Eskom	Standard	Technology

Title: **PROTECTION PHILOSOPHY: FOR BREAKER-AND-A-HALF TRANSFORMERS AND SHUNT REACTORS**

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1. Introduction

Transformers are considered as one of the major electrical equipment in a substation. This is due to the longer lead time and much greater cost per unit. The primary function of a power transformer is to transform system voltage from one nominal level to another. The transformer has to be capable of carrying the power flow under various operating conditions and contingencies. Transformers may be either autotransformers or multi-winding conventional transformers. A three-phase installation may consist of a three-phase unit or three-single phase units. Three-phase units have lower construction and maintenance costs and can be built to the same efficiency ratings as single-phase units.

Auto-transformers are considered primarily because of cost advantages where the voltage transformation ratio is favorable, up to possible 3:1. Furthermore, auto-transformers are wye connected and for that reason they provide only an in-phase angular relationship between primary and secondary voltages. They are also smaller in physical size, lighter weight, lower regulation (voltage drop in transformer), smaller excitation currents and lower losses.

Transformers experience different kinds of stresses that include overheating as a result of transformer overloading, short circuits and open circuits.

The primary function of the shunt reactors in the power system network is to provide compensation for the capacitive shunt reactance of transmission lines.

This document provides minimum transformer protection scheme design requirements in order to ensure that it is adequately protected against any system disturbances. Differential protection is a primary protection scheme that is normally applied on a percentage differential basis to allow for differences in transformer ratios, magnetizing current, and current transformer mismatch. Over-current and earth fault protection relays are normally applied to provide backup protection to the differential protection. Restricted earth fault protection is normally applied to provide increased sensitivity to ground faults. Shunt reactor protection is similar to the transformer protection which will also be dealt with in the later chapters of this document.

2. Supporting clauses

2.1 Scope

The document covers protection philosophy and design standard of transformers and reactors for breaker-and-a-half applications

2.1.1 Purpose

The purpose of this document is to provide a summary of a recommended protection philosophy as applied to Transmission power transformers and shunt reactor protection.

- To define why functions are applied.
- To define minimum requirements that protection scheme design must meet.

2.1.2 Applicability

This standard is applicable to all Transmission breaker-and-a-half transformer protection schemes in order to provide a general description of the protection relay functions required for the transformer and shunt reactor protection scheme design.

2.2 Normative/informative references

Parties using this document shall apply the most recent edition of the documents listed in the following paragraphs.

2.2.1 Normative

[1] ISO 9001, Quality Management Systems.

[2] IEEE Std C37.91 – 2008, IEEE Guide for Protecting Power Transformers.

[3] Theory, Design, maintenance and life management of Power Transformers- Prepared by a Staff of experts from Eskom Holdings Ltd and ABB Powertech Transformers- April 2008.

[4] IEC 60255, Electrical relays (All parts).

[5] SANS 6007-Ed.2:2011 Power Transformers – Part 2: Temperature Rise for Liquid Immersed Transformers.

[6] EPDG series - Electrical Protection Design Guide – Volume 1.

[7] ANSI/IEEE C37.109 – 1988, IEEE Guide for the Protection of Shunt Reactors.

[8] DGL 34-466: Distribution Transformer Protection Philosophy.

[9] IEC 50: International Electro-technical Vocabulary; Chapter 448 Power system protection.

[10] CIGRE SC23, WG05: Design and Maintenance practice for substation secondary systems, April 1994.

[11] A Review of Existing protection Schemes for Line Reactors on the Transmission System – Prepared by: AS Williams, June 1994.

[12] DSP 34-1690, Specification for combined three-phase neutral electro-magnetic couplers (NECs) with neutral earthing resistors (NERs) and auxiliary transformers

[13] Earthing of Tertiary Delta Windings, H Norman, 24 November 1971

2.2.2 Informative

[14] ST 240-76212647: Standard for the Protection and Control of Extra High Voltage Transmission Lines on the Eskom Network (Superseded TST41-689)

[15] ST 240-56364481: Protection settings philosophy for EHV and HV networks (Superseded SPL 46-101)

2.3 Definitions

2.3.1 General

Definition	Description
Dependability	The probability of not having a failure to operate under given conditions for a given time interval (IEC 50-448).
Discrimination	The ability to select zones in order to trip the minimum number of breakers to clear the fault.
Fast clearance	Minimum time delay so as to limit damage and possible power system instability.
Fault clearance system	The fault clearance system comprises the two tripping systems, plus the circuit- breakers.
NEC/RT	Combined three-phase neutral electromagnetic compensator with earthing resistor and auxiliary transformer
Protection	Protection provides for switching off, by means of circuit-breaker, a network element affected by a fault.
Protection system	The protection system is that part of the tripping system which provides the requisite primary, back-up system and auxiliary protection functions.
Redundancy	The doubling up of protection equipment to serve the same purpose and must have the level of importance.

Definition	Description
Reliability	The ability of the protection to operate consistently for all faults to which it should respond and remain inoperative to all faults to which it should not.
Security	The probability of not having unwanted operation under given conditions for a given time interval (IEC 50-448).
Selectivity	The ability to detect a fault within a specified zone of a network and to trip the appropriate circuit-breaker(s) to clear this fault with a minimum disturbance to the rest of that network.
Sensitivity	It is the lowest level of fault current at which operation should occur.
Stability	The ability to differentiate between internal faults (in-zone) and external faults.
Tripping system	A tripping system comprises the protection system, an independent DC source, a dedicated CT core, a separately fused input from a shared VT core and trip coils of the circuit breakers.

2.3.2 Disclosure classification

Controlled disclosure: controlled disclosure to external parties (either enforced by law, or discretionary).

2.4 Abbreviations

Abbreviation	Description
A	Amp
A.C	Alternating current
CB	Circuit Breaker
CT	Current Transformer
CTR	Current Transformer Ratio
DC	Direct Current
DTL	Definite Time Lag
E/F	Earth fault
EHV	Extra High Voltage
EMF	Electro Magneto Field
HMI	Human Machine Interface
HV	High voltage
IDMT	Inverse Definite Minimum Time
IDMTL	Inverse Definite Minimum Time Lag
IED	Intelligent Electronic Device
kV	kiloVolt
LDC	Line drop compensation
LED	Light Emitting Diode
LV	Low voltage
mA	milliAmp

Abbreviation	Description
MTR	Master trip relay
MV	Medium voltage
MVA	Apparent power
MVar	Reactive power
MW	Real or active power
NEC	Neutral electromagnetic compensator
NER	Neutral earthing resistor
O/C	Over- current
OLTC	On-Load Tap Changer
ONAN	Oil natural, air natural
PTM&C	Protection Telecontrol Metering and Control
REF	Restricted Earth Fault
RTU	Remote Terminal Unit
s	Second
SFT	Sustained fault timer
TNS	Test normal switch

2.5 Roles and responsibilities

The PTM&C should take responsibility of this breaker-and-a-half Transformer Protection philosophy document.

2.6 Process for monitoring

The document shall be updated with any changes in philosophy and/or when revision date is due.

2.7 Related/supporting documents

Not applicable.

3. Transformer Protection

3.1 General

These transformers can be single-phase or three-phase windings. There are various types of faults which they can experience such as earth faults, phase-to-phase faults, inter-turn faults and overheating, resulting from transformer overloading or from some internal cause such as core-heating. However, to ensure continuity of supply and quality of supply to customers and fast fault clearance, adequate protection should be applied to this equipment.

3.2 Transformer Applications

- ***Coupling Transformers***: This type of transformer application is probable the most common in the power system network. The transformer couples two portions of the electrical network which are at different voltage levels (e.g. 765kV to 400kV network).

3.3 Transformer Configurations

Transformers can be connected in star and delta, and with primary, secondary, tertiary and auto-connected windings. Various types of transformer configurations are discussed below:

- ***Star/Star:*** This is economical for small HV transformers as it minimizes the turns/phase and the winding insulation. With star points available on both sides it is possible to provide a neutral connection. Triplen voltages are absent from the lines, and (unless there is a neutral connection) no triplen harmonic currents flow. The neutral voltage may oscillate, and triplen harmonic voltages may be high in shell-type units.
- ***Auto-connection:*** An auto-transformer has a common winding between the primary and secondary, the input and output circuits being electrically connected as one continuous winding per phase, with input and output currents superimposed in the common section. The advantage of using autotransformers is the saving in transformer size, rating and losses. For a voltage ratio of 2:1, about 50 % saving in winding material might be obtained, and the overall cost of the unit might be 60 % to 70 % of that of a nominal transformer with the same input rating.
- ***Tertiary winding:*** A three winding transformer has an extra tertiary winding which is meant for one of the following reasons:
  - o To supply station auxiliaries;
  - o To supply phase-compensating devices (e.g. synchronous condensers or reactors) requiring a different voltage or connection;

3.3.1 Philosophy

The practice of utilizing the 11 kV or 22 kV tertiary winding to supply rural loads is **not** supported in this document, as the number of faults that the transformer is subjected to could have a detrimental effect on the life of the transformer due to number of faults that can be experienced.

