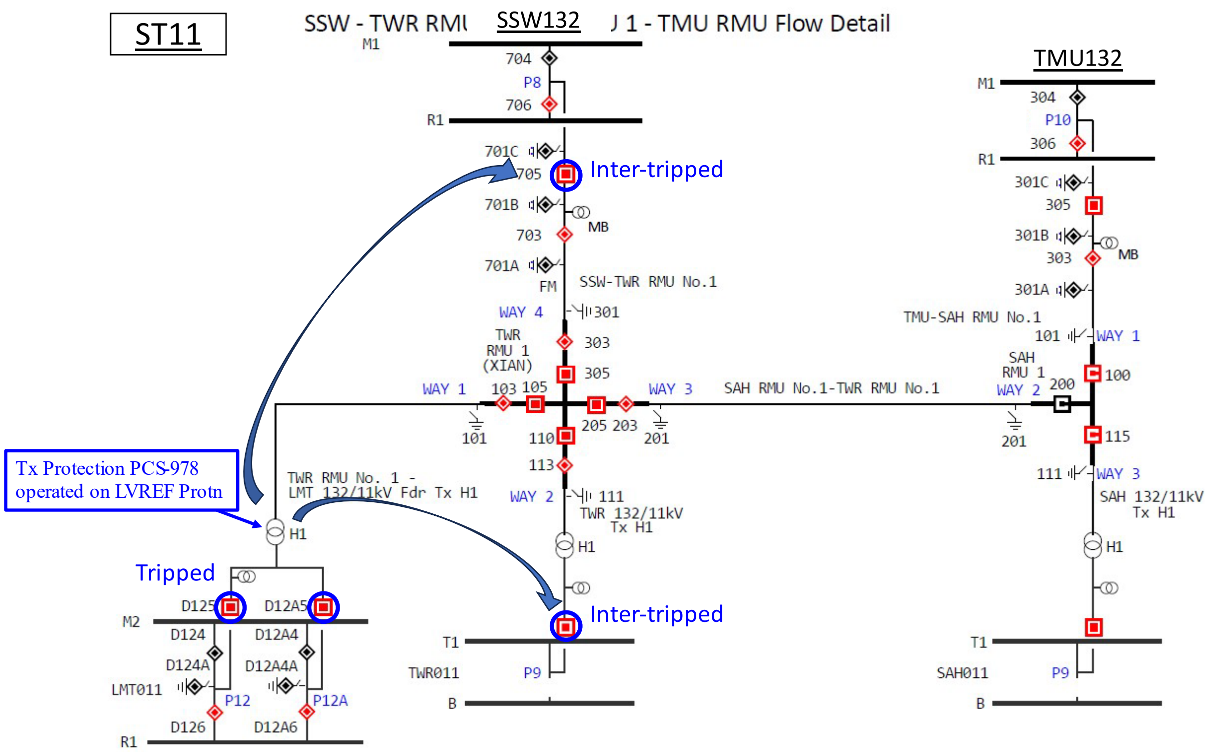
☑ Director - Asset Management
☑ Director - North Region
☑ Director - East & West Region
☑ Director - Technical Services
☑ Director - System Operation
☑ Associate Director - Asset Development (Asset Management)

☑ Principal Manager - Operations (East & West Region)
☑ Principal Manager - Operations (North Region)
☑ Duty Principal Manager Shift Account (System Operation)
☑ Associate Director – Operational Planning (System Operation)
☑ Associate Director – Plant (Transmission)
☑ Senior Manager - Protection O&M (Transmission)
☑ HSSEQ-MS-006
☑ Mr Barry Chen / POS File

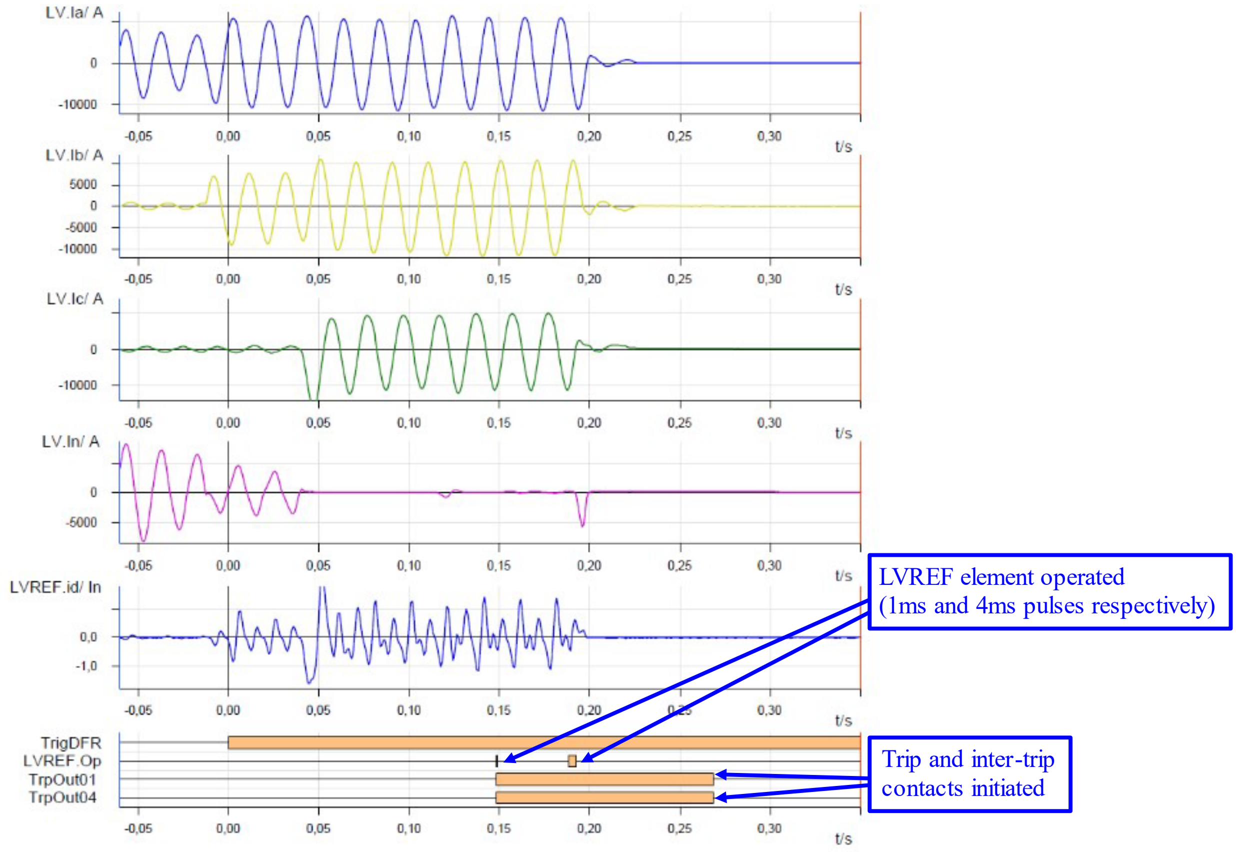
INVESTIGATED BY	CHECKED BY	ISSUED BY & DATE
YS Lai	Barry Chen	Dickson Lau Principal Manager - Protection Engineering 28 Sep 2023

Appendix 1 – Network Diagram

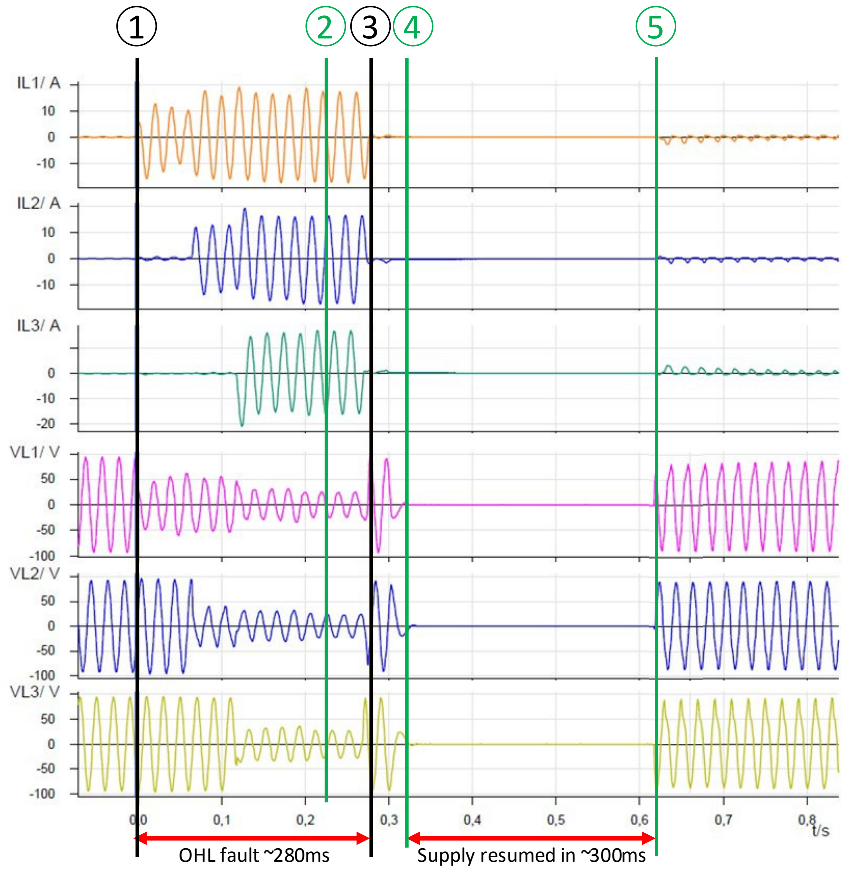




Appendix 2 – Fault Waveform Retrieved at PCS-978



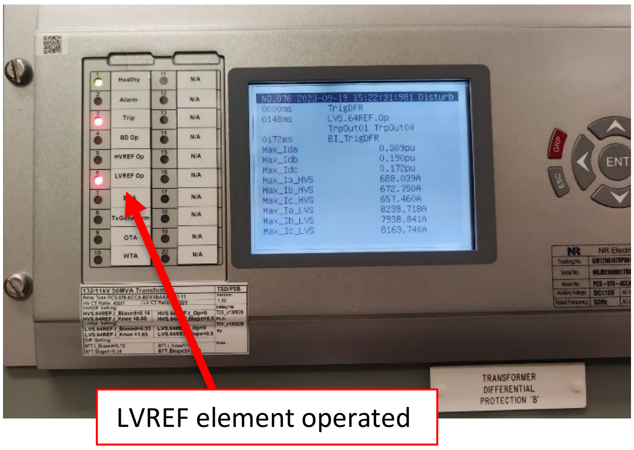
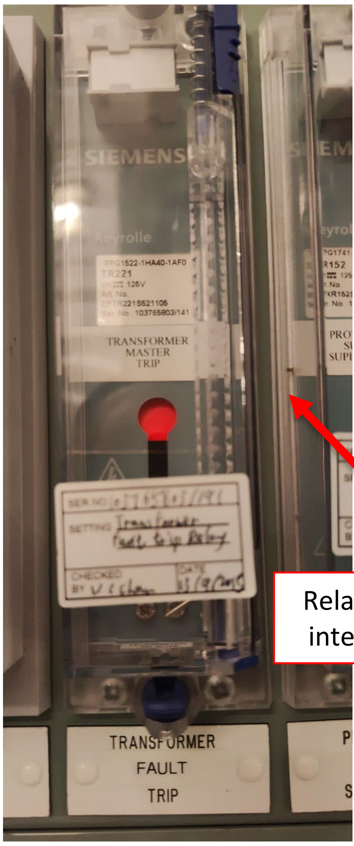
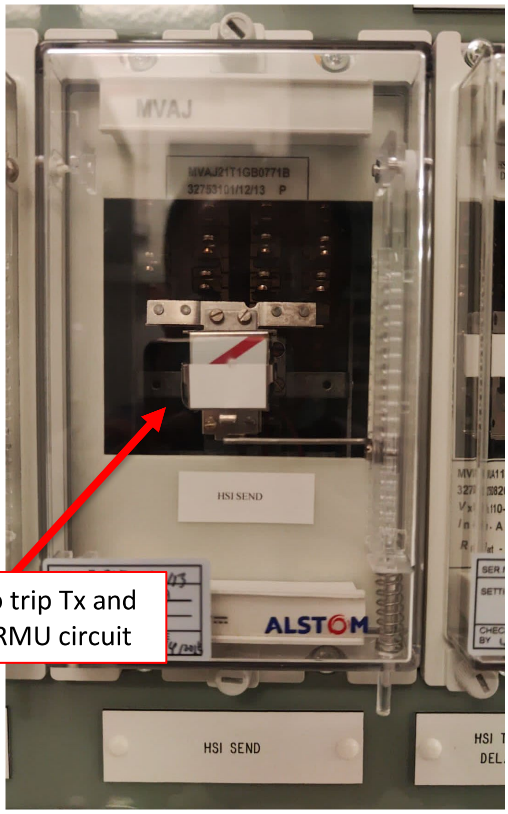
Appendix 3 – Event Timeline at LMT011



