Transformer Fault Categories

1. Winding and terminal faults
2. Sustained or uncleared external faults
3. Abnormal operating conditions such as overload, overvoltage and overfluxing
4. Core faults
Transformer Protection (1)

- Transformer Connections
- Overcurrent Protection
- Directional Protection of Parallel Transformers
- Partial Differential Protection of Parallel Transformers
- Earth Faults on Transformer Windings
- Unrestricted Earth Fault Protection
- Restricted Earth Fault Protection
- Biased Differential Protection of 2 and 3 Winding Transformers
Transformer Protection (2)

- Combined Differential and Restricted Earth Fault Protection
- Protection of Auto-Transformers
- Inter-Turn Faults and Buchholz Protection
- Overfluxing Protection
- Overload Protection
- Transformer Feeder Protection
Transformer Connections
Transformer Protection (4)
Transformer Protection (5)
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.
<table>
<thead>
<tr>
<th>Group</th>
<th>Phase Displacement</th>
<th>Transformer Vector Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>0° Phase displacement</td>
<td>Yy0, Dd0, Zd0</td>
</tr>
<tr>
<td>Group 2</td>
<td>180° Phase displacement</td>
<td>Yy6, Dd6, Dz6</td>
</tr>
<tr>
<td>Group 3</td>
<td>30° Lag phase displacement</td>
<td>Yd1, Dy1, Yz1</td>
</tr>
<tr>
<td>Group 4</td>
<td>30° Lead phase displacement</td>
<td>Yd11, Dy11, Yz11</td>
</tr>
</tbody>
</table>
“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.

**Example 1: Dy 11 Transformer**

Question: How to connect windings?
Dy 11
1. Draw Phase-Neutral Voltage Vectors
2. Draw Delta Connection
3. Draw A Phase Windings

Dy 11
4. Complete Connections (a)
4. Complete Connections (b)
### 11kV Distribution Transformers
#### Typical Fuse Ratings

<table>
<thead>
<tr>
<th>Transformer rating</th>
<th>Full load current (A)</th>
<th>Rated current (A)</th>
<th>Operating time at 3 x rating(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>kVA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>5.25</td>
<td>16</td>
<td>3.0</td>
</tr>
<tr>
<td>200</td>
<td>10.5</td>
<td>25</td>
<td>3.0</td>
</tr>
<tr>
<td>300</td>
<td>15.8</td>
<td>36</td>
<td>10.0</td>
</tr>
<tr>
<td>500</td>
<td>26.2</td>
<td>50</td>
<td>20.0</td>
</tr>
<tr>
<td>1000</td>
<td>52.5</td>
<td>90</td>
<td>30.0</td>
</tr>
</tbody>
</table>
Traditional Small Transformer Protection Package

3.3kV

200/5

51 50

51 50

1500/5

1MVA
3.3/0.44kV

51

64

1500/5
Traditional Medium Transformer
Protection Package

11kV

5MVA
11/3.3kV

1000/5

3.3kV
Overcurrent Protection
Transformer Overcurrent Protection

Requirements

- Fast operation for primary short circuits
- Discrimination with downstream protections
- Operation within transformer withstand
- Non-operation for short or long term overloads
- Non-operation for magnetising inrush
Use of Instantaneous Overcurrent Protection

50 set to 1.2 - 1.3 x through fault level
Concerns relay response to offset waveforms (DC transient)

**Definition**

\[
\frac{I_1 - I_2}{I_2} \times 100
\]

- \(I_1\) = Steady state rms pickup current
- \(I_2\) = Fully offset rms pickup current
Instantaneous High Set Overcurrent Relay Applied to a Transformer
2-1-1 Distribution (1)
2-1-1 Distribution (2)

2-1-1 Distribution (2)
Parallel Transformers
Directional Relays (1)
Parallel Transformers
Directional Relays (2)

Grid supply

Bus Section

Feeders
Parallel Transformers
Partial Differential Scheme

Advantage: Reduced number of grading stages
Earth Fault Protection
Transformer Earth Faults