The use of fault current limiting reactors for this application does, however reduce the effects of this on the transformer.

The standard Eskom practice is to connect all tertiary bushings through a suitable surge arrester to earth and to protect the windings with HI-SET and IDMTL over current elements.

In the past it has been practise to earth one terminal of the tertiary winding and to protect it via a CT placed in the path of the earth. This practise is not recommended as the transformer is still subject to damage from magnetically transferred voltage transients from the primary winding. It is recommended that each tertiary terminal is earthed via a surge arrestor.

3.4 CT Requirements

3.4.1 Philosophy

- The relay performance depends on the CT which drives it.
- The ratings of the CTs should be selected to avoid steady-state saturation.
- Protection CTs are required to maintain their performance up to several times the rated primary current.

3.4.2 Rationale

- During an internal fault, or a fault external to the transformer but in the protected zone one or more CTs may saturate and result in the failure of a transformer differential relay to operate or cause delay in its operation.
- The performance of a CT is a function of the burden connected to the secondary winding of the CT.

3.4.3 Design requirements

The following design requirements should be considered:

- CTs must be selected after the fault current levels and relay burdens have been considered.
- Capabilities of the relay should be evaluated against the CT to be selected.
- Biased differential protection should be supplied from external, post type current transformer cores.
- If it is optimal to share current transformer cores for the Biased Differential protection and other back-up protection functions, the current transformer cores used should be post-type to ensure full coverage of the zone between the bushings and the post type current transformer.
- The requirement for EHV transformers is to have REF supplied only via bushing CTs and not post type CTs. This is important for proper identification of faults in transformer bay – lack of REF operation indicates fault outside of transformer tank e.g. on surge arrestors or CTs. In this way restoration of supply can be quicker
- HV instantaneous Over-current protection must be supplied from HV post type current transformer cores, where this is not available the transformer HV bushings may be used.
- HV IDMT Over-current protection must be supplied from HV post type current transformer core.
- HV IDMT Earth fault protection must be supplied from HV post type current transformer core and can share the core used with other protection functions, if it is optimal to do so. Calculated residual current would be used in this scenario.
- MV IDMT Over-current protection must be supplied from MV post type current transformer core
- MV IDMT Earth fault protection must be supplied from current transformer core in the MV earthing circuit (transformer earthed neutral, NEC neutral or NEC/NER neutral). Where possible the outer core shall be used.
- Tertiary IDMT Over-current protection should be supplied from current transformer cores internal to the Delta winding, where not possible LV post type current transformer core can be used.
- Tertiary IDMT Earth fault protection must be supplied from current transformer core in the LV or tertiary earthing circuit (NEC neutral or NEC/NER neutral).
- Measurement and Metering functions should be supplied from post – type current transformer cores specified for the accuracy class required.

3.4.4 Checking for Saturation of Class P CTs

The secondary voltage developed across the CT is defined by:

$$EMF = ALF\,(R_{CT} + R_b)\,I_{sn}$$

Where: EMF = Voltage developed

ALF = Accuracy limit factor = If/CTR

R_{CT} = CT resistance

R_b = Rrel + Rlead, Where: Rlead = loop resistance

For phase –ground fault

Isn = nominal secondary current of CT

These CTs do not have transient performance capability, and if as a result of this the voltage developed is above the knee-point voltage of the CT, given by 1V/turn, the following measures must be taken:

- Increase the CTR
- Decrease the burden (if possible)
- Speed up the relay time

3.4.5 Checking for Saturation of Class X (TPS) CTs

Due to the fact that most system fault currents contain a transient DC component, the total flux in the core is several times the alternating flux (which would be the only flux required if there was no DC component of current). The ratio of maximum flux to the peak value of the AC component of the flux is defined as the Transient factor (K_{td}). This is approximately equal to the X/R ratio of the primary circuit.

Rated transient dimensioning factor of the CT $K_{td} = \left[w.T_P.T_s / \; (T_P - T_S)\right]e^{-t/T_P} - e^{-t/T_s})$

Where: t = duration of fault current

The required CT knee-point voltage (rated equivalent limiting secondary e.m.f) E_{al} is then given by:

$$E_{al} = K_{ssc}.K_{td}(R_{CT} + R_b) \text{ x } I_{sn} \quad \text{Where: } K_{ssc} = \frac{I_f}{CTR}$$

$K_{td} =$ Rated transient dimensioning factor of the CT

$R_{CT} =$ CT resistance

$R_b =$ Rrel + Rlead, where Rlead = loop resistance

Phase-ground fault

I_{sn} = nominal secondary current of CT

The secondary fault e.m.f can be practically calculated as follows:

$$V = [\frac{I_f}{CTR\,(R_{CT} + R_b)}]\left(1 + \frac{X}{R}\right)$$

This may be checked against the specified V_k of the CT (can be approximated to be based on 1V/turn for Class X and TPS CTs) [2].

Note: Any special CT requirements should be provided in the suppliers transformer protection scheme application guidelines.

3.5 Analogue processing

The breaker-and-a-half Transformer protection IED shall have the ability to independently interface with both the bay CTs (3 phases and neutral) and the tie bay CTs (3 phases and neutral). The bay CT and tie bay CT quantities shall be available independently and summated, in the protection IED, for the required protection functions. The independent and summated CT quantities are also required to be connected to the internal disturbance recorder. The breaker-and-a-half protection IED shall interface with the transformer HV CVT (3 phase), on the transformer side of the HV transformer isolator and the transformer MV CVT (3 phase), on the transformer side of the MV transformer isolator.

The HV analogue quantities for the transformer protection functions and HV stub protection shall be controlled by the HV transformer isolator status and with no HV transformer isolator discrepancy condition. The MV analogue quantities for the transformer protection functions and MV stub protection shall be controlled by the MV transformer isolator status and with no MV transformer isolator discrepancy condition.

All the analogue quantities shall be synchronised within the IED as not to influence the measured accuracy and dependability of the protection functions.

3.5.1 Rationale

The independent CT requirements are required for the bay and tie bay breaker failure protection and trip seal in the summated current quantities are required for the transformer protection.

Internal summation of the CTs is required to prevent magnetisation of the disconnected CT in the event of external summation.

3.6 Transformer Protection and Control Schemes Design Guide

3.6.1 Introduction

The application of protection relays to a specific power transformer in the power system is a true engineering task. This section deals briefly with the processes involved and with some of the finer points relating to protection scheme design.

3.6.2 General Philosophy

As with most protection systems, the philosophy which is adopted depends on the size, rating and importance of the primary plant being protected i.e. small transformers – minimally protected and large transformers – extensivelyprotected.

On account of the variety of faults that can occur on a transformer circuit it is necessary to adopt a “1 out of n” approach to tripping. This obviously lends itself towards a more dependable system which is favoured in this over security, as a transformer internal fault normally results in significant plant damage which has the combined effect of a high outage rate and a high cost of repair/replacement.

Another factor which has to be into consideration in the power distribution area is that of the economic ratio: protection cost versus primary plant cost. One cannot often justify the application of expensive protection at the lower HV levels. As with the protective relaying systems, all in-zone faults have to be adequately protected against. Back-up protection must also be provided for the surrounding network.

In recent times, other important considerations are those of ease of replacement/refurbishment and standardisation. Whatever systems are put in place must be able to be replaced or refurbished with a minimum amount of effort. In the interest of reducing engineering costs, more emphasis is being placed on the development of standardised schemes of protection and control which can be used for a variety of different applications.

Eskom’s design philosophy has been to utilise proven electrical and energy efficient equipment to match the application and minimum performance required.

Note:

Energising a power transformer from the MV side through a transformer in parallel will subject the busbar voltage to a voltage depression due to the inrush current being supplied through the paralleled transformer. Interlocking the MV “close” circuit with a HV CB contact can prevent this. It is however not the current standard practise in Eskom. Future schemes will provide this functionality.

3.6.3 Protection system design

3.6.3.1 Auto- transformers for EHV application (>80MVA rating)

3.6.3.1.1 Philosophy

At these higher ratings the transformer should be adequately protected and a certain level of redundancy be provided in order to ensure dependable protection operation.

3.6.3.1.2 Rationale

Transformers of this level normally come equipped with dual Buchholz relays, pressure relief valves, sudden pressure relief device, bag leakage detectors, oil/water flow monitors, winding/oil temperature devices. The tap changer has its own pressure relief valve and oil surge protection. Bushing CTs are fitted for restricted earth fault protection and tertiary Over-current elements.