Event Timeline

1. Start of OHL fault
2. Tx LVREF Protn. operated
   Trip and Inter-trip signal initiated
3. OHL fault cleared by OHL OCEF
4. Tx and 132kV circuit tripped
   LMT011 suffering supply loss
5. Supply resumed by NAS

Appendix 4 – Site Photos at LMT011 Tx H1 Panel

Main protection 'A' – Toshiba GRT100	Main protection 'B' – NARI PCS-978
	
Transformer Fault Trip Relay	**High Speed Inter-trip Send Relay**
	

PROTECTION OPERATION SUMMARY

REFERENCE NO.
POS366

To: Director – North Region

SUBSTATION / CIRCUIT

San Shek Wan (SSW) - Tsun Wen Road (TWR) RMU No. 1, TWR RMU No. 1 - Lam Tei (LMT) Feeder Tx H1; TWR RMU No. 1 – TWR Tx H1, TWR RMU No. 1 – San Hui (SAH) RMU No. 1

IDR NO.			DATE	TIME	CASE NO.
946272-1			06 June 2018	10:19 hr	N766

FAULT DESCRIPTION

On 6 June 2018 at 10:19, transformer H1 at LMT substation was tripped by transformer differential protection 'B' (PCS-978, NR Electric) upon energization, after a planned outage for cable slewing. There was no supply loss in the incident as the transformer at TWR substation was running in parallel with another transformer.

INVESTIGATION & FINDING

Relay event log and fault record at transformer differential protection 'A' (GRT100, Toshiba) and 'B' (PCS-978, NR Electric) of LMT Tx H1 were downloaded for analysis on 7 June 2018. According to fault records, both relays were picked up for a short duration (<10ms) during transformer energization (Appendix 2 & 3 refer).

Harmonic restraint algorithm is commonly adopted in transformer protection relays for stabilizing differential protection during energization. However, the harmonic content recorded by both relays in this incident was relatively low and marginal to the restraint setting. The restraint function was found reset and allowing operation of relay for a short period of time. Finally, the transformer differential protection 'B' relay picked up to trip the LMT Tx H1.

FOLLOW-UP ACTION / RECOMMENDATION

Focus on LMT Tx H1, the following items were suggested:

- Replacing the operated relay for investigation
- After relay replacement, as temporary measure, revising the harmonic restraint setting to suit the behaviour of transformer

For re-energization of other Tx using same relay models (i.e. PCS-978 and GRT100), it is recommended to revise the setting to extend the harmonic restraint capability for lower harmonic content (with appropriate event triggering enabled). Moreover, energization information of related transformers (using same relay models in general), including data from manufacturers and past energization record captured by protection relays, are being collected for further analysis. Details of work items will be discussed with Regions and SO accordingly.

DATE OF LAST CORRECT OPERATION IN THE PAST 5 YEARS	LAST MAINTENANCE DATE	SCHEDULED MAINTENANCE DATE
N/A	N/A	N/A

REMARKS

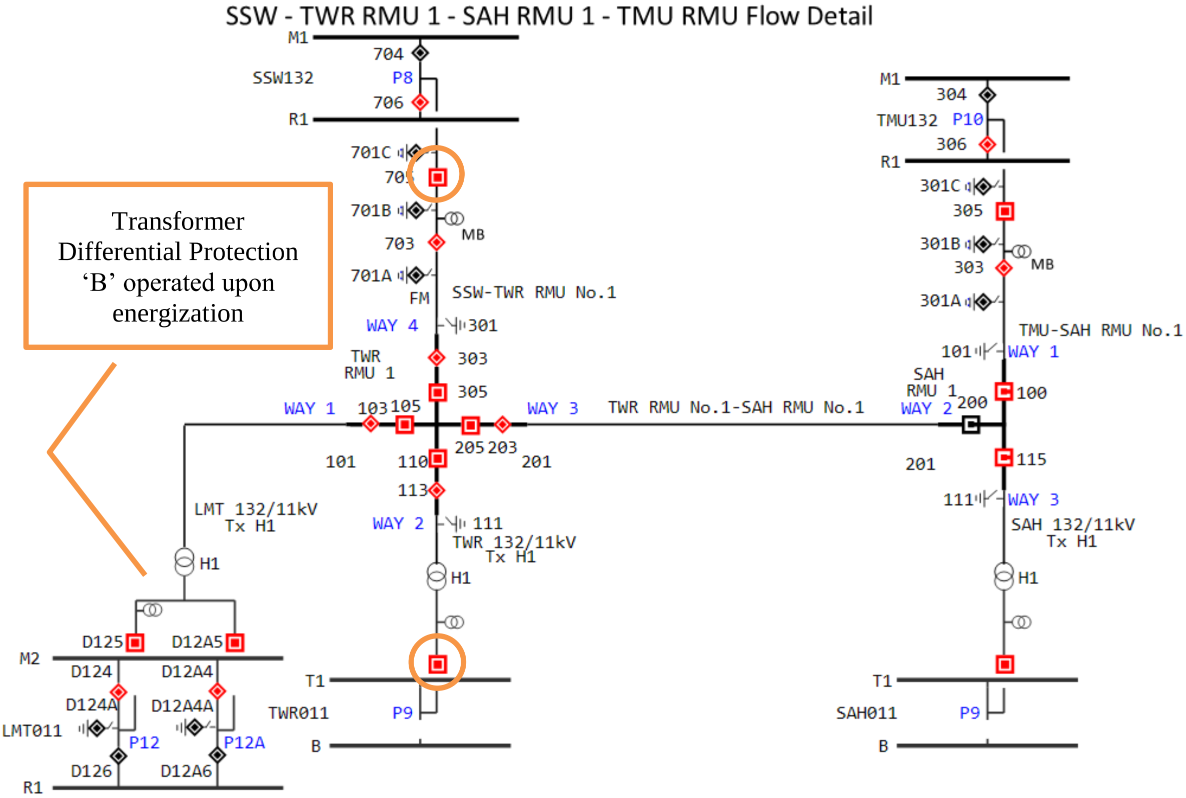
The LMT Tx H1 was put on load successfully at 02:41 on 8 June 2018 with the restraint setting revised. The transformer had been energized for more than 11 times of inrush without tripping since first commissioning. However, no information was recorded by relays to support subsequent study or reference.

COPY TO

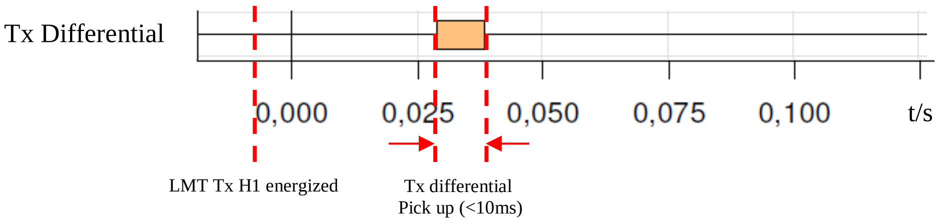
☑ Director – Asset Management
☑ Director – East & West Region
☑ Director – System Operation
☑ Deputy Director – Technical Services
☑ Acting Senior Asset Utilisation Manager (Asset Management)
☑ Acting Senior Maintenance Manager (East & West Region)
☑ Senior Maintenance Manager (North Region)
☑ Mr Rocky Yiu (East & West Region)
☑ Mr Y.P. Cheng (North Region)
☑ HSSEQ MS-006
☑ Mr C.W. Chiu / Mr. Alvin Lit / POS File

INVESTIGATED By	CHECKED BY	ISSUED BY & DATE
CY Cheung	Alvin Lit	H.F. Kwan Senior Protection Support Manager 15 June 2018

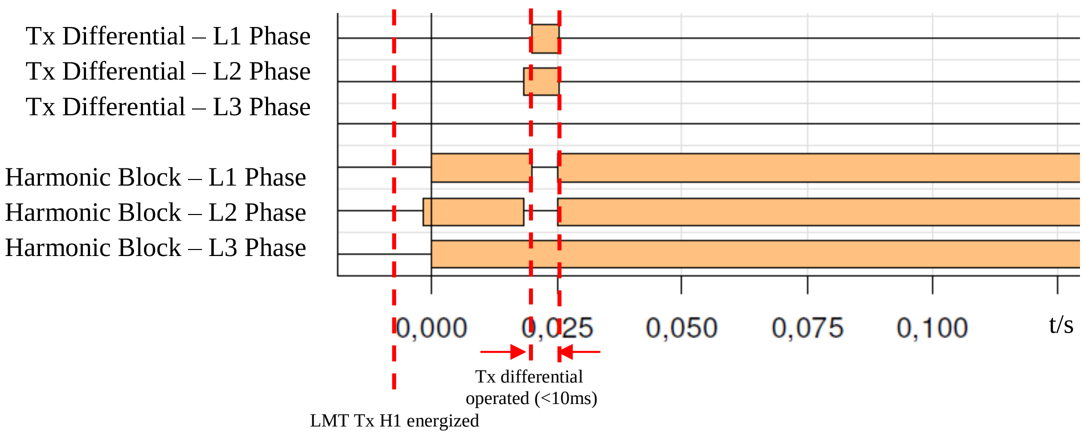
Appendix 1 – Network Diagram



Appendix 2 – Relay Event Log (NR Electric PCS-978)



Appendix 3 – Relay Event Log (Toshiba GRT100)



REFERENCE NO.
POS381

PROTECTION OPERATION SUMMARY

To: Director – Transmission Department

SUBSTATION / CIRCUIT

Fanling (FNL) RMU No.3 - Heung Yuen Wai (HYW) Feeder Tx H2, FNL132 - FNL RMU No.3, FNL RMU No.3 - FNL Tx H5, FNL RMU No.3 - Fanling KCR (FLK) Feeder Tx H1

IDR NO.			DATE	TIME	CASE NO.
1205023-1			31 May 2021	15:05	N803

FAULT DESCRIPTION

Upon de-energization of HYW Tx H2 at FNL RMU No.3 CB 805, Tx differential relay ‘A’ (Toshiba GRT100) operated and all other ways were inter-tripped.

INVESTIGATION & FINDING

The analysis of relay settings and fault records at Tx differential protection ‘A’ (GRT100) and ‘B’ (NR Electric PCS-978) of HYW Tx H2 shows that both relays detected oscillation during transformer de-energization (Appendix 2 & 3). The second harmonic content of the oscillation was marginal relative to the harmonic restraint setting in use (20%), and there was a short duration (< 5 ms) where the harmonic blocking elements of the GRT100 relay reset for all 3 phases, leading to Tx differential trip.

From the study of previous oscillations which tended to occur on feeder transformer circuits with long cable, the standard harmonic restraint setting was recommended as 15% for better security, and the setting tables for GRT100 and PCS-978 were revised in May 2019 accordingly.

FOLLOW-UP ACTION / RECOMMENDATION

At HYW Tx H2, the harmonic restraint setting has been set to 15% for both relays, and recorded waveforms were replayed to the relays to verify the effectiveness of the setting. The circuit was successfully restored.