Resistor limits E/F current to full load values

For a fault at $\chi$ : Fault current = $\chi \cdot I_{F.L.}$

Effective turns ratio = $\sqrt{3} : \chi$

Thus primary current, $I_p = \frac{\chi}{\sqrt{3}} \cdot I_{F.L.}$

If C.T. ratio (on primary side) is based on full load current of transformer, then C.T. secondary circuit = $\frac{\chi^2}{\sqrt{3}}$
Overcurrent Relay Sensitivity to Earth Faults (1)

Overcurrent Relay Setting > $I_{F.L.}$

$I_f$ as multiple of $I_{F.L.}$

Star Side

Delta Side

$p.u.$
Overcurrent Relay Sensitivity to Earth Faults (2)

Iₕ as multiple of $I_{F.L.}$.

Star Side

Delta Side

$p.u.$
Overcurrent Relay Sensitivity to Earth Faults (3)

$I_f$ as multiple of $I_{F,L}$.

![Diagram with symbols and curves representing current flows and fault sensitivity.](image)
Earth Fault on Transformer Winding

\[ I = \frac{\chi^2}{\sqrt{3}} \]

For relay operation, \( I > I_S \)

e.g. If \( I_S = 20\% \), then \( \frac{\chi^2}{\sqrt{3}} > 20\% \) for operation

i.e. \( \chi > 59\% \)

Thus 59\% of winding is not protected

<table>
<thead>
<tr>
<th>Differential Relay Setting</th>
<th>% of Star Winding Protected</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>58%</td>
</tr>
<tr>
<td>20%</td>
<td>41%</td>
</tr>
<tr>
<td>30%</td>
<td>28%</td>
</tr>
<tr>
<td>40%</td>
<td>17%</td>
</tr>
<tr>
<td>50%</td>
<td>7%</td>
</tr>
</tbody>
</table>
Provides back-up protection for system
• Time delay required for co-ordination
Can provide better sensitivity
(C.T. ratio not related to full load current)
(Improved “effective” setting)

Provides back up protection for transformer and system
- Relay only operates for earthfaults within protected zone.
- Uses high impedance principle.
- Stability level: usually maximum through fault level of transformer
Restricted E/F Protection
Low Voltage Windings (1)

LV restricted E/F protection trips both HV and LV breaker

Recommended setting : 10% rated
LV restricted E/F protection trips both HV and LV breaker
Recommended setting: 10% rated
Delta winding cannot supply zero sequence current to system

Stability: Consider max LV fault level

Recommended setting: less than 30% minimum earth fault level

(41)
High Impedance Principle

Voltage Across Relay Circuit  \[ V_S = I_F (R_{CT} + 2R_L) \]

Stabilising resistor \( R_{ST} \) limits spill current to \( I_S \) (relay setting)

\[ \therefore R_{ST} = \frac{V_S}{I_S} - R_R \quad \text{where } R_R = \text{relay burden} \]

CT knee point

\[ V_{KP} = 2V_S = 2I_F (R_{CT} + 2R_L) \]
During internal faults the high impedance relay circuit constitutes an excessive burden to the CT’s.

A very high voltage develops across the relay circuit and the CT’s.

- Causes damage to insulation of CT, secondary winding and relay.

Magnitude of peak voltage $V_p$ is given by an approximate formula (based on experimental results)

$$V_p = 2\sqrt{2V_K(V_F - V_K)}$$

Where $V_F = \text{Swgr. Fault Rating in amps} \times Z$ of relay circuit \@ setting

- Metrosil required if $V_p > 3kV$
Non-Linear Resistors (Metrosils)

Metrosil Characteristic

\[ V = C I^\beta \]

Suitable values of \( C \) & \( \beta \) chosen based on:

- Max secondary current under fault conditions
- Relay setting voltage
REF Protection Example

Calculate:
1) Setting voltage ($V_S$)
2) Value of stabilising resistor required
3) Effective setting
4) Peak voltage developed by CT’s for internal fault