3.6.3.1.3 Design requirements

The protection relays that are normally added are:

Main 1:

- Biased differential
- Restricted earth fault
- HV instantaneous Over-current
- HV IDMT Over-current and earth fault
- HV Stub protection
- HV bay breaker fail protection
- HV Tie breaker fail
- MV instantaneous Over-current
- MV IDMT Over-current and earth fault
- MV stub protection
- MV bay breaker fail protection
- MV Tie breaker fail protection
- Tertiary instantaneous and IDMT Over-current

Main 2:

- Biased differential
- Restricted earth fault (for each earthed winding)
- HV instantaneous Over-current
- HV IDMT Over-current and earth fault
- HV Stub protection
- HV bay breaker fail protection
- HV Tie breaker fail
- MV instantaneous Over-current
- MV IDMT Over-current and earth fault
- MV Stub protection
- MV bay breaker fail protection
- MV Tie breaker fail protection
- Tertiary instantaneous and IDMT Over-current

With the modern numerical relays, all the functions can be supplied from one current transformer core that makes it easier to apply all the functions on both mains.

3.6.4 Tripping related issues

3.6.4.1 Speed of operation

3.6.4.1.1 Philosophy

It is essential that, under internal fault conditions, the transformer be isolated from the network in a minimum time, but this must be seen in conjunction with cost considerations and the performance requirements for the specific application. This becomes more important with increasing transformer rating.

3.6.4.1.2 Rationale

The high operating speed of transformer protection relays applied on the transmission network is required so that the fault clearing system prevents or limits the damage to primary equipment, safety to personnel and protects power system stability. The pressure relief valve can operate in a few milliseconds. The Buchholz relay can operate quickly depending on the nature of the fault. The restricted earth fault relays can operate in more or less +/-15ms. The overall differential relay can operate in less than 20ms.

3.6.4.1.3 Design requirements

It is imperative that any relays placed in series with the unit type protection be extremely fast acting.

3.6.4.2 Master trip relay

3.6.4.2.1 Philosophy

The HV and MV master trip relay shall be a latching type relay that trip all circuit-breakers and shall be operated by all unit protections. The HV and MV master trip relay shall prevent closing of all circuit breakers after an internal fault. Operation of all the circuit breaker trip coils of all possible in-feeds shall be secured through the master trip relay, while the unit protection functions shall trip at least one circuit breaker trip coil of all possible in-feeds. The master trip relays shall also trip the cooler fans. The HV master trip relay shall trip the HV bay breaker and HV tie breaker only when the HV transformer isolator is closed and with no HV transformer isolator discrepancy. The MV master trip relay shall trip the MV bay breaker and the MV tie breaker only when the MV Transformer isolator is closed and with no MV transformer isolator discrepancy.

On operation of the master trip relays, inspection of the transformer must be initiated before re-energizing the unit, thus the "circuit breaker close" circuits must be interlocked with a master trip normally-closed contact.

3.6.4.2.2 Rationale

It is important to discriminate in the tripping caused by "unit type protection and that caused by "back-up" protection type devices, so that the transformer can effectively be "locked out" after an internal fault. If the isolation of the transformer was caused by a "back-up" protection type function, then there is a good chance that the transformer could be switched back in without ill effect.

3.6.4.2.3 Design requirements

The protection elements that operate the master trip relays are listed as follows:

- Transformer pressure relief valve
- Rapid pressure relief device
- Gas actuated/ Buchholz device
- Tap change pressure relief device
- Differential protection
- Restricted earth fault protection

- Tap change surge trip
- HV instantaneous over-current
- MV instantaneous over-current
- Tertiary instantaneous over-current (and IDMT O/C if no LV breaker)

3.6.4.3 Cross – tripping

3.6.4.3.1 Philosophy

Each protection system shall be directly connected to the trip-coil of the circuit-breaker specific and via a cross-tripping arrangement to the other trip-coil. Cross-tripping within transformer protection systems is somewhat different from that achieved within feeder protection systems in that it is HV or MV circuit breaker specific. Main 1 element which trips the MV breaker is cross connected to trip main 2/ back-up trip coil of the same breaker and vice versa.

3.6.4.3.2 Rationale

Circuit-breakers by design provide two independent trip-coils, which are assigned one per tripping system. As trip-coil supervision is not employed, and therefore the failure of a trip-coil would go undetected and not alarmed, cross-tripping, whereby each protection system is configured to trip both trip-coils directly, via separate paths, without the mixing of DC supplies, is employed to overcome the weakness posed by failure of trip-coils and to restore the overall dependability. A single, failed trip-coil, and a single, failed protection system, will still permit tripping of the circuit breaker.

Cross tripping is also considered to be a less expensive and simpler option than adopting trip-circuit supervision. Its added advantage is simplicity derived from Eskom’s philosophy of routing all circuit-breaker tripping via a single node within each main protection system.

Cross-tripping further enhances the dependability of the fault clearance system during routine maintenance should it be necessary to perform this with the primary circuit in service. A further benefit of employing cross-tripping is when a protection system of unequal performance capability is employed within the two tripping systems. The intention is to ensure that the probability of the superior faster protection system effecting the tripping is maximized. This will be achieved not only by ensuring the maximum in-service availability of the superior protection system, but also by means of the cross-tripping, whereby the superior protection system is able to effect tripping via either trip-coil.

3.6.4.3.3 Design Requirements

Cross- tripping design of the protection system shall have capability to permit the removal from service and testing of one protection system, while the other protection scheme, and hence the transformer, remains in service. Under these conditions, the cross-tripping shall ensure the energisation of both trip-coils should the single in–service protection scheme operates.

The application of equipment (cross-tripping, secure supply) connected to both DC systems shall not compromise the galvanic isolation and independence of the two tripping systems. The design shall be such that all maintenance and availability testing which may be required during power system operation can be carried out without a reduction in the effectiveness of each system below the minimum allowable requirements.

3.6.4.4 Sustained fault tripping

3.6.4.4.1 Philosophy

The sustained fault timer shall be initiated upon a High side (HV) or low side (MV) breaker trip command. The protection scheme logic should facilitate maximum maintenance of substation supplies (auxiliary transformers). This is attained by selectively tripping an associated circuit breaker prior to tripping the HV (energising) circuit breaker through a sustained fault timer (SFT). The SFT feature provides a degree of protection for MV "breaker fail" and MV end zone conditions. Similarly the winding temperature trip as well as the MV bus protection functions must be configured in series with a MV circuit breaker auxiliary contact prior to allowing SFT starting function.

3.6.4.4.2 Rationale

For faults which appear to the protection system as system faults on the MV or LV side, (e.g. MV IDMT O/C or EF) discriminative tripping is achieved by first tripping the associated breaker (MV or LV) and at the same time initiating a sustained fault timer, so that if the fault is actually an in-zone fault (or the MV/LV circuit breaker failed to operate) then tripping of the HV breaker is effected from the output of the sustained fault timer.

3.6.4.4.3 Design requirements

The sustained earth fault function shall operate the circuit breaker main and back-up trip coils.

The sustained earth fault timer shall be initiated by the operation of the following protection functions:

- MV over-current and earth fault;
- Transformer winding temperature trips;
- HV over-current and earth fault;
- LV over-current and earth fault.

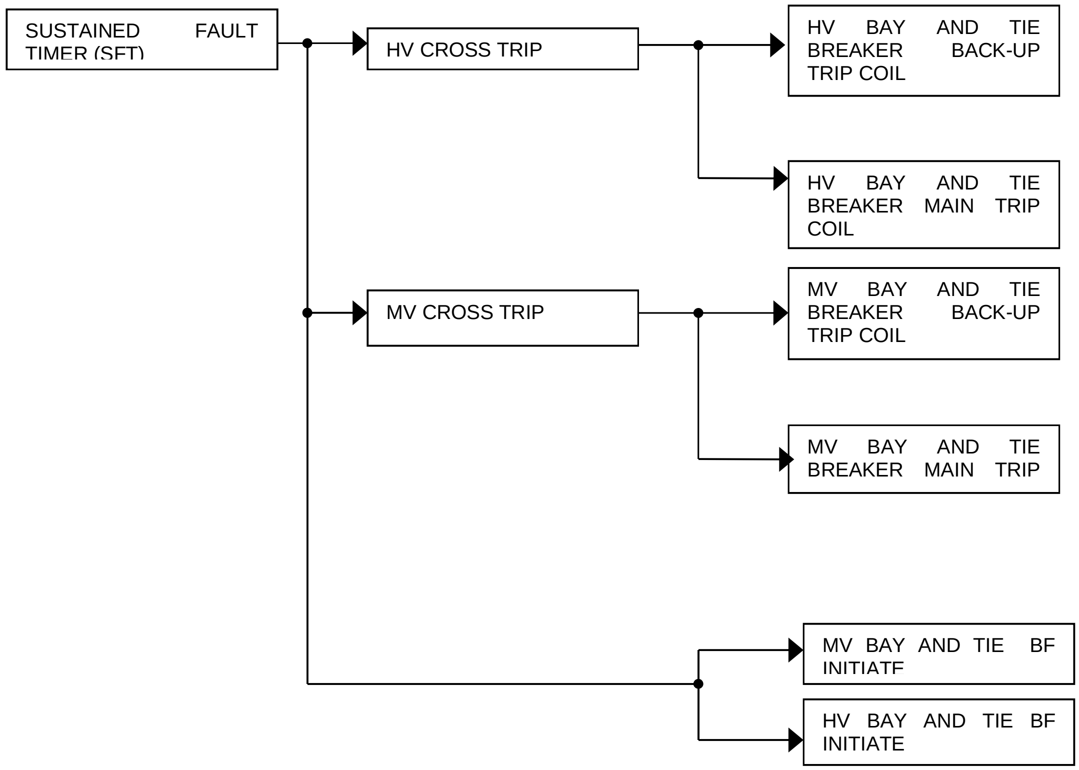

Figure 1: Main1 and/or Main2 Sustained Fault Timer tripping logic

3.6.4.5 Breaker - failure protection

3.6.4.5.1 Philosophy

Each protection system shall include a circuit breaker failure protection function. Circuit - breaker failure functionality shall be initiated by the HV earth fault function and by master trip relay i.e. all unit protections, and the sustained fault timer.