To avoid recurrence of similar cases, the following actions are recommended:

- Set harmonic restraint setting of all GRT100 and PCS-978 relays to 15%, especially for circuits with relatively long cables and circuits whose pre-commissioning tests were conducted before May 2019
- In addition to meetings and emails, issue Protection General Guidelines (PGG) for similar system-wide setting reviews to achieve more effective communication

DATE OF LAST CORRECT OPERATION IN THE PAST 5 YEARS	LAST MAINTENANCE DATE	SCHEDULED MAINTENANCE DATE
N/A	N/A	N/A

REMARKS

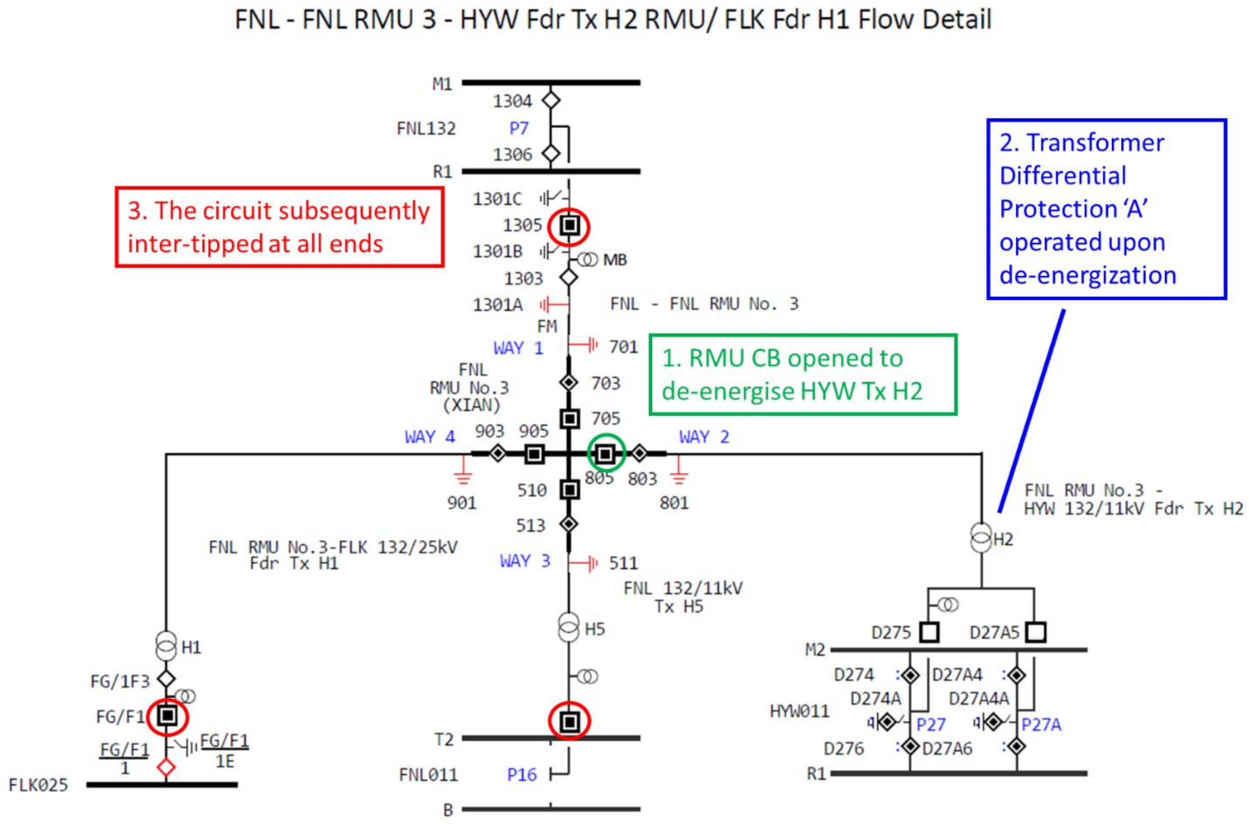
N/A

COPY TO

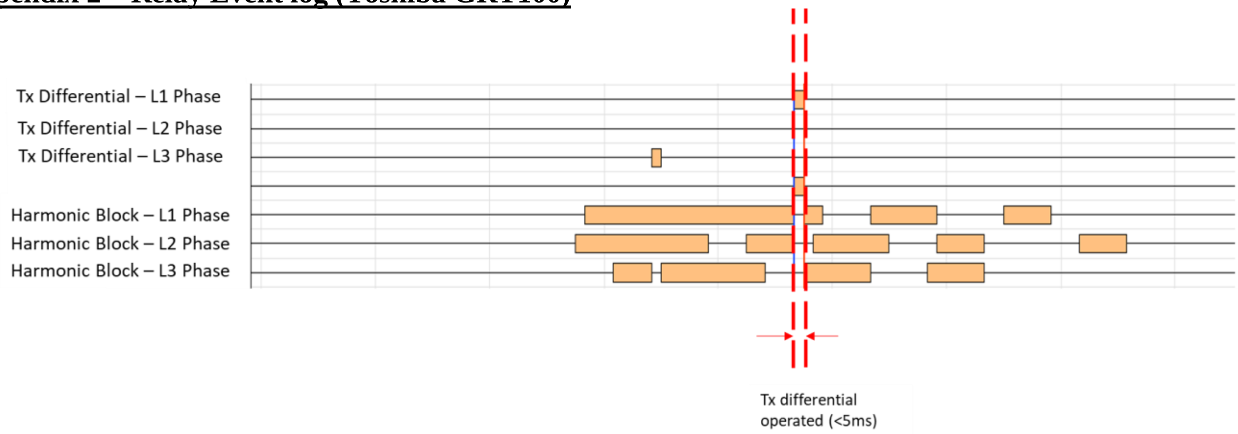
☑ Director - Asset Management
☑ Director - Technical Services
☑ Director - System Operation
☑ Senior Asset Utilisation Manager (Asset Management)
☑ Protection O&M Manager (Transmission)
☑ Mr Rocky Yiu (Transmission)
☑ Mr YP Cheng (Transmission)
☑ HSSEQ-MS-006
☑ Mr Herman Man / POS File

INVESTIGATED BY	CHECKED BY	ISSUED BY & DATE
YS Lai	Herman Man	Tony Chan Senior Protection Engineering Manager 9 Jun 2021

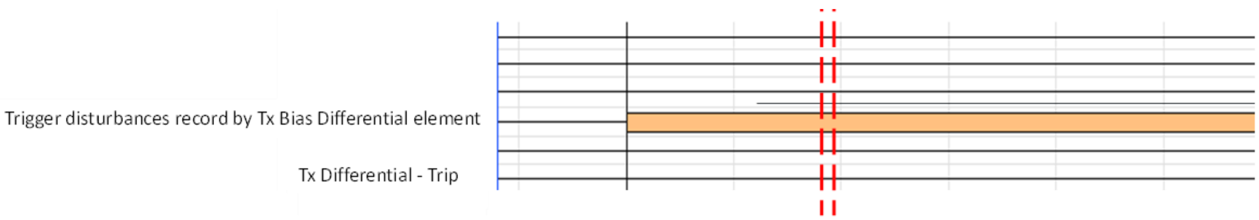
Appendix 1 – Network Diagram



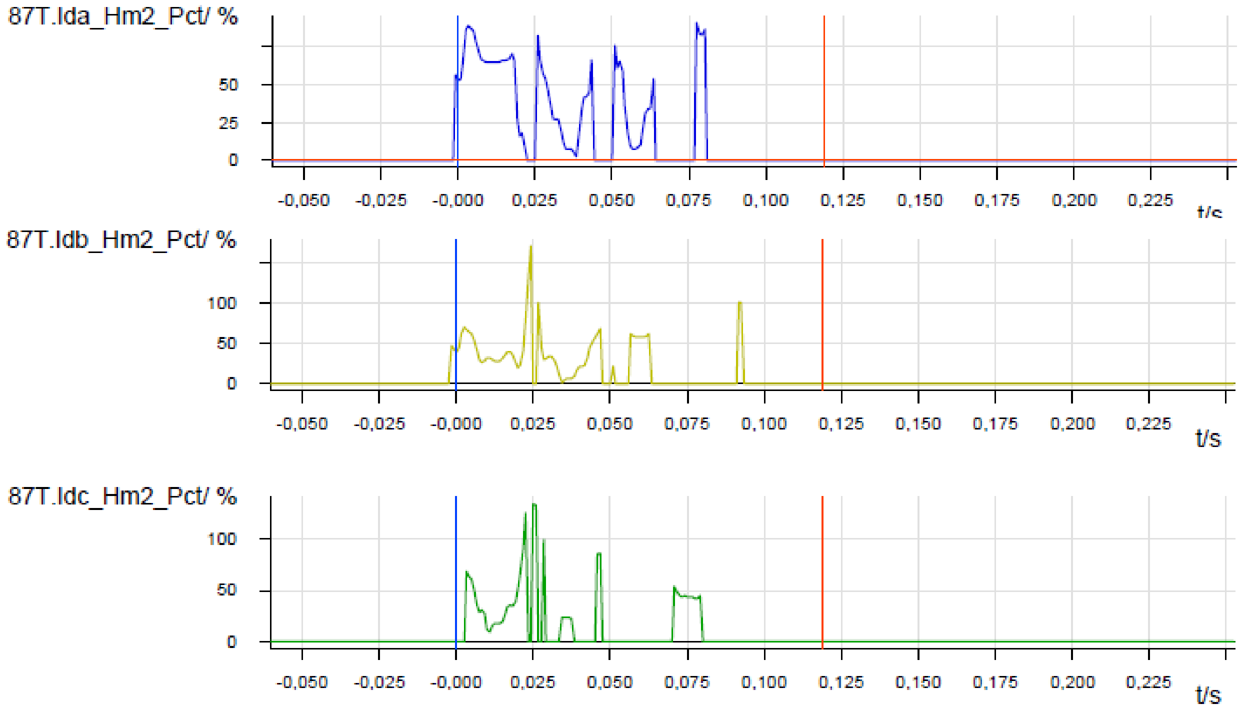
Appendix 2 – Relay Event log (Toshiba GRT100)



Appendix 3a – Relay Event log (NR electric PCS-978)



Appendix 3b – Relay disturbance record (NR electric PCS-978)



Appendix 4 – EMS Event Log

Event-Time	Substation	Event
31-05-2021 15:05:06	FNL	FNL FNL RMU 3-HYW FT H2 CB 805 OPEN BY BCSCEAS1
31-05-2021 15:05:06	HYW	HYW FNL TF H2 Main Protection OPERATED
31-05-2021 15:05:06	HYW	HYW FNL TF H2 ASI OPERATED
31-05-2021 15:05:07	FNL	FNL TX H5 ASI OPERATED
31-05-2021 15:05:07	FNL	FNL FNL RMU 3 CB 1305 OPEN
31-05-2021 15:05:07	FNL	FNL TX H5 011 CB OPEN
31-05-2021 15:05:07	FLK	FNL @FLK FNL TF H1 025 CB OPEN
31-05-2021 15:05:23	HYW	HYW FNL TF H2 Main Protection RESET

REFERENCE NO.
POS385

PROTECTION OPERATION SUMMARY

To: Director – Transmission Department

SUBSTATION / CIRCUIT

(ST6) SHE132 - SIU RMU No.3, SIU RMU No.3 - YCH 132/11kV FT H3, SIU RMU No. - ONS 132/11kV FT H3, SIU 132/11kV Tx H3

IDR NO.			DATE	TIME	CASE NO.
1284254-1			27 Jun 2022	19-24	N839

FAULT DESCRIPTION

Prior to the incident, HV VT fuse at ONS011 for Tx H3 was blown out. Planned outage TR22-1275A was scheduled for VT fuse replacement at 01:00hrs on 28 Jun 2022. At 19:24hrs on 27 Jun 2022, ONS 132/11kV Tx H3 tripped on DOCEF protection and all other ends of the RMU circuit were inter-tripped. (see Appendix 1) Supply to ONS011 Rear busbar was restored by Numerical Auto Switching (NAS) scheme.

INVESTIGATION & FINDING

Investigation revealed that the 11kV CB of ONS Tx H3 was tripped by DOC element of DOCEF protection (NR Electric type PCS-9611 4000series). The concerned relay was replaced and sent to PEB for further investigation. The analysis of EMS event log and relay record revealed that backup protection defective/out of control (BUP DEF/OOC) alarm, which was triggered by LV DOCEF VT Supply failure, activated and resumed intermittently. (See Appendix 2) It was verified that the relay detected dirty voltage with the VT fuses blown out.