Diagram: 1MVA 11000V 415V 1600/1 $R_{CT} = 4.9\,\Omega$

RS

MCAG14

$I_S = 0.1\,\text{Amp}$

2 Core 7/0.67mm (7.41Ω/km) 100m Long
Earth fault calculation :-

Using 80MVA base

Source impedance = 1 p.u.
Transformer impedance = $0.05 \times 80 = 4\text{ p.u.}$

Total impedance = 14

\[ \therefore I_1 = \frac{1}{14} = 0.0714\text{ p.u.} \]

Base current = $80 \times 10^6 \sqrt[3]{3 \times 415}$

= 111296 Amps

\[ \therefore I_F = 3 \times 0.0714 \times 111296 \]

= 23840 Amps (primary)

= 14.9 Amps (secondary)
(1) Setting voltage

\[ V_S = I_F (R_{CT} + 2_{RL}) \]

Assuming “earth” CT saturates,

\[ R_{CT} = 4.8 \text{ ohms} \]

\[ 2_{RL} = 2 \times 100 \times 7.41 \times 10^{-3} = 1.482 \text{ ohms} \]

\( \therefore \) Setting voltage = 14.9 \((4.8 + 1.482)\)

\[ = 93.6 \text{ Volts} \]

(2) Stabilising Resistor \((R_S)\)

\[ R_S = \frac{V_S}{I_S} - \frac{1}{I_S^2} \]

Where \(I_S\) = relay current setting

\( \therefore \) \(R_S = \frac{93.6}{0.1} - \frac{1}{0.1^2} = 836 \text{ ohms} \)
Solution (3)

### Graph

- **AT/mm** (multiply by Ki to obtain total exciting current in Amps)
  - 0
  - 0.04
  - 0.08
  - 0.12

- **Weber/m² (Tesla)** (multiply by Kv to obtain RMS secondary volts)
  - 0
  - 0.04
  - 0.08
  - 0.12
  - 0.16

### Table

<table>
<thead>
<tr>
<th></th>
<th>Kv</th>
<th>Ki</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line &amp; Neutral CT</td>
<td>158</td>
<td>0.341</td>
</tr>
<tr>
<td>Earth CT</td>
<td>236</td>
<td>0.275</td>
</tr>
</tbody>
</table>
(3) Effective setting \( I_p = \text{CT ratio} \times (I_s + \sum I_{\text{MAG}}) \)

Line & Neutral CTs

\[
\text{Flux density at } 93.6\text{V} = \frac{93.6}{158} = 0.592 \text{ Tesla}
\]

From graph, mag. Force at 0.592 Tesla = 0.015 AT/mm

\[ \therefore \text{Mag. Current} = 0.015 \times 0.341 = 0.0051 \text{ Amps} \]

‘Earth’ CT

\[
\text{Flux density at } 93.6\text{V} = \frac{93.6}{236} = 0.396 \text{ Tesla}
\]

From graph, mag. Force at 0.396 Tesla = 0.012 AT/mm

\[ \therefore \text{Mag. Current} = 0.012 \times 0.275 = 0.0033 \text{ Amps} \]

Thus, effective setting = \( 1600 \times (0.1 + [(4 \times 0.0051) + 0.0033]) \)

Effective setting = 198 Amps

Transformer full load current = 1391 Amps

\[ \therefore \text{Effective setting} = \frac{198}{1391} \times 100\% = 14.2\% \times \text{rated} \]
(4) Peak voltage = \(2\sqrt{2} V_K (V_F - V_K)\)

\[ V_F = 14.9 \times \frac{V_S}{I_S} = 14.9 \times 936 = 13946 \text{ Volts} \]

For ‘Earth’ CT, \(V_K = 1.4 \times 236 = 330 \text{ Volts (from graph)}\)

\[ V_{PEAK} = 2\sqrt{2} \times 330 \times (13946 - 330) \]

\[ = 6\text{kV} \]