The breaker fail relay outputs initiate the associated bus-zone protection operation as per normal practice. In addition, however, the output of the breaker fail relay also initiates a trip of the other transformer circuit-breakers in order to clear the fault. The circuit-breaker function shall be supervised by a settable current element (current detector).

For the breaker-and-a-half application four of the circuit breaker fail functions (RBRF) shall be used. They shall be used for:

3.6.4.5.2 HV bay breaker circuit breaker fail (RBFR1)

The HV bay breaker circuit breaker fail is triggered by HV master trip, unit protection, HV instantaneous overcurrent, HV buszone, sustained fault timer, HV overcurrent and HV earth fault. The HV bay breaker circuit breaker fail shall trip the HV buszone, HV tie breaker, MV bay breaker and MV tie breaker. It will start the HV tie breaker’s circuit breaker fail, MV bay breaker circuit breaker fail and MV tie breaker circuit breaker fail.

The HV bay breaker circuit breaker fail require the status from the plant to confirm that the bay breaker poles are closed and the test normal switch is selected to normal or test 1.

3.6.4.5.3 HV tie breaker circuit breaker fail (RBFR2)

The HV Tie breaker circuit breaker fail is triggered by HV master trip, unit protection, HV instantaneous overcurrent, HV buszone, sustained fault timer, HV overcurrent and HV earth fault. The HV tie breaker circuit breaker fail shall trip the HV buszone, HV bay breaker, MV bay breaker and MV tie breaker. If there is only one object on the diameter and the HV tie breaker is connected to the other buszone it will also trip the other bus zone. The tie bay breaker circuit breaker fail will start the HV bay breaker's circuit breaker fail, MV bay breaker circuit breaker fail and MV tie breaker circuit breaker fail.

The HV tie breaker circuit breaker fail requires the status from the plant to confirm that the bay breaker poles are closed and the test normal switch is selected to normal or test 1.

3.6.4.5.4 MV bay breaker circuit breaker fail (RBFR3)

The MV bay breaker circuit breaker fail is triggered by the unit protection, MV instantaneous over current, HV and MV over current, MV earth fault and MV buszone

The MV bay breaker circuit breaker fail shall trip the MV buszone, MV tie breaker, Hv bay breaker and HV tie breaker. The MV bay breaker circuit breaker fail shall start the MV tie breaker circuit breaker fail, the HV bay breaker circuit breaker fail and the HV tie breaker circuit breaker fail.

3.6.4.5.5 MV tie breaker circuit breaker fail (RBFR4)

The MV bay breaker circuit breaker fail is triggered by the unit protection, MV instantaneous over current, HV and MV over current, MV earth fault and MV buszone

The MV tie breaker circuit breaker fail shall trip the MV buszone, MV bay breaker, HV bay breaker and HV tie breaker. If there is only one object on the diameter and the MV tie breaker is connected to the other buszone it will also trip the other bus zone. The MV tie breaker circuit breaker fail will start the MV bay breaker circuit breaker fail, the HV bay breaker circuit breaker fail and the HV tie breaker circuit breaker fail.

The MV tie breaker requires the status from the plant to confirm that the tie breaker poles are closed and the test normal switch is selected to normal or test 1 position.

3.6.4.5.6 Rationale

Circuit – breaker failure protection provides a fundamental component of the local back – up protection. Circuit-breaker failure protection is necessary for remote breaker clearing, when a breaker fails to trip and /or when failure to clear a fault occurs. The failure to trip can be due to:

- Contacts do not open after circuit was energized.
- Short or open circuit in trip coil.
- Mechanical - problems with breaker.
- DC supply loss to the breaker.

The failure to clear the fault can be due to the following:

- Contacts open but fault not extinguished.
- Current continues to flow.
- Problem with dielectric strength.

In order to ensure initiation of the circuit – breaker failure function every time a trip signal is issued, a duplication of the function is necessary, i.e. one per protection system. This could be integrated within the same hardware device as the primary protection functions in order to realize an effective cost saving. Breaker – failure protection should only operate when necessary. The use of auxiliary contacts shall be the last resort for breaker–fail initiate.

3.6.4.5.7 Design requirements

The following shall be considered when designing breaker – failure protection functionality:

- Total breaker failure clearing time should be less than system stability limit.
- Circuit breaker failure functionality should be independent of the type of failure detected.
- Circuit breaker failure functionality should operate during loss of dc to the breaker.
- Seal-in circuit should be used to ensure breaker failure function does not drop-out prematurely, but shall incorporate a high speed resetting capability on drop-off of current.
- Design should consider minimum fault current use where the current magnitude may not be enough to pick up the current detector in transformers.

The current detector drop off should not be delayed by DC offset.

3.6.4.6 Bus zone tripping

3.6.4.6.1 Philosophy

Bus zone trip relays should hit each breaker trip coil directly, instead of via master trip relay, and should initiate breaker failure protection.

3.6.4.6.2 Rationale

- 99, 9% of bus-bar faults occur on bus-bars themselves rather than on short piece of stringer between breaker and CT.
- If bus zone hits breaker trip coil direct, then only that breaker is tripped, so maintaining any loads on transformer tertiary (e.g. Station auxiliaries which may be vital, reactors or synchronous condensers).
- Faster speed is achieved on tripping as the operating time of master trip relay is saved.
- For a fault between breaker and CT (which is rarity), this would have to be cleared by transformer IDMT back-up. If there is a weak in-feed from MV source, the IDMT may not operate and one must rely on LV system back-up for clearance (e.g. remote zone III or IDMT). Alternatively rely on transformer winding temperature trip. In special cases it may be worthwhile considering the provision of a 2-step distance relay (readily available on modern relays) on MV side looking into transformer.
    - o Step 1 set instantaneous to cover MV.
    - o Step 2 delayed to cover HV
- If system LV back-up protection cannot be set to cover this fault between the breaker and CT, and there is no vital load on tertiary then an option for the bus zone to hit the master trip which in turn will hit the HV and LV breakers can be considered.

3.6.4.6.3 Design requirements

- Trip caused by bus- zone shall be alarmed locally and remotely.
- Operation of bus zone shall always initiate breaker failure protection associated with that breaker.

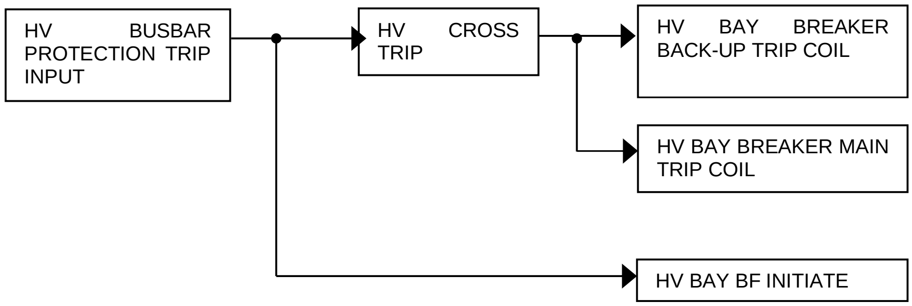

Figure 2: Main 1 and Main 2 HV bus bar protection tripping logic

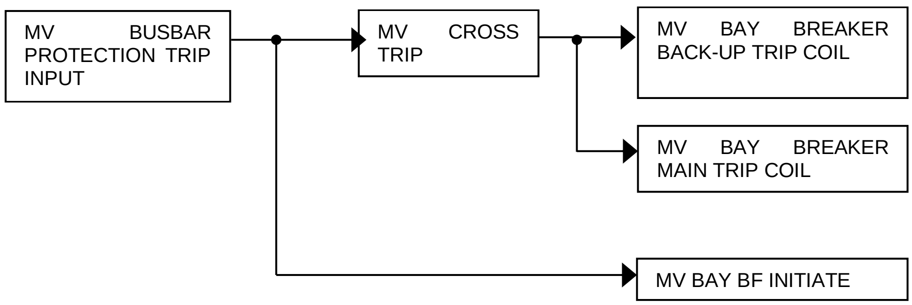

Figure 3: Main 1 and Main 2 MV bus bar protection tripping logic

3.6.4.7 Circuit breaker pole discrepancy

3.6.4.7.1 Philosophy

Circuit breaker pole discrepancy detection shall be included within each protection system to detect a discrepancy between the phases of circuit breakers having three mechanisms i.e. two phases closed and one open or vice versa. The pole discrepancy detection shall produce a trip output whenever the states of the three poles of the circuit breaker are different for a pre-determined period of time.