From fault recorder waveform retrieved, dirty voltage signal with significant deformation in both magnitude and phase angle could be observed in L3 voltage. (See Appendix 3) Owing to the abnormality in L3 voltage, the forward region of directional element would be shifted accordingly, resulting in the operate current marginally within the forward operation region. (See Appendix 4) With load current of around 1500A and forward direction detected, the DOC element would therefore operate as designed. The relay operation was verified through simulation test by replaying the retrieved waveform on another healthy relay, with DOC element triggered. The related relay was checked healthy.

FOLLOW-UP ACTION / RECOMMENDATION

DOCEF relay should be defeated if voltage signal in dirty with significant magnitude.

DATE OF LAST CORRECT OPERATION IN THE PAST 5 YEARS	LAST MAINTENANCE DATE	SCHEDULED MAINTENANCE DATE
N/A	N/A	N/A

REMARKS

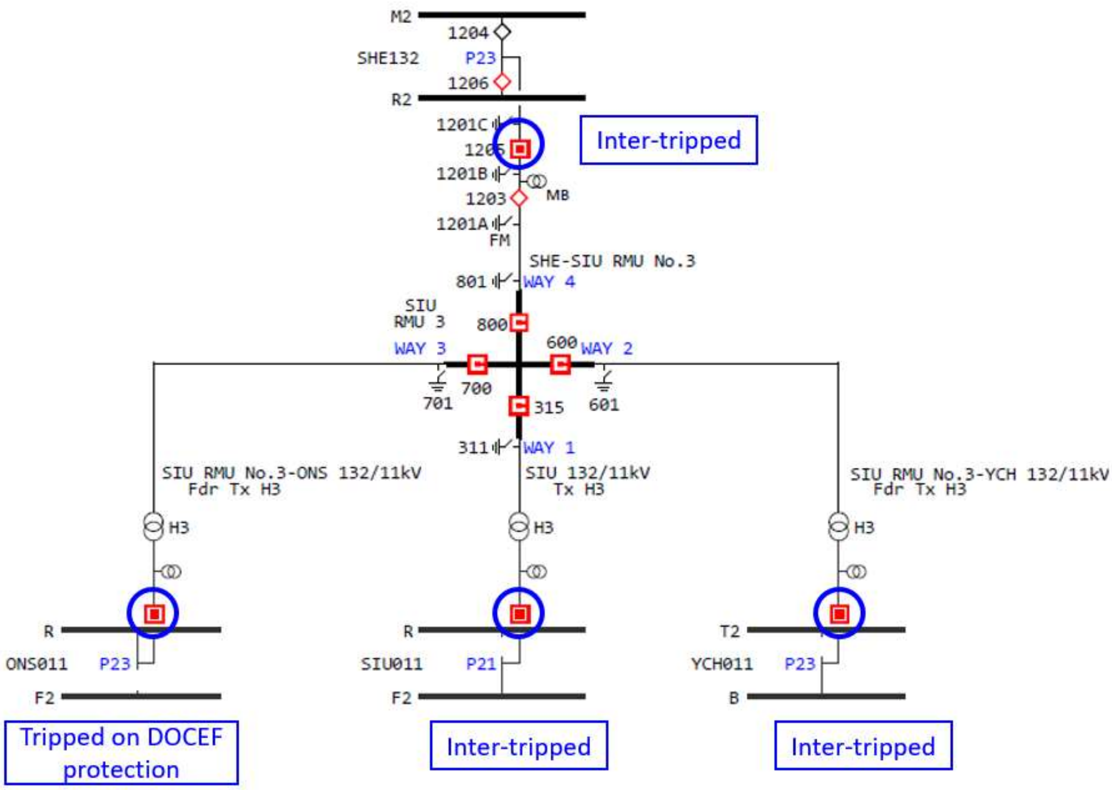
N/A

COPY TO

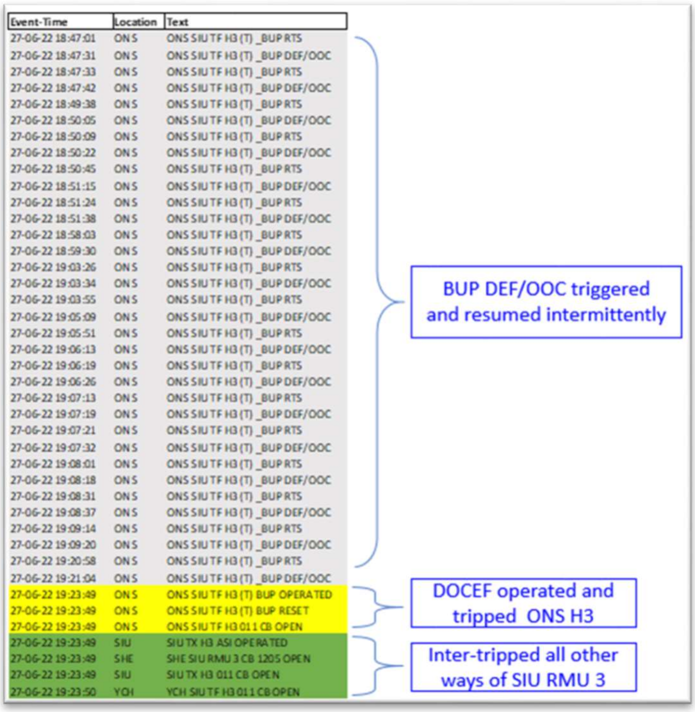
- ☑ Director - Asset Management
- ☑ Director - North Region
- ☑ Director - East & West Region
- ☑ Director - Technical Services
- ☑ Director - System Operation
- ☑ Principal Manager - Asset Utilisation (Asset Management)
- ☑ Principal Manager - Operations (East & West Region)
- ☑ Principal Manager - Operations (North Region)
- ☑ Associate Director – Plant (Transmission)
- ☑ Manager - Protection O&M (Transmission)
- ☑ HSSEQ-MS-006
- ☑ Mr Herman Man / POS File

INVESTIGATED BY	CHECKED BY	ISSUED BY & DATE
Colin Ng	PY Ng	Dickson Lau Principal Manager - Protection Engineering 5 Jul 2022

Appendix 1 – Network Diagram



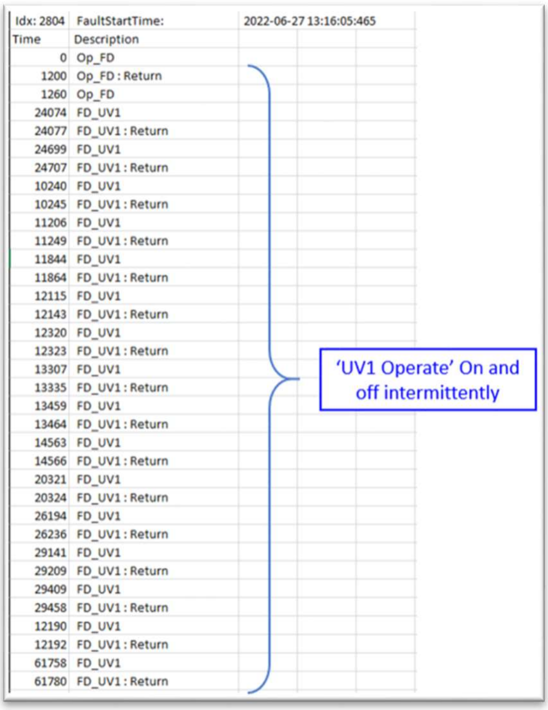
Appendix 2a – EMS event log



Event-Time	Location	Text
27-06-22 18:47:01	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 18:47:31	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 18:47:33	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 18:47:42	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 18:49:38	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 18:50:05	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 18:50:09	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 18:50:22	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 18:50:45	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 18:51:15	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 18:51:24	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 18:51:38	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 18:58:03	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 18:59:30	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:03:26	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:03:34	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:03:55	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:05:09	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:05:51	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:06:13	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:06:19	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:06:26	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:07:13	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:07:19	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:07:21	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:07:32	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:08:01	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:08:18	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:08:31	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:08:37	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:09:14	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:09:20	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:20:58	ONS	ONS SIU TF H3 (T) _BUP RTS
27-06-22 19:21:04	ONS	ONS SIU TF H3 (T) _BUP DEF/OOC
27-06-22 19:23:49	ONS	ONS SIU TF H3 (T) BUP OPERATED
27-06-22 19:23:49	ONS	ONS SIU TF H3 (T) BUP RESET
27-06-22 19:23:49	ONS	ONS SIU TF H3 011 CB OPEN
27-06-22 19:23:49	SIU	SIU TX H3 ASI OPERATED
27-06-22 19:23:49	SHE	SHE SIU RMU 3 CB 1205 OPEN
27-06-22 19:23:49	SIU	SIU TX H3 011 CB OPEN
27-06-22 19:23:50	YCH	YCH SIU TF H3 011 CB OPEN

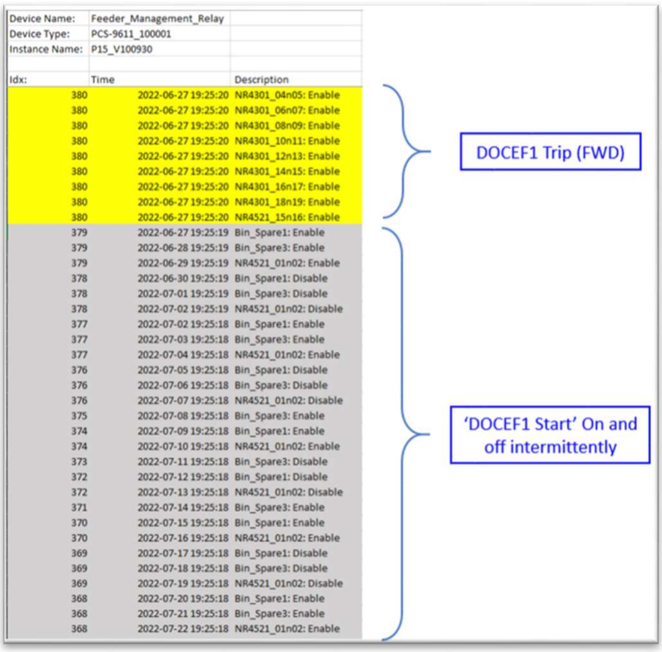
EMS event log at ONS, SIU, YCH and SHE

Appendix 2b – Relay record (NR Electric PCS9611 4000series)



Idx: 2804	FaultStartTime:	2022-06-27 13:16:05:465
Time	Description	
0	Op_FD	
1200	Op_FD : Return	
1260	Op_FD	
24074	FD_UV1	
24077	FD_UV1 : Return	
24699	FD_UV1	
24707	FD_UV1 : Return	
10240	FD_UV1	
10245	FD_UV1 : Return	
11206	FD_UV1	
11249	FD_UV1 : Return	
11844	FD_UV1	
11864	FD_UV1 : Return	
12115	FD_UV1	
12143	FD_UV1 : Return	
12320	FD_UV1	
12323	FD_UV1 : Return	
13307	FD_UV1	
13335	FD_UV1 : Return	
13459	FD_UV1	
13464	FD_UV1 : Return	
14563	FD_UV1	
14566	FD_UV1 : Return	
20321	FD_UV1	
20324	FD_UV1 : Return	
26194	FD_UV1	
26236	FD_UV1 : Return	
29141	FD_UV1	
29209	FD_UV1 : Return	
29409	FD_UV1	
29458	FD_UV1 : Return	
12190	FD_UV1	
12192	FD_UV1 : Return	
61758	FD_UV1	
61780	FD_UV1 : Return	