Thus, Metrosil voltage limiter will be required.
Parallel Transformers

[Diagram showing a electrical system with labels for T, T2, Bus Section, 415 Volt Switchboard, and switch markings.]
Parallel Transformers
CT in Earth
Parallel Transformers CT in Earth and Neutral

T1 Bus Section Open

415 Volt Switchboard
Will maloperate if bus section is open for fault at F1

No maloperation for fault at F2 (but setting must be greater than load neutral current)
Traditional Large Transformer Protection Package

33K V

10MVA 33/11K V

600/5

5/5A

600/5

200/5

51 5 0

87

N

64

51 N
Differential Protection
Overall differential protection may be justified for larger transformers (generally > 5MVA).

- Provides fast operation on any winding

Measuring principle:

- Based on the same circulating current principle as the restricted earth fault protection
- However, it employs the biasing technique, to maintain stability for heavy through fault current

Biasing allows mismatch between CT outputs.

It is essential for transformers with tap changing facility.

Another important requirement of transformer differential protection is immunity to magnetising in rush current.
### Biased Differential Scheme

**Graphical Representation:**

- **OPERATE**
- **RESTRAIN**
- **Differential Current**
- **Mean Through Current**

**Mathematical Expressions:**

- \( I_1 - I_2 \)
- \( \frac{I_1 + I_2}{2} \)
Correct application of differential protection requires CT ratio and winding connections to match those of transformer. CT secondary circuit should be a “replica” of primary system. Consider:

1. Difference in current magnitude
2. Phase shift
3. Zero sequence currents
Differential Connections
Use of Interposing CT

Interposing CT provides:

- Vector correction
- Ratio correction
- Zero sequence compensation

\[\text{(Eq)}\]
Given above: Need to consider -

1. Winding full load current
2. Effect of tap changer (if any)
3. C.T. polarities

Assuming no tap changer

Full load currents:
- 66kV: 131 Amp = 4.37 Amps secondary
- 11kV: 787 Amp = 4.92 Amps secondary

However, require 11kV C.T.’s to be connected in Δ

Thus, secondary current = \(\sqrt{3} \times 4.92 = 8.52\)A

\[ \therefore \text{RATIO CORRECTION IS REQUIRED} \]
It is usual to connect 11kV C.T.’s in \( \Delta \) and utilise a \( \Delta / \Delta \) interposing C.T. (this method reduces lead VA burden on the line C.T.’s)

Current from 66kV side = 4.37 Amp

Thus, current required from \( \Delta \) winding of int. C.T. = 4.37 Amp

Current input to \( \Delta \) winding of int. C.T. = 4.92 Amp

\[ \text{Required int C.T. ratio} = \frac{4.92}{4.37} = \frac{4.92}{2.52} \]

\[ = \frac{\sqrt{3}}{3} \]

May also be expressed as : 5 / 2.56
e.g. Assume 66kV +5%, -15%

Interposing C.T. ratio should be based on mid tap position

Mid Tap (-5%) = 62.7 kV

Primary current (15 MVA) = 138 Amp

Secondary current = 4.6 Amp

∴ Interposing C.T. ratio required = \( \frac{4.92}{4.6} \frac{\sqrt{3}}{} \)

\( \frac{\triangle \triangle}{\triangle \triangle} \)

= 4.92 / 2.66

May also be expressed as : 5 / 2.7

Compared with 5 / 2.56 based on nominal voltage
Connections Check
Arbitrary Current Distribution
Connections Check
Add Delta Winding Current
Connections Check
Complete Primary Distribution
Connections Check
Complete Secondary Distribution
In-Zone Earthing Transformer
In-Zone Earthing Transformer Alternative (1)
In-Zone Earthing Transformer
Alternative (2)
In-Zone Earthing Transformer Alternative (3)

Diagram showing an earthing transformer with labels 300/1, 1/0.33, and TO DIFFERENTIAL RELAY.
Combined Differential and Restricted Earth Fault Protection