3.6.4.7.2 HV bay breaker pole discrepancy

The HV bay breaker pole discrepancy shall trip the HV bay breaker with the tie breaker closed. If the discrepancy is sustained it will alarm the discrepancy only. With the HV tie breaker open a HV bay breaker discrepancy sustained it will trip the HV bay breaker, MV bay breaker and MV tie breaker. The HV bay breaker pole discrepancy shall not initiate breaker fail.

3.6.4.7.3 HV tie breaker pole discrepancy

The HV tie breaker pole discrepancy shall trip the HV tie breaker with the HV bay breaker closed. If discrepancy is sustained it will alarm the discrepancy only, With the HV bay breaker open and a tie breaker pole discrepancy sustained it will trip the HV tie breaker, MV bay breaker and MV tie breaker The HV tie breaker pole discrepancy shall not initiate breaker fail protection.

3.6.4.7.4 MV bay breaker pole discrepancy

The MV bay breaker pole discrepancy shall trip the MV bay breaker with the MV tie breaker closed. If the discrepancy is sustained it will alarm the discrepancy only. With the MV tie breaker open and a MV bay breaker pole discrepancy sustained it will trip the MV bay breaker, HV bay breaker and HV tie breaker. The MV bay breaker pole discrepancy shall not initiate breaker fail protection.

3.6.4.7.5 MV tie breaker pole discrepancy

The MV tie breaker pole discrepancy shall trip the MV tie breaker with the MV bay breaker closed. If the discrepancy is sustained it will alarm the discrepancy only. With the MV bay breaker open and the MV tie breaker pole discrepancy sustained it will trip the MV tie breaker, HV bay breaker and HV tie breaker. The MV tie breaker pole discrepancy shall not initiate breaker fail protection.

3.6.4.7.6 Rationale

This method covers a disagreement condition brought about by a failure in the electrical circuitry of the breaker e.g. open-circuited trip coil or close coil, dirty auxiliary contacts etc. The power system should not be exposed to a situation where circuit breaker poles are not in the same position for longer than a pre-determined period of time. This is due to the unbalance in the current flow which would occur during this period. During the unbalance time, currents would flow in the neutral and could cause spurious operation of the residual over-current protection.

The voltage distribution in the system would also be distorted while the poles and thus the current flow, are not symmetrical, a phenomenon which could impact quality of supply to the connected customers.

Pole discrepancy is required for all manually initiated opening and closing of the circuit breaker, as for these operations, no other protection function exists to remove a pole discrepancy from the system. For tripping of the circuit breaker initiated by protection, any resultant discrepancy in the poles of the circuit breaker would be dealt with via the circuit breaker failure protection first, followed by pole discrepancy detection for any resultant unequal pole status.

The exception to this is for a protection initiated trip for the conditions where the faulted phase/s current is above the circuit breaker failure current threshold, while the current in the un-faulted phase/s is below the threshold. If a pole of the un-faulted phase/s fails to open, this would not be detected by the circuit breaker failure protection, but only by the pole discrepancy.

3.6.4.7.7 Design requirements

The electrical type of pole disagreement detection that has been adopted by Eskom Transmission is using a combination of circuit breaker “make” and “break” auxiliary contacts and a timer which gives an output after a set time.

- This shall be a delay on pick-up type relay timer with a settable time delay range of 0.1 to 0.5 sec (steps of 0.01).
- Operation of the pole discrepancy function shall not initiate circuit breaker failure protection.
- The pole discrepancy detection shall cater for a circuit breaker phase disagreement following these actions:
    - Manual initiated close (local or from remote).
    - Manual initiated opening (local or from remote).
- The contacts shall be rated for control/interlock duty.
- A separate local and remote alarm must be provided.

3.6.4.8 Circuit Breaker Anti-pumping Timer

3.6.4.8.1 Philosophy

Anti-pumping device should be incorporated in the protection scheme to prevent repetitive closing of the circuit breakers in the case of a fault. Circuit breakers are often equipped with their own anti-pumping devices, in such cases anti-pumping function is duplicated.

3.6.4.8.2 Rationale

Anti-pumping is employed to ensure that a permanent close command issued to the breaker does not result in repetitive closure of the breaker in the event of a trip signal being issued. This could result in the breaker being damaged.

3.6.4.8.3 Design requirements

Anti-pumping timer shall be a delay on pick-up type relay with a settable time delay range of 0.1 second to 0.5 seconds (steps of 0.01). The contacts shall be rated for control/interlock duty.

3.6.4.9 Spring Rewind function

3.6.4.9.1 Philosophy

Spring rewind facility shall be provided to ensure that the circuit breaker is ready for both manual and automatic re-closing.

3.6.4.9.2 Rationale

Spring rewind operation will occur every time the breaker opens either manually or tripping due to fault. The condition of the spring is monitored by spring limit switches, which indicates the circuit breaker condition for readiness for closing. Spring limit or breaker not charged will be locally and remotely alarmed as closing not healthy.

3.6.4.10 Circuit Breaker Charge Fail

The purpose of this protection is to prevent the spring charging motor from continuously running should a defect develop within a spring rewind circuit.

3.6.4.10.1 Design requirements

Circuit breaker charge fail timer shall be a delay on pick-up relay type with a settable time delay range of 0 seconds to 99 seconds. The contacts shall be rated for control/interlock duty. The breaker charged alarm shall not reset if the condition is latched. The alarms shall be powered by a secure supply. The spring rewind and SF6 low or inhibit alarms shall be common to the circuit breaker not healthy lamp on the panel. It shall be possible to reset these alarms from the protection panel.

3.6.4.11 On-line testing and trip blocking

3.6.4.11.1 Philosophy

All transformer protection schemes shall allow for in service testing of the individual protection systems via Test Normal Switch (TNS) whist yet insuring limited “on line” protection.

3.6.4.11.2 Rationale

Where two protection systems are applied (Main 1 and Main 2) one often needs to be able to test one of the protection systems while the transformer is in service. This is done in Eskom’s case via a switching mechanism whereby one of the two protection systems is prevented from tripping any of the transformer breakers or initiating a bus-zone protection operation.

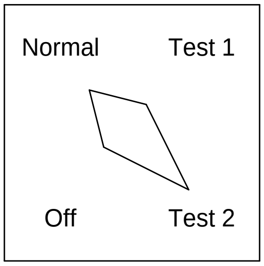

Figure 4: Layout of four position TNS switch

3.6.4.11.3 Design requirements

With the “new technology” relays, careful analysis would have to be undertaken such that an acceptable mix of protection is retained (on line) during in service testing of the protection systems.

TNS switches shall provide the following positions:

Normal: In this position the transformer protection and both HV and MV breaker fail protection are switched on.

Test 1: In this position bus stripping from the breaker fail relays is inhibited by isolating the breaker fail output contacts. The rest of the transformer protection is not affected and the relay operation will trip the circuit breaker.

Test 2: This position is required when secondary injection testing is done on the protection relays. Tripping from the protection relays as well as the breaker fail relay output is isolated while maintaining the DC supply to the auxiliary relays and to the DC/DC converters.

3.6.4.12 Motorized Isolator/ Link Local Control and Status Indication

3.6.4.12.1 Philosophy

All 765kV, 400kV, 275kV and 220kV isolators shall be motorized. It shall be possible to control from local in the panel via control switches and from remote via supervisory. The motorized control of isolators 132kV and below shall be on individual merit.

3.6.4.12.2 Rationale

In the event of the control systems equipment out of service, local/emergency control shall be enabled from switches on the protection panel.

3.6.4.12.3 Design requirements

Isolator status indication shall be displayed on the protection panel.

3.6.4.13 Measurements Indications

3.6.4.13.1 Philosophy

Measurements quantities shall be made available, on a real time basis, both locally and remotely.

3.6.4.13.2 Rationale

Primary quantities are required both locally and remotely to enable the optimum running of the power system, load forecasting, system expansion planning and for statistical purposes.

3.6.4.13.3 Design requirements

The following primary quantities are required:

- HV MW
- HV MVars
- HV volts per phase
- HV current per phase
- MV MW
- MV MVars
- MV volts per phase
- MV current per phase
- Tap change tap position

With modern IEDs, measurement quantities are integrated within the protection device, and are displayed on the HMI. This application eliminates the use of external transducers. The inputs must however be rated for accuracy class accepted for measurements.