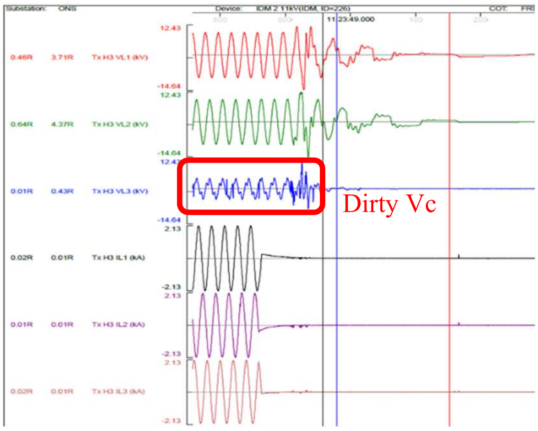
Relay Fault Record

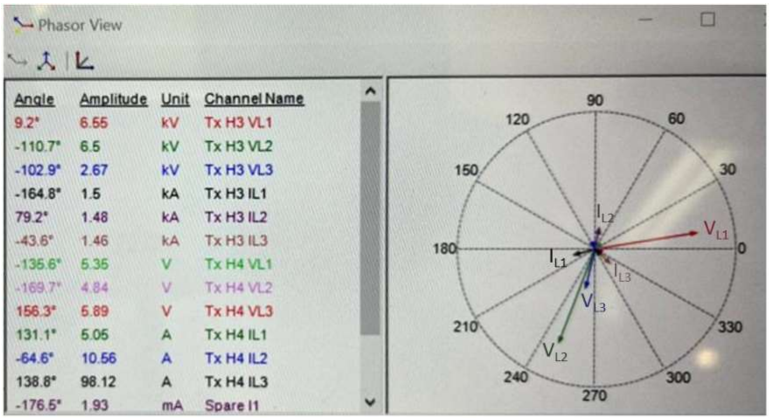


Device Name:	Feeder_Management_Relay	
Device Type:	PCS-9611_100001	
Instance Name:	P15_V100930	
Idx:	Time	Description
380	2022-06-27 19:25:20	NR4301_04n05: Enable
380	2022-06-27 19:25:20	NR4301_06n07: Enable
380	2022-06-27 19:25:20	NR4301_08n09: Enable
380	2022-06-27 19:25:20	NR4301_10n11: Enable
380	2022-06-27 19:25:20	NR4301_12n13: Enable
380	2022-06-27 19:25:20	NR4301_14n15: Enable
380	2022-06-27 19:25:20	NR4301_16n17: Enable
380	2022-06-27 19:25:20	NR4301_18n19: Enable
380	2022-06-27 19:25:20	NR4521_15n16: Enable
379	2022-06-27 19:25:19	Bin_Spare1: Enable
379	2022-06-28 19:25:19	Bin_Spare3: Enable
379	2022-06-29 19:25:19	NR4521_01n02: Enable
378	2022-06-30 19:25:19	Bin_Spare1: Disable
378	2022-07-01 19:25:19	Bin_Spare3: Disable
378	2022-07-02 19:25:19	NR4521_01n02: Disable
377	2022-07-02 19:25:18	Bin_Spare1: Enable
377	2022-07-03 19:25:18	Bin_Spare3: Enable
377	2022-07-04 19:25:18	NR4521_01n02: Enable
376	2022-07-05 19:25:18	Bin_Spare1: Disable
376	2022-07-06 19:25:18	Bin_Spare3: Disable
376	2022-07-07 19:25:18	NR4521_01n02: Disable
375	2022-07-08 19:25:18	Bin_Spare3: Enable
374	2022-07-09 19:25:18	Bin_Spare1: Enable
374	2022-07-10 19:25:18	NR4521_01n02: Enable
373	2022-07-11 19:25:18	Bin_Spare3: Disable
372	2022-07-12 19:25:18	Bin_Spare1: Disable
372	2022-07-13 19:25:18	NR4521_01n02: Disable
371	2022-07-14 19:25:18	Bin_Spare3: Enable
370	2022-07-15 19:25:18	Bin_Spare1: Enable
370	2022-07-16 19:25:18	NR4521_01n02: Enable
369	2022-07-17 19:25:18	Bin_Spare1: Disable
369	2022-07-18 19:25:18	Bin_Spare3: Disable
369	2022-07-19 19:25:18	NR4521_01n02: Disable
368	2022-07-20 19:25:18	Bin_Spare1: Enable
368	2022-07-21 19:25:18	Bin_Spare3: Enable
368	2022-07-22 19:25:18	NR4521_01n02: Enable

Relay Input/Output Change Record

Appendix 3 – Dirty Vc voltage signal recorded by fault recorder

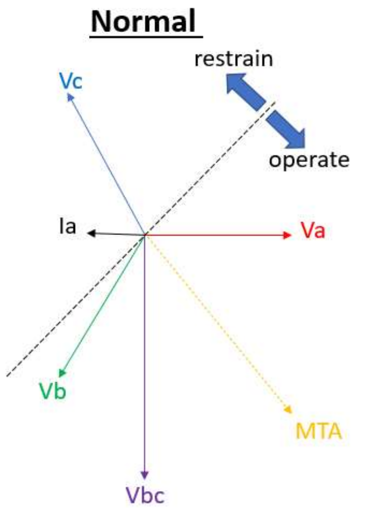




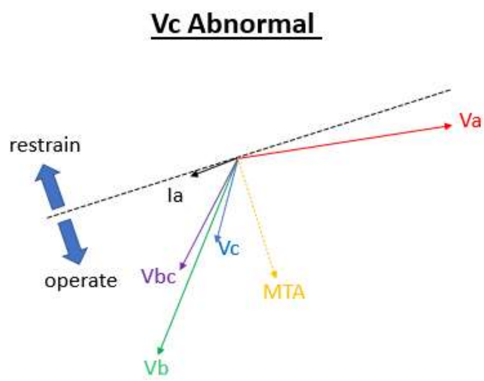
Phasor View

Angle	Amplitude	Unit	Channel Name
9.2°	6.55	kV	Tx H3 VL1
-110.7°	6.5	kV	Tx H3 VL2
-102.9°	2.67	kV	Tx H3 VL3
-164.8°	1.5	kA	Tx H3 IL1
79.2°	1.48	kA	Tx H3 IL2
-43.6°	1.46	kA	Tx H3 IL3
-135.6°	5.35	V	Tx H4 VL1
-169.7°	4.84	V	Tx H4 VL2
156.3°	5.89	V	Tx H4 VL3
131.1°	5.05	A	Tx H4 IL1
-64.6°	10.56	A	Tx H4 IL2
138.8°	98.12	A	Tx H4 IL3
-176.5°	1.93	mA	Spare I1

Appendix 4 – Directional OCEF operation zone under normal condition and abnormal Vc voltage



I_a in restrain region.
Remain stable under normal condition



I_a marginally in operate region.
Operate under abnormal L3 voltage

GE

Grid Solutions

MFAC

High Impedance Differential Relay

MFAC relays provide high speed differential protection for various types of power systems plants including generators, reactors, busbars, motors and the individual windings of power transformers.

Application

When circulating current protection schemes are subjected to through faults, the sudden and often asymmetrical growth in the system current can cause the line current transformers to reach saturation. In this condition, variation in transformer magnetising characteristics can cause large ratio errors with a consequent circuit imbalance and maloperation of the protective relays.

To ensure stability, it is common practice to employ high impedance relays set to operate at a slightly higher voltage than that developed in the worst theoretical case of this condition for a given through fault current. On a balanced earth fault system for example, this is when one current transformer of a group is saturated whilst the others remain unaffected. The saturated transformer presents a low impedance path in parallel with the relay and limits the voltage applied. On internal faults this limitation does not exist and voltages of twice the setting are easily reached.

Description

The relay measuring element is an attracted armature unit of simple and robust construction, supplied from a bridge rectifier. Settings are determined by a series of resistors, selected on a seven-way plug bridge. Relays with a fine control facility have an additional plug bridge, which is calibrated in intermediate settings. An overall setting is obtained by adding together each plug bridge reading. A capacitor is connected in series with the operating coil to make the relay insensitive to the DC component of fault current. The setting voltage can thus be calculated in terms of RMS alternating quantities, without regard for the degree of offset produced by the point on wave at which the fault occurs. A reactor connected in series with the capacitor forms a resonant circuit tuned to the relay rated frequency.

MFAC Types

- Type MFAC 14, is applied when protection is required for earth faults only. Applications for protecting power transformer windings are shown in Fig. 1
- The three element version, Type MFAC 34, provides both phase and earth fault protection. A typical application for generator protection is shown in Fig. 2.
- An external Metrosil unit having a non-linear resistance characteristic is recommended for each relay element, to limit the peak voltage appearing across the secondary differential circuits under internal fault conditions.

Key Benefits

- High speed operation
- Wide range of settings
- Simple application technique
- High stability for through faults
- Compact robust design

Imagination at work

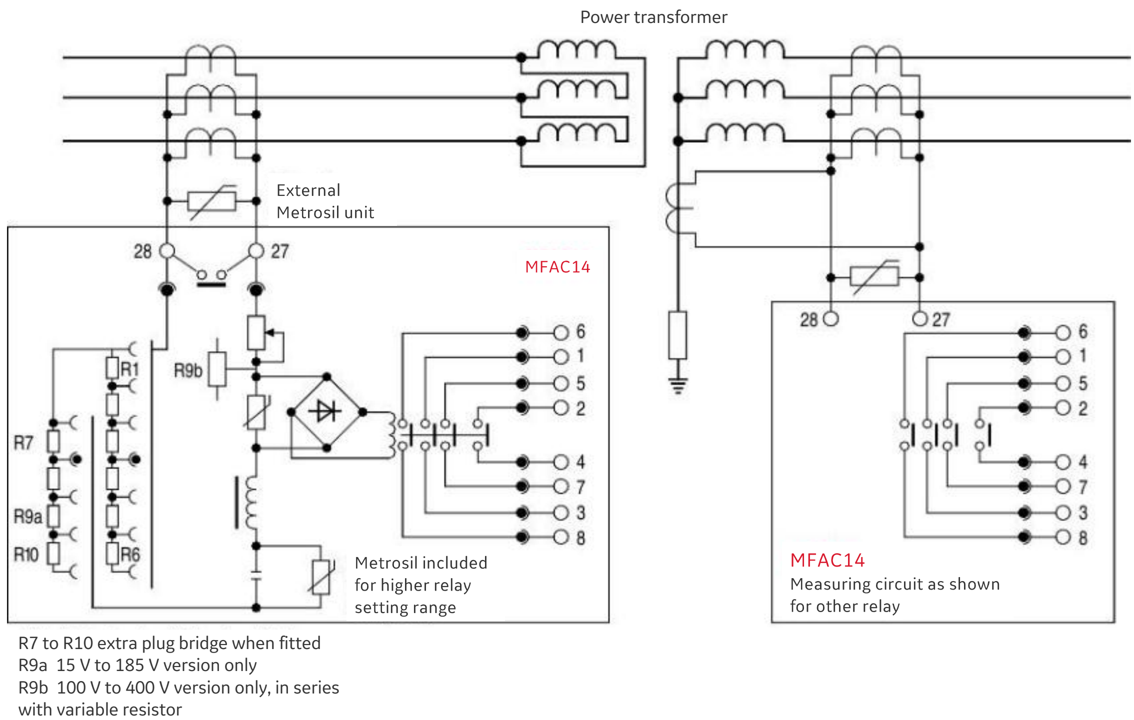


Figure 1 Type MFAC 14 relays applied to restricted earth fault protection of power transformer windings

External Metrosil Units

Single element or three element Metrosil units are provided with single element or three element relays respectively. The type of Metrosil characteristic differs for each of the alternative relay setting ranges.
The nominal characteristic for a Metrosil unit is conventionally of the form V = CIß, specified in DC quantities for convenience in some applications and also to facilitate testing during manufacturing.

The constant (C) and the index (ß) are nominally fixed for a particular Metrosil design. Hence, when a sinusoidal voltage is applied across the Metrosil, the rms current drawn by the Metrosil is given by:

$$I_{(rms)} = 0.52 \left(\frac{V2V1}{C}\right)^{1/\beta}$$

V1 = voltage (V, rms sinusoidal)
This approximates the circuit conditions at the voltage setting. Details of the alternative Metrosil designs used with MFAC relays are given in the Technical Data section.