To differential relay
Using Summation Auxiliary Current Transformer

Restricted earth fault relay

Bias windings

Differential relay operating windings

Combined Differential and Earth Fault Protection
Three Winding Transformer

All interposing C.T. ratio's refer to common MVA base (63MVA)
Traditional Use of Interposing CT

Interposing CT provides:

- Vector correction
- Ratio correction
- Zero sequence compensation
Integral Vectorial and Ratio Compensation

Differential element

Numeric Relay

Power transformer

Virtual interposing CT

Ratio correction

Vectorial correction

Differential element

Virtual interposing CT
Transformer Magnetising Characteristic

- Twice Normal Flux
- Normal Flux
- Normal No Load Current
- No Load Current at Twice Normal Flux
Magnetising Inrush Current
Steady State

\[ + \Phi_m \]

\[ - \Phi_m \]

\[ V \quad \Phi \]

\[ I_m \]

(80)
Magnetising Inrush Current
Switch on at Voltage Zero - No residual flux
Transformer Differential Protection  
Effect of Magnetising Current

- Appears on one side of transformer only
- Seen as fault by differential relay
- Normal steady state magnetising current is less than relay setting
- Transient magnetising inrush could cause relay to operate
Transformer Differential Protection
Effect of Magnetising Inrush

SOLUTION 1: TIME DELAY

- Allows magnetising current to die away before relay can operate
- Slow operation for genuine transformer faults
Transformer Differential Protection
Effect of Magnetising Inrush

*SOLUTION 2: 2ND (and 5TH) HARMONIC RESTRAINT*

- Makes relay immune to magnetising inrush
- Slower operation may result for genuine transformer faults if CT saturation occurs
- Used in MiCOM P63x
SOLUTION 3: GAP MEASUREMENT TECHNIQUE

- Inhibits relay operation during magnetising inrush
- Operate speed for genuine transformer faults unaffected by significant CT saturation
- Used in MBCH & KBCH relays
Typical Magnetising Inrush Waveforms
Detection of Typical Magnetising Inrush (50Hz)

Differential comparator

Bias
Differential
Threshold

T1 = 5ms
T2 = 22ms
Trip
Restraint for Transformer Magnetising Inrush

Bias → Differential comparator → T1 = 5ms → T2 = 22ms → Trip

Differential → Threshold

Differential input

Comparator output

T1

Trip

Reset

(88)
Operation for Transformer Faults

Bias
Differential
Threshold

Differential comparator

T1 = 5ms
T2 = 22ms

Trip

Differential input

Comparator output

T1

Trip

T2

Reset
Protection of Auto-Transformer by High Impedance Differential Relays

(a) Earth Fault Scheme

Diagram showing high impedance differential relays for transformer protection.
Protection of Auto-Transformer by High Impedance Differential Relays

(b) Phase and Earth Fault Scheme
Inter-Turn Fault Protection
Inter-Turn Fault

Nominal turns ratio: \(-11,000 / 240\)
Fault turns ratio: \(-11,000 / 1\)
Current ratio: \(-1 / 11,000\)

Requires Buchholz relay
Interturn Fault Current / Number of Turns Short Circuited

Fault current in short circuited turns

Primary input current

Fault current (multiples of rated current)

Primary current (multiples of rated current)

Turn short-circuited (percentage of winding)
Buchholz Relay Installation

Transformer

Conservator

Oil conservator

5 x internal pipe diameter (minimum)

3 x internal pipe diameter (minimum)

3\" minimum
Buchholz Relay

- Petcock
- Counter balance weight
- Oil level
- From transformer
- Aperture adjuster
- Alarm bucket
- Mercury switch
- To oil conservator
- Trip bucket
- Drain plug
- Deflector plate
Overfluxing Protection
Overfluxing

- Generator transformers
- Grid transformers

Usually only a problem during run-up or shut down, but can be caused by loss of load / load shedding etc.