3.6.4.14 Disturbance recording

3.6.4.14.1 Philosophy

Disturbance and event recording feature shall be called to be integral part of the relays.

3.6.4.14.2 Rationale

Modern numerical relays can cope well with the scanning speeds, storage capabilities and data interface formats, e.g. COMTRADE required for disturbance recordings. Protection relays with recording function integrated are recommended.

3.6.4.14.3 Design requirements

The recording function should be able to capture and record the following

- Analogue signals-
    - Voltage per phase
    - Current per phase
- Derived analogue signals-
    - Diff currents
    - Bias currents
- Neutral currents – calculated or measured
    - Binary signals

3.6.4.15 Protection Reset Function

3.6.4.15.1 Philosophy

The scheme shall include a protection reset pushbutton.

3.6.4.15.2 Rationale

This facility is provided where the protection forces a lock-out state under internal fault conditions.

The conditions under which the protection latches normally necessitate in-depth study of the faulted circuit.

Design requirements

The function shall be located in the protection panel, not remotely. The reset activity must only be of human intervention.

3.6.4.16 Emergency Trip Function

3.6.4.16.1 Philosophy

Emergency trip functionality shall be provided in all the transformer schemes and its operation shall be independent of the main protection relay.

3.6.4.16.2 Rationale

Sometimes protection functionality might not detect immediately the unsafe conditions, and then by means of emergency trip pushbutton, such conditions can be prevented.

3.6.4.16.3 Design requirements

The emergency function shall directly be routed to the circuit breakers and not via the main relays that can also fail. Emergency tripping shall be alarmed locally and remotely. Emergency tripping shall activate the master trip relay. The pushbutton for emergency tripping shall not be locked, however, means to make them safe shall be provided e.g. pushbutton cap.

3.6.5 Duplication

3.6.5.1 Philosophy

For all EHV applications, the fault clearance system shall incorporate two tripping systems, each of which shall contain a protection system. Eskom transmission has adopted to use dual main protection systems for all transformer applications, which can be realised by employing identical dual standard performance, and dual superior performance or dual reduced performance.

Deviations from the above philosophy may occur for those applications, where the benefits of saving cost outweigh the benefits of identical protection systems. It is therefore permissible to employ, on selected standard performance applications, one standard performance protection system with one reduced performance protection system instead of two identical standard performance protection systems, or, on selected superior performance applications, one superior performance protection system with one standard performance protection instead of two identical superior performance protection systems.

The chosen application option for a given application must be based on a thorough analysis of the potential cost saving versus the performance requirements for that application, and must ensure that the integrity of the power system is not to be compromised.

3.6.5.2 Rationale

In order to satisfy the single failure criterion, dual tripping systems are employed. However Eskom makes a distinction between a failure to operate as a result of a failed or defective protection system, and a failure to operate as a result of a performance deficiency inherent within the design of the protection system. Eskom's interpretation of the single failure criterion is that it shall cater for a failed component within one tripping system (protection system), and not a performance deficiency.

Eskom does not, therefore, stipulate that the two protection systems should use different relays with similar, or different, measuring methods. In fact, Eskom believes that no compromise in dependability is incurred by employing carefully selected and tested identical protection systems, and that employing identical protection systems can yield a more secure solution than non-identical.

The only purpose behind employing more cost effective protection systems is to reduce the overall cost of the protection scheme. During development stage, there shall always be a drive to strike a balance between equipment costs and superior performance. It is now necessary to engineer schemes smarter by better understanding and designing for the associated risks, and by eliminating unnecessary cost premiums by applying suitable functionality and performance capability to meet the specific requirements.

3.6.5.3 Design requirements

The Main 1 and Main 2 protection schemes shall be kept segregated physically and electrically as far as possible; however in trying to reduce costs, Main 1 and Main 2 protection relays are housed in the same relay panel.

The Main 1 has dedicated DC supply which operates the main trip coils of the HV and MV breakers. The Main 2 protection is also supplied from the Main 2 DC board which operates the back-up trip coils of the HV and MV breakers.

3.6.6 Unit and Non-Unit Protection

3.6.6.1 Philosophy

Transformer protection is divided into unit and non-unit protections. Transformer unit protection shall only operate for those faults which are in the transformer protected zone or faults between the HV and MV CTs only. Unit protection relays shall operate a master relay which is a latching relay that can only be reset by means of the protection reset-push button which shall always be located on the control panel.

Non-unit protection shall comprise those protection functions which can operate for system conditions or not cleared system faults not necessarily due to a fault on the transformer

3.6.6.2 Rationale

Operation of the master relay inhibits closing of the HV and MV breakers locally or remotely, this ensures that the transformer is not re-energised until the transformer is inspected as it was operated by the unit protection.

Generally these faults result from insulation failure due to temperature rise or deterioration of transformer oil. The cooler fans are tripped when a master relay has operated as a precaution in case a fault is as a result of fire in the transformer.

Non-unit protection shall not be considered as back-up protection for transformer faults but provides back-up protection for faults on other parts of the system, for instance when a busbar fault occurs while the buszone protection is switched off or fails to operate. This fault can be cleared either tripping the HV or MV breaker, but not both breakers.

3.6.6.3 Design requirements

Transformer tripping from the non-unit protection functions shall be arranged to trip either the transformer HV or MV breaker in order to maintain the station auxiliary supplies, which are normally supplied from the transformer tertiary winding, as far as possible, and also to ease restoration of the system when the non-unit protection has operated due to not cleared system fault, as only one breaker has to be closed to bring the transformer back in service. This can even be done from supervisory because closing of the breakers is not inhibited.

3.6.7 The Main Protection Functionality

3.6.7.1 Differential Protection

3.6.7.1.1 Philosophy

This shall be the main transformer protection for earth faults and phase to phase faults. This functionality is a unit-type protection and shall always operate master trip relay.

3.6.7.1.2 Rationale

The electrical protection measures currents in the phases (through currents and differential currents). The differential relay compares the currents which enters and leave the transformer on a per phases basis. The relays are de-sensitized by certain features such as harmonic and through load bias. The harmonic bias feature is required to prevent mal-operation under magnetizing inrush conditions, such as when energizing a transformer.

The current waveforms of magnetizing current have a heavy 2nd harmonic component. The relay shall de-sensitize automatically when significant 2nd harmonic currents flow in the CT circuit. The through load bias shall de-sensitise the relay when large currents flow through the transformer.

The differential protection should be incorporated with over-excitation restraints blocking feature. This phenomenon occurs when an excessive voltage is applied on the transformer terminals in combination with low frequency which tends to increase the flux density in the transformer core. This is not a fault condition hence a transformer differential protection relay should not operate under these conditions. Transformer over-excitation produces more fifth harmonic currents than is present in fault currents. Therefore, fifth harmonic current is the determining criterion to prevent the transformer differential protection relay from unnecessary tripping.

3.6.7.1.3 Design requirements

Maximum sensitivity is required, while ensuring no incorrect operation for the following:

- load conditions
- Through fault conditions
- Magnetising inrush currents
- DC offset

The transformer differential relay should preferable provide for the respective transformer vector group correction and CT ratio compensation. This is to obviate the need for matching interposing current transformers

The over-excitation feature shall be alarmed locally and remotely.

3.6.7.2 Restricted Earth Fault Protection

3.6.7.2.1 Philosophy

This protection is an additional protection for the transformer differential relay to cater for earth faults close to the star - point of the transformer winding, where phase –to- phase faults are most unlikely to occur. The differential relay may be either the high impedance or the low impedance type. The relay used for this protection shall operate the master trip relay for latching purposes.

3.6.7.2.2 Rationale

The restricted earth fault relay measures zero sequence differential current. For high impedance, no harmonic restraint or through current bias features are provided, whereas low impedance types will require biasing feature and directional comparison criterion in order to discriminate between internal and external faults.

3.6.7.2.3 Design requirements

For transformers with Delta winding, the earthing transformer must be used to provide earthing. It must be electrically placed between the winding and the current transformers.

A high impedance REF protection design requires the following:

- The ratio of the phases and neutral CTs must always be the same;
- The CTs should have the same transient performance response, i.e. matched characteristics;
- The knee-point voltage should be higher than the stabilisation voltage for external faults;
- The voltage across the relay and CTs (all in parallel) should be kept at safe levels while still being sufficiently high to allow operation of the relay when required. The magnetising current of the CTs depends on the voltage across it, but too high a voltage could cause a high magnetising current that leads to a less sensitive scheme.
- Metal oxide varistor (MOV) or surge arrester is connected across the parallel connection of the CTs and relay to clamp the voltage to a safe limit, without affecting relay operation. The MOV protects the relay against high voltage developed during in-zone faults.

Restricted earth fault relays shall have fast operating times and a sensitivity of 20mA or less shall be provided.