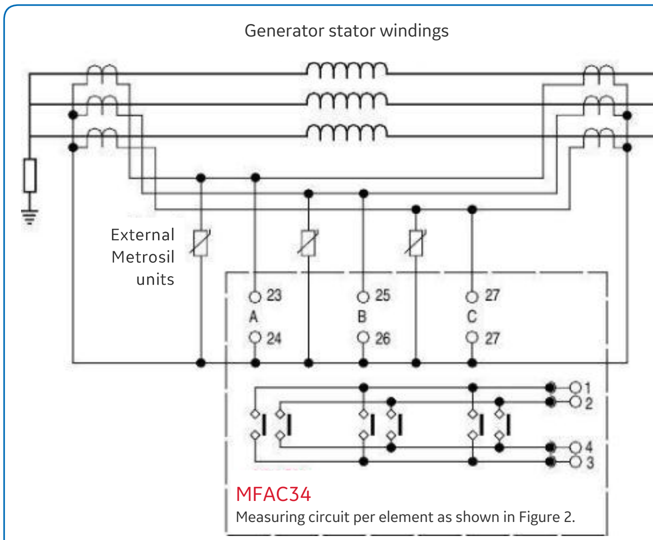


Figure 2 Type MFAC 34 relay applied to phase and earth fault protection of a generator

Reliable and secure high impedance unit protection

Technical Data

Rated frequency

50/60 Hz

Operating time

The operating time characteristics are shown in Figures 3 & 4

Operating current

Setting range	Setting selections	Nominal operating current for relay alone:
15 to 185 V	35 equal 5 V steps	38 m A at setting
25 to 175 V	7 equal 25 V steps	19 m A at setting
25 to 325 V	7 equal 50 V steps	19 m A at setting
100 to 400 V	7 equal 50 V steps	19 m A at setting

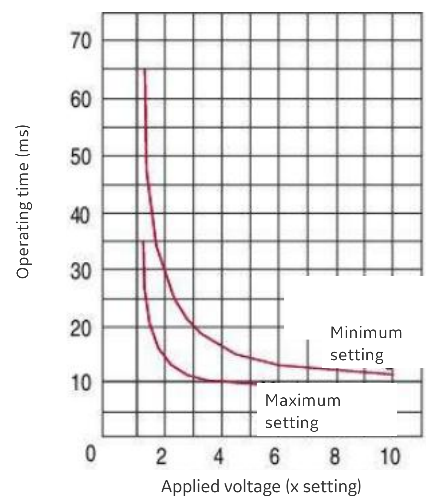


Figure 3: Typical time operating characteristics

Metrosil Characteristics

Standard with a single 152.4 mm disc per element (maximum secondary internal fault current <50 A [rms])

Relay Setting Range	Nominal Characteristics	
	C	
15 V to 185 V	450	0.25
25 V to 175 V	450	0.25
25 V to 325 V	900	0.25
100 V to 400 V	1100	0.25

Each characteristic is shown graphically in detail in Figure 5.

Contacts

Four pairs of make self-resetting contacts are provided on single element relays and two on three element relays. In three element relays the contacts are connected in parallel, as shown in Figure 2, or brought to separate case terminals if required.

Contact Ratings

Make and carry -	AC 1250 VA with maxima of 5 A continously and 660 V DC 1250 W with maxima of 5 A and 660 V
Make and carry for 3 seconds	AC 7500 VA with maxima of 30 A and 660 V DC 7500 W with maxima of 30 A and 660 V
Break -	AC 1250 VA with maxima of 5 A and 660 V DC 100 W (resistive) 50 W (inductive) with maxima of 5 A and 660 V

Durability

Load contact 10,000 operations minimum
Unloaded contact 100,000 operation minimum

Operation Indicator

A hand reset operation indicator is fitted to each element as standard.

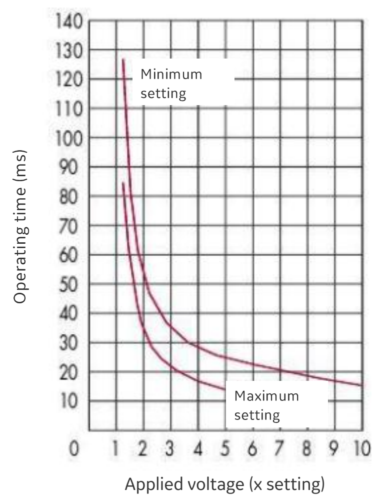


Figure 4 Typical time operating characteristics for 15-185 V relays only

Current Transformer Requirements

Type MFAC relays are suitable for use with 0.5 A, 1 A and 5 A current transformers, at 50 Hz or 60 Hz. Since selection of the optimum relay setting is based on the loop resistance of the secondary circuit, there are advantages in using current transformers with either of the lower secondary ratings. The current transformers used in high impedance circulating current differential protection systems must have equal turns ratios and have reasonably low secondary winding resistance. The knee-point voltage is defined as the point on the magnetisation curve at which a 10% increase in excitation voltage produces a 50% increase in excitation current. For use with type MFAC relays, the knee-point voltage (Vk) should be at least twice the voltage setting, thus Vk = 2 Vs actual.

Selection of Optimum Relay Setting

The required voltage setting (Vs) is calculated using the formula:

$Vs = \frac{I_f (R_{ct} + 2R_W)}{n}$ volts

where

I_f = maximum primary through fault current for which stability is required (A rms)

n = current transformer turns ratio

R_{ct} = current transformer secondary winding resistance (Ω)

R_W = resistance of each lead between the relay and current transformer (Ω)

A value of Vs is calculated for each current transformer circuit in the differential system, and the relay setting finally chosen (Vs actual) is made equal to, or nearest above the highest of these calculated values.

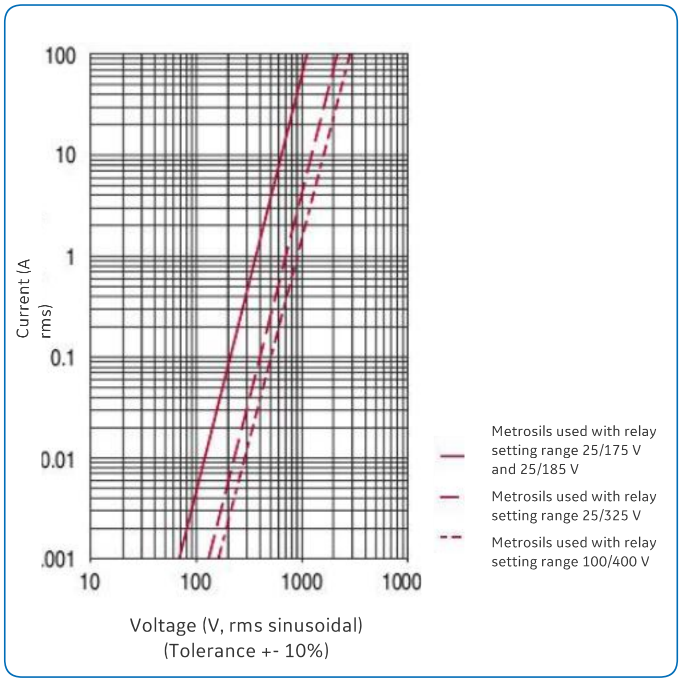


Figure 5 Nominal and extreme AC characteristics of external Metrosils for use with MFAC relays

Effective Primary Operating Current

During internal fault conditions, the relay and Metrosil current and the magnetizing current of all connected current transformers is supplied from the fault current. The primary operating current is given by:

$$I_{op} = n (I_R + NI_m)$$

where

I_R = relay operating current and Metrosil current at setting voltage, as given in the table below

I_m = current transformer magnetizing current at setting voltage (A)

N = number of connected current transformers

n = current transformer turns ratio

Setting Range

Setting range (V)		15	50	75	100	125	150	175	185
I_R	Nominal (mA)	38	38	39	42	46	55	72	81
	Limits (mA)	37 - 39	37 - 39	37 - 42	38 - 47	39 - 58	43 - 79	52 - 114	62 - 125
Setting range (V)		25	50	75	100	125	150	175	
I_R	Nominal (mA)	19	19	20	23	27	36	53	
	Limits (mA)	18 - 20	18 - 20	18 - 23	19 - 28	20 - 39	24 - 60	33 - 95	
Setting range (V)		25	75	125	175	225	275	325	
I_R	Nominal (mA)	19	19	20	22	24	31	44	
	Limits (mA)	18 - 20	18 - 20	18 - 22	19 - 25	19 - 33	22 - 48	28 - 76	
Main setting range (V)		100	150	200	250	300	350	400	
I_R	Nominal (mA)	19	19	20	20	23	27	36	
	Limits (mA)	18 - 20	18 - 20	18 - 23	18 - 23	19 - 28	20 - 39	24 - 60	

Should the natural effective operating current after applying the above formula be lower than designed, it can be raised to the required level by adding a shunt resistor across the differential relay input circuit.

Reyrolle Protection

TYPES 4C21 & 4C21/BC Duo-bias High-Speed Differential Transformer Protection

SECTION 6

March 1984

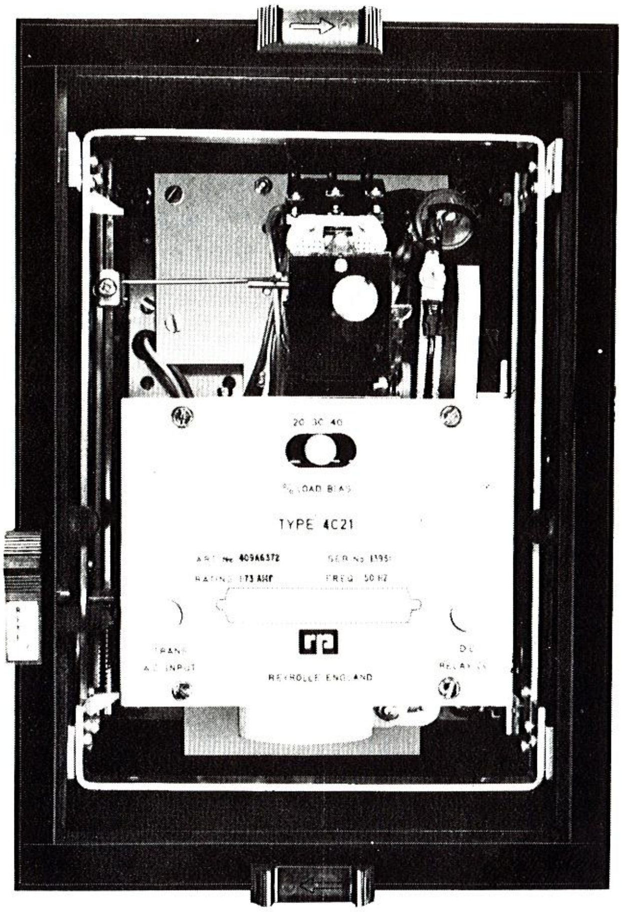
APPLICATION

The protection of two winding and three winding power transformers.

Duo-bias differential transformer-protection is basically a conventional current-balance system employing current-transformers on the high-voltage and low-voltage sides of the power transformer. The C.T. ratios and connections are such that current circulates between the secondary windings under load or through-fault conditions, whilst under internal-fault conditions, the secondary equivalent of the fault current flows in the relay-operating circuits. However, the inherent characteristics of power-transformers introduce the following complications:

1. When a power-transformer is energised the magnetising-current surge produces an out-of-balance current in the relay-operating circuit.
2. The majority of large power-transformers are equipped with tap changers, but voltage-transformation ratios can only be matched by the C.T. ratios at one tap-position. At the other tap positions, the C.T. secondary currents will not balance and out-of-balance currents flow in the relay-operating circuits.
3. Differences in the design characteristics of the C.T.'s on the high-voltage and low-voltage sides of a power-transformer are often unavoidable.