Flux $\Phi \propto \frac{V}{f}$

Effects of overfluxing:
- Increase in magnetising current
- Increase in winding temperature
- Increase in noise and vibration
- Overheating of laminations and metal parts (caused by stray flux)

Protective relay responds to V/f ratio
- Stage 1 - lower A.V.R.
- Stage 2 - Trip field
Overfluxing Basic Theory

\[ V = k_f \Phi \]

**CAUSES**
- Low frequency
- High voltage
- Geomagnetic disturbances

**EFFECTS**
- Tripping of differential element (Transient overfluxing)
- Damage to transformers (Prolonged overfluxing)
V/Hz Overfluxing Protection

\[ V_f \alpha K\Phi \]

Trip and alarm outputs for clearing prolonged overfluxing

Alarm: definite time characteristic to initiate corrective action

Trip: IDMT or DT characteristic to clear overfluxing condition

Settings

Pick-up 1.5 to 3.0 i.e. \[ 110V \times 1.05 = 2.31 \] 50Hz

DT setting range 0.1 to 60 seconds
Enables co-ordination with plant withstand characteristics

\[ t = 0.8 + 0.18 \times K \]
\[ \frac{1}{(M - 1)^2} \]

\[ M = \frac{V/Hz}{\text{Setting}} \]
Overfluxing Relay
Application of Overfluxing Relay

Circuit breaker position repeat relay

VAA relay

Lower AVR
Inhibit AVR
Raise
Alarm

Generator field circuit breaker trip coil

RL1-1
RL2-1
RL2-2

DC

(103)
Thermal Overload Protection
Effect of Overload on Transformer Insulation Life

With ambient of 20°C. Hot spot rise of 78°C is design normal. A further rise of 6°C doubles rate of using life.
Overheating Protection

- Top oil of power transformer
- Heater
- Thermal replica
- Temperature sensing resistor
- TD setting
- Load

Control System:
- Trip
- Alarm
- Fan control
- Pump control
- Temp. indication
- Local
- Remote

(106)
Overload Protection

- Overcurrent protection designed for fault condition
- Thermal replica provides better protection for overload
  - Current based
  - Flexible characteristics
  - Single or dual time constant
  - Reset facility
  - Non-volatile
Thermal Overload
Oil Filled Transformers

Trip time (s)

Current (multiple of thermal setting)

Single characteristic: \( \tau = 120 \) mins

Dual characteristic

Single characteristic: \( \tau = 5 \) mins

(108)
Thermal Trip Time

\[ \text{TripTime} = \tau \ln \left( \frac{\left( \frac{I}{I_{\text{REF}}} \right)^2 - \theta_P}{\left( \frac{I}{I_{\text{REF}}} \right)^2 - K \theta_{\text{TRIP}}} \right) \]

where \( \tau \) = heating time constant
\( I \) = actual current measured by relay
\( I_{\text{REF}} \) = continuous current rating of protected plant
\( \theta_P \) = previous thermal state
\( \theta_{\text{TRIP}} \) = trip threshold
\( K \) = multiplier (for actual temperature)
Transformer Feeders
Protection of Parallel Transformer Feeders

Higher - voltage busbar

Load

Lower - voltage busbar

SBEF 2 stage

DOC

DOC

Bh

WT

FTS

DP

REF

REF

Higher voltage busbar

1 2

2 stage
Protection of Transformer Feeders

Diagram showing the protection system for transformer feeders, including transformer differential protection and feeder differential protection, with connections and indicators for trip and un stabilise.
Transformer Feeders

- For use where no breaker separates the transformer from the feeder.
- Transformer inrush current must be considered.
- Inrush is a transient condition which may occur at the instant of transformer energisation.
- Mag. Inrush current is not a fault condition
  \[\therefore \text{ Protection must remain stable.}\]
- MCTH provides a blocking signal in the presence of inrush current and allows protection to be used on transformer feeders.
Transformer Feeder Protection
P541/ P542 - Protection of Transformer Feeders

Power transformer

Virtual interposing CT

P540 Scheme

Virtual interposing CT

Ratio correction

Vectorial correction