Care must be taken into account where the earth fault current is limited via earthing impedance as far as the choice of relay sensitivity and the CT magnetising current is concerned so that there is always sufficient current to operate the relay. For a Delta winding earthed through an NEC/R there is always a sufficient voltage to drive fault current through the fault and NEC/R. In theory, there is always at least half the phase-to-phase voltage available to drive the fault.

3.6.7.2.4 Low- Impedance REF Relay Element

This type of protection is provided within numerical or microprocessor-based protection relays.

For low-impedance REF protection, ratio correction is done via the software; hence no interposing CTs are required. However, the CT transient response must be the same.

3.6.8 Back up Protection

3.6.8.1 HV Instantaneous Over-current Protection

3.6.8.1.1 Philosophy

The HV instantaneous Over-current protection shall be provided for fast clearance of faults which occur between the HV CTs and the HV terminals of the transformer and is backup protection for the unit protection. The instantaneous over-current protection shall detect bushing faults

3.6.8.1.2 Rationale

This back protection is to cater for flashovers external to the transformer on the HV side and should operate for minimum fault conditions and possible earth fault conditions.

3.6.8.1.3 Design requirements

The HV instantaneous Over-current shall not operate for through faults, magnetizing inrush current, MV busbar faults or twice full load current.

3.6.8.2 MV Instantaneous over-current protection

3.6.8.2.1 Philosophy

The MV instantaneous protection shall be provided for fast clearance of MV bushing faults.

3.6.8.2.2 Rationale

This backup protection is to cater for flashovers external to the transformer on the MV side and should operate for minimum fault conditions and possible earth fault conditions.

Design requirements

The MV instantaneous over-current shall not operate for through faults, magnetic inrush, HV busbar faults, MV busbar faults or twice full load current

3.6.8.3 HV Over-current Protection

3.6.8.3.1 Philosophy

The HV over-current protection shall be provided to prevent damage to the transformer if a fault external to the transformer is not cleared. The protection relay shall trip the MV breaker immediately and if the fault current persists, the fault must be internal to the transformer or the MV breaker has failed, so the transformer must be totally isolated if this fault persists for longer than 0.5 seconds.

3.6.8.3.2 Rationale

The HV Over-current relay is a fault current protection, not an overload protection, Overload protection is provided by the winding temperature device. This function also offers back up protection for the unit protection on the transformer.

- Provides back up to faults in transformer or MV side of transformer.
- Covers faults between MV breaker and its CTs, as HV breaker will only be tripped 0.5 seconds after this protection has operated.
- Backup protection for bus bar fault, if MV bus bar protection has failed or is out of service.

3.6.8.3.3 Design requirements

The HV over-current shall be directionalised with voltage and shall look forward towards the transformer. The HV over-current shall provide backup protection for external as well as transformer unit protection and MV busbar faults. The HV Over-current shall not operate for twice transformer full load.

3.6.8.4 HV STUB protection

3.6.8.4.1 Philosophy

The HV STUB protection function shall be used to provide instantaneous protection for the STUB between the HV bay breaker, HV tie breaker and the transformer HV isolator in the event the HV transformer isolator is in the open position and without a HV transformer isolator discrepancy.

3.6.8.4.2 Rationale

The STUB protection is required due to the absence of differential protection when the HV transformer isolator is open and without a HV transformer isolator discrepancy.

3.6.8.4.3 Design requirements

The STUB protection function shall trip the HV bay breaker and initiate the HV bay breaker's breaker fail protection. The STUB protection shall trip the HV tie breaker and initiate the HV tie breaker's breaker fail protection.

3.6.8.5 MV over-current protection

3.6.8.5.1 Philosophy

The MV over-current protection shall be provided to prevent damage to the transformer if a fault external to the transformer is not cleared. The protection relay shall trip the MV breaker immediately and if the fault current persists, the fault must be internal to the transformer or the MV breaker has failed, so the transformer must be totally isolated if this fault persists for longer than 0.5 seconds.

3.6.8.5.2 Rationale

The MV Over-current relay is a fault current protection, not an overload protection, Overload protection is provided by the winding temperature device. This function also offers back up protection for the unit protection on the transformer.

- Provides back up to faults in transformer or HV side of transformer.
- Covers faults between MV breaker and its CTs, as HV breaker will only be tripped 0.5 seconds after this protection has operated.

Backup protection for bus bar fault, if HV bus bar protection has failed or is out of service.

3.6.8.5.3 Design requirements

The MV over-current shall be directionalised with voltage and shall look forward towards the transformer. The MV over-current shall provide backup protection for external as well as transformer unit protection and HV busbar faults. The HV Over-current shall not operate for twice transformer full load

3.6.8.6 MV STUB protection

3.6.8.6.1 Philosophy

The MV STUB protection function shall be used to provide instantaneous protection for the STUB between the MV bay breaker, MV tie breaker and the transformer MV isolator in the event the MV transformer isolator is in the open position and without a HV transformer isolator discrepancy.

3.6.8.6.2 Rationale

The STUB protection is required due to the absence of differential protection when the MV transformer isolator is open and without a MV transformer isolator discrepancy.

3.6.8.6.3 Design requirements

The STUB protection function shall trip the MV bay breaker and initiate the MV bay breaker’s breaker fail protection. The STUB protection shall trip the MV tie breaker and initiate the MV tie breaker’s breaker fail protection.

3.6.8.7 HV Earth Fault Protection (EF4PTOC:1)

3.6.8.7.1 Philosophy

This protection shall operate the HV breaker directly and trip the other breakers after time delay of no longer than 0.5 seconds. For the breaker-and-a-half scheme all stages will be used.

3.6.8.7.2 Rationale

The purpose of the HV IDMT earth fault step1 protection is to provide backup protection for not cleared HV busbar faults.

The purpose of the HV IDMT earth fault step2 protection is to provide backup protection for not cleared transformer faults.

The purpose of the HV IDMT earth fault step3 protection is to provide backup protection for not cleared system faults.

The HV IDMT earth fault step4 will be used to trigger the disturbance recorder.

3.6.8.7.3 Design requirements

The HV IDMT earth fault step1 shall be selected as follows:

- It shall be directionalised and looking towards the HV busbar.
- The pickup current must exceed 5% of twice the full load current of the transformer.
- The primary pick up current should be between 300A and 1000A.
- The pickup current must be selected so that a HV earth fault can be detected with all transformers in service in minimum conditions.

The IDMT earth fault step2 shall be selected as follows:

- It shall be directionalised and looking towards the transformer.
- The pickup current must exceed 5% of twice the full load current of the transformer.
- The primary pick up current should be between 300A and 1000A.
- The pickup current must be selected so that an earth fault on the MV busbar can be detected with all transformers in service in minimum conditions.

The IDMT earth fault step 3 shall be selected as follows:

- It shall be non-directional.
- The pickup current must exceed 5% of twice the full load current of the transformer.
- The primary pick up current should be between 300A and 1000A.
- The pickup current must be selected so that a MV earth fault can be detected with all transformers in service in minimum conditions.

3.6.8.8 MV earth fault protection

3.6.8.8.1 Philosophy

This protection shall operate the MV breaker directly and trip the other breakers after time delay of no longer than 0.5 seconds .For the breaker-and-a-half scheme all stages 3 and 4 will be used. The MV breakers are tripped by the MV IDMT earth fault protection.

3.6.8.8.2 Rationale

The MV IDMT earth fault protection step 3 is to provide back-up protection for not cleared transformer faults.

The MV IDMT earth fault protection step 4 is used to trigger the disturbance recorder.

3.6.8.8.3 Design requirements

The MV IDMT earth fault step3 shall be selected as follows:

- The pickup current must exceed 5% of twice the full load current of the transformer.
- The primary pick up current should be between 300A and 1000A.
- The pickup current must be selected so that a HV earth fault can be detected with all transformers in service in minimum conditions.

3.6.8.9 Impedance Protection

3.6.8.9.1 Philosophy

In special cases, it may be worthwhile considering the provision of a 2- step impedance relay on the MV side looking into the transformer.

3.6.8.9.2 Rationale

For interconnectors, a disadvantage of with IDMT overcurrent protection is that it is very difficult to set it to co-ordinate in both directions, often impossible. Then provision of this impedance functionality can solve this difficulty. Step 1 shall be instantaneous to cover MV faults and step 2 delayed to cover HV. This will definitely improves co-ordination, where it's difficult.

3.6.8.9.3 Design requirements

Two step distance elements are required.

3.6.9 Primary Protection

3.6.9.1 Buchholz Protection

The buchholz relay shall detect the generation of gas and detects surges in the oil. Buchholz relay is considered as a unit protection as it protects the transformer windings and core faults. The gas detection portion of the relay shall also act as an oil level alarm.

3.6.9.1.1 Rationale

The gas detection will operate for low intensity faults, which may be undetected by the other protection. The surge detection will operate for heavy faults within the tank.