The effect of magnetising inrush-current is eliminated by means of a harmonic bias-unit which selects the second-harmonic component of this current and uses it to restrain the relay during the surge period. Fig. 1 shows a typical magnetising-current surge. The asymmetrical



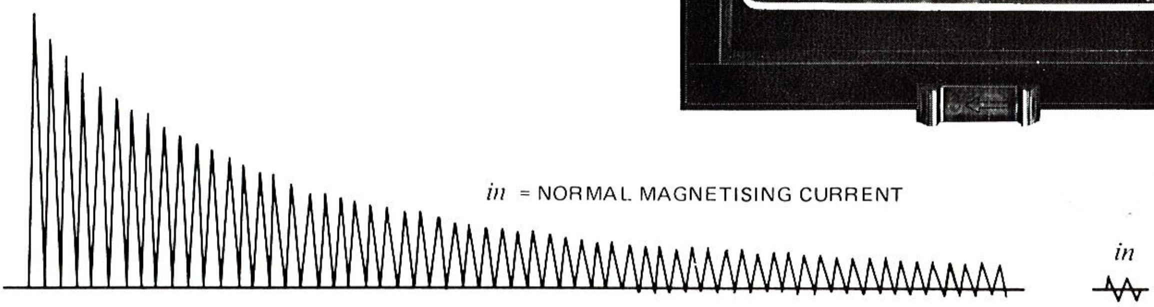


Fig. 1. Typical Magnetising Current when switching in a power transformer at instant E = O.

wave-form indicates that the inrush current contains large even-harmonics of which the second is predominant.

The out-of-balance current produced by tap-changing or C.T. mismatch is catered for by means of a percentage-bias feature. This causes the current required for relay-operation to increase in direct proportion to the load or through-fault current passing through the power-transformer, thus ensuring that the current required for relay operation is always greater than the out-of-balance current under through-fault conditions.

Although the Duo-bias relay has been so designed that a high-set element is unnecessary, a separately mounted three pole type BC overcurrent relay can be provided, to meet the requirements of engineers who have a preference for a high speed back-up feature.

OPERATION

NORMAL/THROUGH-FAULT CONDITIONS

The type 4C21 relay is illustrated schematically in Fig. 2. Under normal load or through-fault conditions the line C.T. secondary-currents circulate through the primary winding of the bias transformer, the rectified output of which is applied to the bias-windings of the transductor via the shunt resistor. Out-of-balance current flows from the centre tap on the primary winding of the bias transformer energising the transductor input-winding and the harmonic-bias unit.

The input and output windings of the transductor are inductively linked but minimum induction between these and the bias-windings is arranged by the physical build up of the two cores and the disposition and direction of the two halves of the bias-winding.

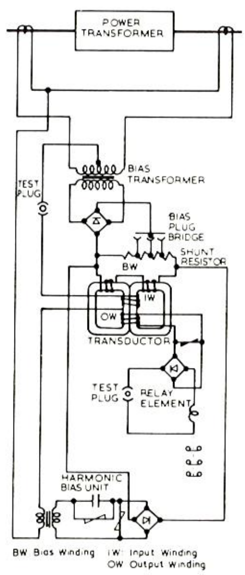


Fig. 2. Type 4C21 Relay: Single-phase Diagram.

As long as the power-transformer is healthy, the transductor bias-winding is energised by full-wave rectified-current which is proportional to the load or through-fault current; this bias-current saturates the transductor. Out-of-balance currents in the transductor input-winding, produced by power-transformer tap-changing or by current-transformer mismatch, superimpose an alternating m.m.f. upon the d.c.-bias m.m.f., as illustrated by fig. 3. The resulting

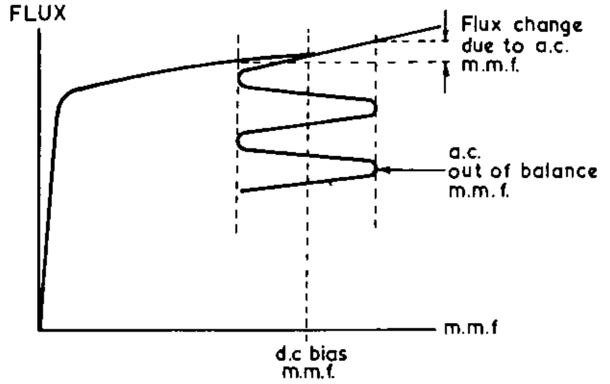


Fig. 3. Fluxes due to operating and biasing ampere-turns.

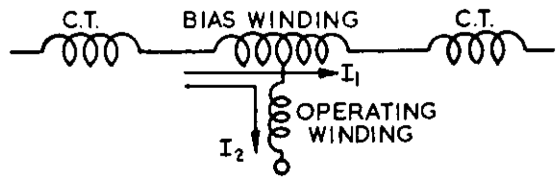
change in working flux-density is small and consequently the output to the relay is negligible. The shunt-resistor tappings enable adjustment of the relationship between the bias-transformer primary-current and the input to the transductor bias-winding. This resistor also serves to suppress any ripple content which may be present in the bias-m.m.f.

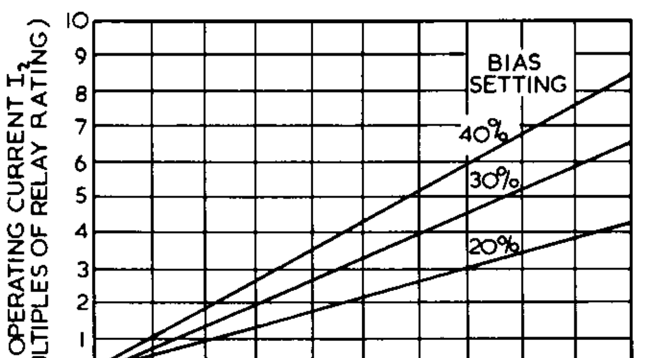
Note:—In addition to the principal components so far described, fig. 2 also shows voltage-limiters (non-linear resistors) which are connected across various components in order to safeguard them against possible over-voltages. Test plugs are provided in the transductor input and output circuits and, together with the plug for bias-slope adjustment, facilitate measurement of the operating, bias, and relay-element currents during installation and routine tests.

INTERNAL FAULT CONDITIONS

If the power-transformer develops a fault, the operating m.m.f. produced by the secondary fault-current in the transductor input-winding exceeds the bias-m.m.f., resulting in a large change in working flux-density. This produces a correspondingly large voltage across the relay-winding; the resultant current operates the relay.

Relay-operation cannot occur unless the operating-m.m.f. exceeds the bias-m.m.f.; and as the bias-m.m.f. is proportional to the load or through-fault current, the required operating-m.m.f. — and hence the required operating-current — is also proportional to the load or through-fault current. Fig. 4 shows the operating characteristics of





NOTE: The bias current I_1 is the component of current which circulates around the balancing loop between the current transformers.
The operating current I_2 is the out-of-balance component which flows in the operating winding.

Fig. 4. Bias characteristics of type 4C21 Relay.

the relay with the 20%, 30%, and 40% percentage-bias slopes corresponding to the 20%, 30% and 40% shunt-resistor tappings.

FAULT-SETTING

Transformer differential-relays generally have a basic setting which is the 'reflected' fault-current required for operation with no through-current in the differential system and internal fault-current fed from only one set of current-transformers. The actual value of fault-current at which a differential relay will operate is thus the basic-setting value under no-load conditions, but when load-current is flowing the setting will be higher, depending on the value of the load and the bias-setting in use. With an internal earth-fault in which the current is limited by a neutral-earthing resistor, the load-current may be little affected by the fault, therefore when considering such a condition, the effect of load-current on the setting should be taken into account. Thus, assuming a 30% bias-setting, the curves of fig. 4 show that a relay with a basic setting of 20% would operate at about 50% of the rated current at full load. As the value of bias used has a major effect on the setting there is little or no virtue in using a lower basic setting than 20%. For example, a 10% basic setting would only reduce the actual fault-setting from 50% to 40% but may result in a disproportionate reduction in magnetising-current stability which may give rise to instability under conditions of system overvoltage. Thus a basic fault-setting of 20% has been chosen.

MAGNETISING-INRUSH CONDITIONS

The harmonic-bias unit is a simple tuned-circuit which responds to the the second-harmonic component of the magnetising current. When magnetising inrush-current flows through the relay-operating circuit, the rectified output of the harmonic-bias unit is injected into the transductor bias-winding and restrains the relay.

An exhaustive series of laboratory and site tests have been made to verify that the relay will remain inoperative under magnetising-inrush conditions. The results of these tests indicate that the relay is completely stable with magnetising-inrush currents of up to 30-times the C.T. rating.

In addition, a further series of tests have been made with the object of confirming that the relay is capable of differentiating between the harmonic content of a magnetising surge and the harmonics present in the output current of a heavily-saturated C.T. under internal-fault conditions. Relays provided with harmonic restraint are often equipped with a separate high-set unbiased element as the biased element cannot differentiate between these quantities and may therefore fail to operate on a heavy internal fault. This however, does not apply to the Duo-bias relay. To illustrate this, data from a test-series is shown in fig. 5; fig. 5 illustrates the test circuit adopted and fig. 5a the relay operating-time which displays a tendency to

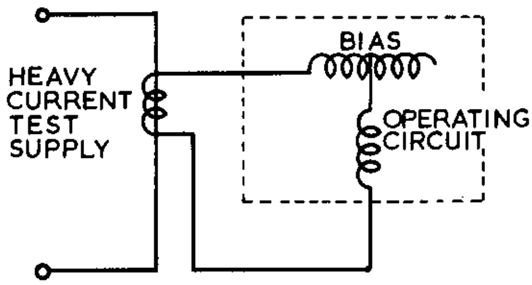


Fig. 5 Operation of Heavy Internal Faults.

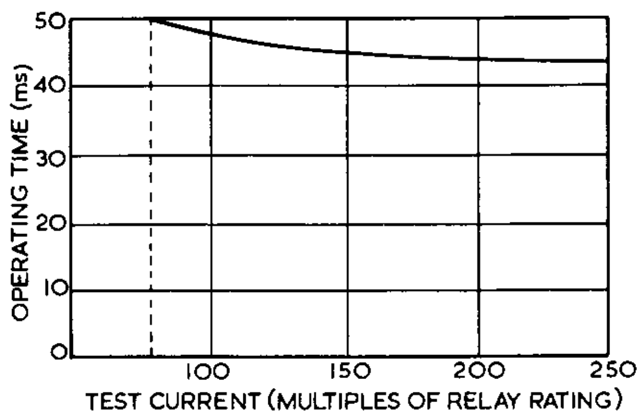


Fig. 5a. Relay Operating Time.

decrease as fault-current is increased, even though the C.T. is driven far beyond its saturation voltage.

When provided the operating coil of the type BC high-set element must be connected in the Duo-bias relay operating circuit. The time/current characteristic of the type-BC high-set element is illustrated by fig. 7 with the time/current characteristic of the type 4C21 Duo-bias relay at low values of fault current.

APPLICATION TO TWO-WINDING AND THREE-WINDING TRANSFORMERS

The relays applied to three-winding power-transformers (fig. 6a) are similar to those applied to two-winding power-transformers (fig. 6b) the exception being a change of tapping on the primary

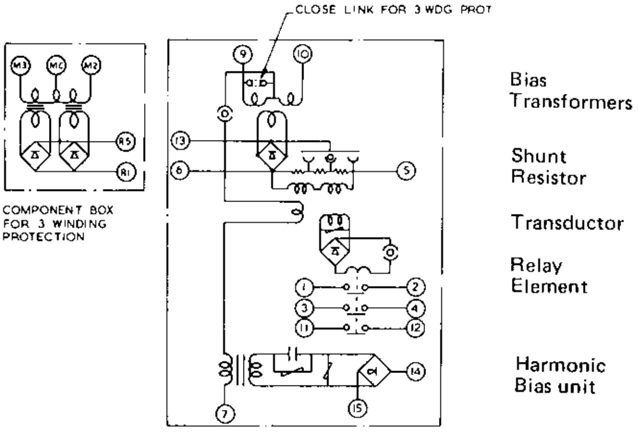


Fig. 6. Typical 4C21 Relay Schematic.

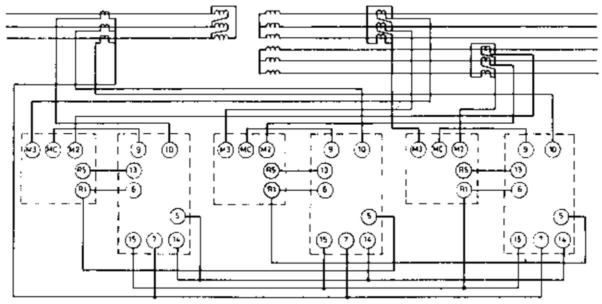


Fig. 6a. Type 4C21 Relays applied to three-winding transformer.

winding of the bias-transformer. The three-winding power-transformer also requires an additional, separately-mounted component box containing two bias-transformers and their associated rectifiers, one component box is connected to each Duo-bias relay. There is, therefore, a separate bias-transformer for each phase of each group of C.T.'s. As illustrated by fig. 6, the summated rectified outputs of all three bias-transformers are fed through the transductor bias-windings so that the relay is biased by the total current flowing in the power-transformer, regardless of its distribution between the windings.

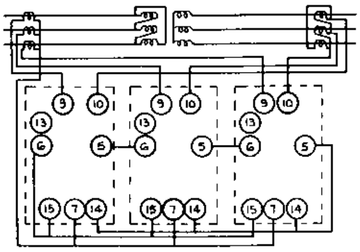


Fig. 6b. Type 4C21 Relays applied to two-winding transformer.

RATING

1.0, 1.73, 5.0A.

The ratio of the primary ratings of the current-transformers on each side of the power-transformer should be as near as possible to the ratio of the power-transformer when on the centre-tap position in order to give the minimum tap-change unbalance. When earth-fault protection is associated with Duo-bias differential protection, the ratios of the C.T.'s are of less significance, as any deviation from the correct ratios can be compensated for in the ratios of the auxiliary interposing transformers – see figs. 10 and 11.

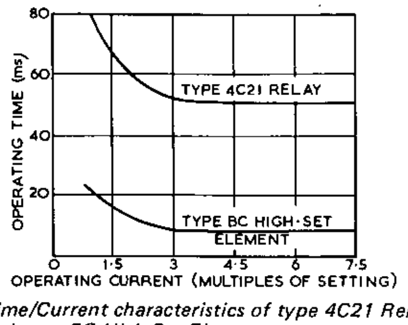


Fig. 7. Time/Current characteristics of type 4C21 Relay and type-BC High-Set Element.

SETTINGS

Duo-bias:	Nominal 20%.
Type BC High Set Element: (when required)	400% to 800% or 800% to 1600%; the range required is selected by plug bridge and is continuously variable by calibrated cam.
STABILITY	Under through-fault conditions, the protection is stable with fault-current equivalent to 25 times the C.T. rating and with tap-change unbalance of 10% to 20% according to the bias-tapping in use.

BURDEN

Duo-bias:	At rated load current: 0.1VA per phase. 3 phase int. fault current: 1.0VA per phase. (1 x full load).
High-Set Element:	1–2VA per phase over setting range.

CONTACT ARRANGEMENT

Duo-bias relay repeat element – 3 make, self-reset.

High-Set element – 2 make, self-reset.

CONTACT RATING

Each contact is capable of making and carrying a burden of 6.6kVA with a maximum current of 30A for 0.2 second.

INDICATION

Hand-reset flag.

CASES

Case type:

Size 3 (Horizontal) Vedette (1 relay per set)
Size 1 Vedette (3 relays per set)

Type BC High-set Elements:

Size $^2/_3$ Vedette

For dimensions see Cases Leaflet

When applied to 3-phase three winding transformers, three additional component boxes are required. These are normally back-of panel mounted and designed to fit closely together in order to economise in panel space, dimensions below:–

Component Box

Length	276.2mm ($10\frac{7}{8}$")	Width:	76.2mm (3")	Height:	117.5mm ($4\frac{5}{8}$")

C.T. REQUIREMENTS

The criteria to determine the C.T. ratios and connections applicable are listed in the appendix.

All C.T.'s associated with a Duo-bias installation should be of the low-reactance type as defined in B.S. 3938. In addition, the knee-point voltage should be equal to, or, exceed twice the maximum steady-state working voltage under any through-fault condition. To assess the steady-state working voltage the impedance of the Duo-bias relays are ignored and only the C.T. winding and interconnecting lead resistances are considered. For example, referring to fig. 6b.

- Let I = Maximum through-fault current referred to the secondary winding of the star-connected C.T.'s with a three-phase system fault.
- Let A = Secondary-winding resistance of each star-connected C.T.
- Let B = Secondary-winding resistance of each delta-connected C.T.
- Let C = Resistance of each lead between the star-connected C.T. terminals and the relay terminals.
- Let D = Resistance of each lead between the delta-connected C.T. terminals and the relay terminals.

Then the knee-point voltage of the star-connected C.T.'s should equal or exceed:

$$2I(A + C)$$

and the knee-point voltage of the delta-connected C.T.'s should equal or exceed: $\frac{2I}{\sqrt{3}}(B + 3D)$

The above information provides a general guide to the points which should be regarded when considering C.T. requirements. However, a wide range of power-transformer connections and C.T. configurations are in common use, all of which cannot be covered in the scope of this publication.

BIAS-SLOPES AND TAP-CHANGING RANGE

The relay is equipped with a bias-adjustment to give 20%, 30% and 40% bias-slopes. Using the 20% bias-tapping the relay is applicable to a power-transformer with a tap-changing range of ± 10%. Using the 30% and 40% bias-tappings the permissable tap-changing ranges are ± 15% and ± 20% respectively.

INFORMATION REQUIRED WHEN ORDERING

Rating.

Whether two or three-winding application.

System frequency.

Case reference.

APPENDIX: EARTH-FAULT PROTECTION

Where a power-transformer is resistance-earthed, the current available on an internal earth-fault for operation of a differential protection may be relatively low and the percentage of the winding protected against earth-faults may be inadequate. This is a fundamental point and applies to all differential protections. In these circumstances it may be necessary to add some separate form of earth-fault protection.

Consider the delta/star-connected transformer illustrated by fig. 8, in which the star-winding is earthed through a resistor. Assume a fault occurs at point F, p% from the neutral side of the winding and that the neutral-earthing resistor is rated to pass the full-load current of the star-winding, with a terminal fault. If the fault is fed from the delta side of the transformer then the current in the primary winding of the faulty phase is:

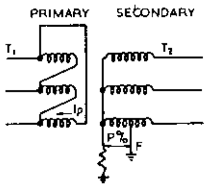


Fig. 8. Earth-fault in Power Transformer Winding.

$$Ip = \frac{p}{100} \times T_2 \times \frac{1}{T_1} \times \frac{p}{100} \times \text{(Full-load secondary current)}$$

$$\text{Since (Full-load secondary current)} = \frac{T_1}{T_2} \times \frac{1}{\sqrt{3}} \times \text{(Full-load primary current)}$$

$$Ip = \frac{p^2}{100} \times \frac{1}{\sqrt{3}} \times \text{(Full-load primary current)}$$

On the other hand a restricted-earth-fault relay on the star-winding would be energised by the fault-current passing through the earthing resistor via a neutral C.T., that is, by

$$\frac{p}{100} \times \text{(Full-load secondary current)}$$

Using the given expressions, the percentages of winding protected can be plotted graphically against the fault-setting, as shown in fig. 9. This demonstrates that a restricted earth-fault relay is a much more efficient device for the detection of winding earth-faults than a differential relay; and in addition, to cover a reasonable percentage of the winding, the latter would need to be extremely sensitive. This however, is impracticable because of the limitations imposed by out-of-balance current due to tap-changing C.T. mismatch and power-transformer magnetisation.

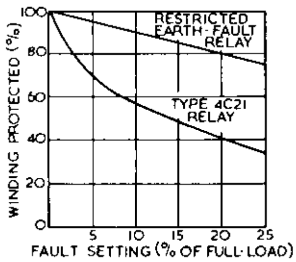


Fig. 9. Percentage of Transformer Winding protected against Earth-faults.

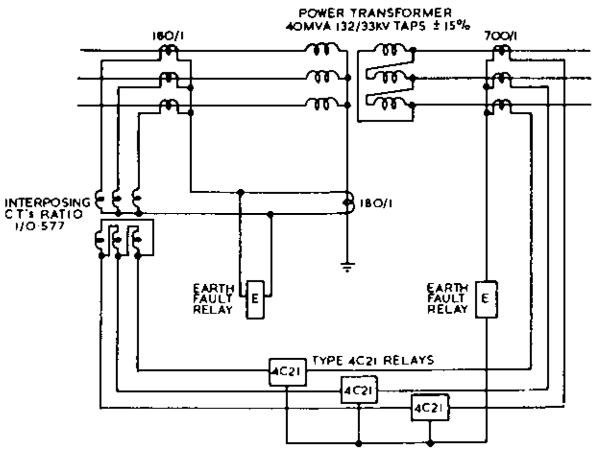


Fig. 10 Typical arrangement of Differential Protection with supplementary Earth-fault Protection.

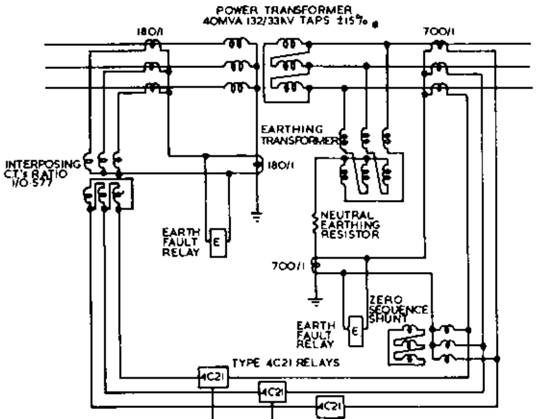


Fig. 11. Typical arrangement of Differential Protection with supplementary Earth-fault Protection including an Earthing Transformer.

Somewhat similar considerations apply to unearthed transformer-windings connected to resistance-earthed systems and to delta-connected windings which are earthed through earthing-transformers and earthing resistors. The general rule is: that where earth-fault current is restricted, earth-fault relays should be included.

Two typical arrangements for supplementary earth-fault protection are shown in figs. 10 and 11. Fig. 10 shows a simple delta/star transformer. For such an arrangement without earth-fault protection the C.T.'s would normally be star-connected on the delta side and delta-connected on the star side. But to facilitate the introduction of earth-fault protection on the star side, the C.T.'s are star-connected and an auxiliary star/delta transformer is interposed in the differential circuit to compensate for the phase-shift between primary and secondary sides. The delta-side earth-fault relay is connected in the residual circuit from the Duo-bias relays to the star point of the C.T.'s and, on the star side, the earth-fault relay is connected directly to the line and neutral C.T.'s in the usual way for balanced earth-fault protection. The earth-fault relays so connected operate only for faults in the power-transformer zone.

Fig.11 shows a more complex arrangement common in high-voltage systems, in which both windings of the transformer are earthed, one directly and the other via an earthing transformer. As in the previous case, both sets of C.T.'s are star-connected and an auxiliary star/delta transformer interposed in order to compensate for the phase-change across the transformer. The star-side earth-fault relay is connected directly to the line and neutral C.T.'s as before. On the delta side, a zero-sequence shunt is required for the differential circuit as it will be appreciated that zero-sequence currents may flow in the C.T.'s to an external earth-fault without there being corresponding currents on the star-connected side. In order to preserve the stability of the protection under this condition the zero-sequence current must not appear in the differential circuit. The shunt takes the form of a star/delta auxiliary transformer which removes the zero-sequence current from the differential circuit. The delta-side earth-fault protection is connected with the line and neutral C.T.'s in the same way as on the star side of the transformer.

It will be appreciated that several arrangements are possible according to the transformer, connections, the method of earthing, and the C.T.'s available. For example, if in fig. 10 a separate set of C.T.'s were used for the 132-kV earth-fault protection, the differential C.T.'s could be delta-connected and the interposing transformer omitted.

In all cases it is recommended that high-impedance earth-fault relays be used as these give the maximum stability under transient conditions.

CURRENT-TRANSFORMER RATIOS AND CONNECTIONS

1. The ratios of the C.T.'s on the two or more sides of a transformer must be suitably matched so that the difference in secondary current under through-fault conditions is minimised. In addition, the ratios must be such that the secondary current under load conditions does not exceed the rating of the relay.
2. If there is a star/delta transformation or its equivalent there must also be a similar transformation in the differential circuit.
3. If a power-transformer is capable of delivering zero-sequence current, then the C.T. secondary circuit must be so arranged that the corresponding zero-sequence secondary current is diverted from the differential circuit.
4. When earth-fault protection is applied to an earthed winding, there must be a C.T. on the neutral earth-connection so that the neutral current is balanced against the line current.

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Printed in England by Colden Offset, Blaydon on Tyne.