3.6.9.1.2 Design requirements

Two or more contacts from the device shall be provided:

- Contact for alarm stage and which shall be provided locally and remotely, preferable separately not as combined output with other devices.
- Contact for trip stage and which shall be provided locally and remotely, preferable separately not as combined output with other devices.

The buchholz device should operate master trip relay. Provision shall be made for two buchholz devices in the scheme, which can be applied independent of each other.

3.6.9.2 Pressure Relief Protection

3.6.9.2.1 Philosophy

This type of protection is intended to release a high pressure inside the tank by opening a vent in the side wall of the tank and trip the transformer. This type of protection is considered as a unit protection hence it operates the master trip relay.

3.6.9.2.2 Rationale

A flash-over or a short circuit occurring in oil filled transformer is usually accompanied by an overpressure in the tank due to gas being formed by the decomposition and evaporation of the oil. The pressure relief device is aimed to limit the tank overpressure on an internal fault and thereby reduce the risk for rupture of the tank and uncontrolled spill of oil, which might also aggravate a fire associated with the fault.

3.6.9.2.3 Design requirements

The valve shall close again when the overpressure is released.

3.6.9.3 Surge or Sudden Pressure Protection

3.6.9.3.1 Philosophy

This type of protection is intended to protect a transformer against any sudden change of pressure in the transformer tank. The relay operates on rate of rise of either oil or gas in the transformer tank. This type of protection is considered as a unit protection hence it operates the master trip relay. The tripping philosophy of this protection is similar to that of Buchholz protection tripping.

3.6.9.3.2 Rationale

The sudden pressure relay is aimed to pick up the oil pressure wave in the transformer tank when a serious fault happens. The device should be able to distinguish between rapid and slow rate of pressure rise and will trip a switch if pressure increase faster than a specified rate. Faster tripping of transformer is achieved.

One drawback to using this relay is its tendency to operate on high-current through-faults. The sudden high current experienced from a close-in through fault causes windings of the transformer to move. This movement causes a pressure wave that is transmitted through the oil and detected by the sudden-pressure relay. If the pressure is large enough, the sudden-pressure relay operates.

3.6.9.3.3 Design requirements

Care should be taken in the application of this device, since it might operate for through faults. An option to use it either as for tripping or alarming only shall be provided.

3.6.9.4 Tap Change Pressure Relief Protection

3.6.9.4.1 Philosophy

This protection only applies to those transformers equipped with tap change facility; the protective device should protect the tap changer compartments against any rise in pressure, or temperature resulting from a fault. This type of protection is considered as a unit protection as it protects the tap change compartments against any internal faults. The tripping of this relay operates both master trip relays.

3.6.9.4.2 Rationale

Tap change has a separate tank; therefore means to detect pressure built up inside this compartment/s is required.

3.6.9.4.3 Design requirements

The pressure relief relay is incorporated in the Main1 and Main2 protection system. This protection shall prevent the further operation of the tap changer. The lock out relay will be activated by this protection.

3.6.9.5 Tap Change Surge Protection

3.6.9.5.1 Philosophy

This protection is intended to protect the tap change compartments against any surges of oil that passes through as a result of an internal fault. The tripping logic of this relay is similar to that of a surge protection relay for a fault in the transformer tank.

3.6.9.6 Transformer Winding and Oil Temperature Protection

3.6.9.6.1 Philosophy

The transformer's top oil temperature is an indicator of the general temperature of the transformer and the ambient temperature but not the overload condition. The winding temperature function will initiate tripping of the appropriate breaker to disconnect the load connected to that winding.

3.6.9.6.2 Rationale

The Winding Temperature and Oil Temperature devices measure the temperature or simulated temperature of the winding and oil. The hottest spot of the transformer windings is used as indicator of loss of life due to transformer loading conditions. The winding temperature function is a load related function preventing continuous erroneous operational condition.

3.6.9.6.3 Design requirement

- A new development is that power transformers will be supplied with digital winding and oil temperature devices.
- This device must alarm its failure to the transformer scheme front panel and also to the control centre.
- The device offers some additional benefits over the traditional electromechanical temperature gauges in that it records the current and temperatures measured by the device. Thus trending can be done.
- The device also has other features such as life time trending, provides analog transducer remote temperature display capability, and checks the state of the PT100 temperature probes and so on.
- The device is still supplied from the traditional winding temperature CT.
- Due to problems with the introduction to the device it has been decided that initially the device will have a back-up traditional electro-mechanical winding temperature gauge.
- The gauges trip contacts are wired in parallel with the digital devices winding temperature trip contact.
- It may be prudent to set the back-up winding temperature device settings a few degrees Celsius higher than the digital device, the idea being to prevent operation of the back-up device first.
- The device does the hot-spot calculation of the winding according to SANS 60076 Ed 2:2011.

3.6.10 Over fluxing and Over-voltage

3.6.10.1 Philosophy

For any power transformer; over fluxing and over-voltage protection shall be provided either to trip or to alarm.

3.6.10.2 Rationale

Transformers over flux when subjected to over voltages or when a frequency decline is experienced below the design limit of the transformer. Over fluxing is an undesirable condition as it causes over heating in the core and associated assembly. If over fluxing is left unchecked, it may lead to the catastrophic failure of a transformer.

Over fluxing is directly proportional to the applied voltage and indirectly proportional to the system frequency. It is for this reason that a volts/hertz (V/Hz) element is specified to protect a unit against over fluxing by disconnecting it from the power system.

3.6.10.3 Design Requirements

The over fluxing and over-voltage protection functions shall be suitable to protect power transformers in accordance with their over voltage and over flux withstand capabilities. Over-voltage based protection functions shall trip the MV circuit-breaker main and back-up trip coils unless indicated otherwise.

The following voltage-based protection functions shall be provided, normally utilising a three-phase or single phase VT supply from the secondary/load-side of the transformer:

a) Over excitation (V/Hz) protection

- Shall have a selectable option to trip or not to trip, both trip coils of the HV and MV circuit-breakers.
- An alarm for this condition shall be provided and reported remotely

b) Over and under voltage elements

- Shall preferably three phase/positive sequence.
- The time-delayed over voltage function shall initially trip only the main and back-up coils of the MV circuit-breaker but shall operate the main and back-up coils of the HV circuit-breaker after a settable additional time delay.

3.6.11 Tap Change Control

3.6.11.1 General

Within the Eskom electrical supply networks practically all transformers of 10 MVA and above have on load tap-changing equipment fitted. The principle use of OLTC equipment is for the voltage regulation within the network and for the control of MW and MVar flows across interconnectors. Location of the tapped part of a winding is partly a construction question. With tappings near the line ends, the number of bushing isolators is reduced; with tappings near the neutral ends, the insulation conditions between phases are eased.

The tap changer compartment is normally segregated from the main transformer tank in order to prevent the contaminated oil from the tap changer mixing with that of the transformer. In this way separate oil actuated protection is provided for within the tap changer.

3.6.11.2 Types of Faults and their Effects

The tap changer equipment can be subjected to earth and phase faults. The main cause of tap changer failure is the stoppage of a tap changer in one of the intermediate positions. Another tap change failure could be as a result of a close in system fault which occurs while the diverter resistors are in service, thus stressing them beyond their thermal limit. When the tap changer switch stops in one of the intermediate positions, it could damage the diverter resistors because they can only sustain high load currents for a short duration.

3.6.11.3 Tap Changer Protection

3.6.11.3.1 Philosophy

The functions that trip the master relay. This protection relates to electrical faults which can damage the transformer or tap change primary equipment such as diverter resistors. These functions are:

- Tap change surge
- Tap change pressure relief
- Tap change over-current

The other protection functions are provided to protect the tap change mechanism and control system.

Operation of this protection causes the transformer scheme to lock-out.

3.6.11.3.2 Rationale

Any further tap changing is blocked until the lock-out relay is manually reset.

Tap change surge function is similar to that of the oil actuated element of the Buchholz relay, similarly for the pressure relief function. The tap change over-current and diverter resistors in service condition were removed from the system as a trip signal. This was to do with unnecessary transformer trips and the statistically low risk of damage to the primary plant under these conditions. As it was implemented, if an over-current condition occurred during the approximate time that the diverter resistor were in service, then the transformer was tripped in order to prevent further damage to the tap changer or transformer.

3.6.11.4 Tap Change Over-current

3.6.11.4.1 Philosophy

The tap change over-current protection protects the tap changer mechanism.

3.6.11.4.2 Rationale

Under simultaneously tap-change and over-current conditions, tap changer components (diverter resistor, contacts) may be subjected to currents in excess of the nominal ratings. It removes the DC to the mechanism control relays when an over-current condition occurs as well as by interrupting the tap change motor supply.

3.6.11.4.3 Design requirements

The design shall be equipped with an input of an over-current blocking signal supplied from the protection scheme. The signal shall be routed to the tap change drive mechanism blocking circuit to block all tap operations.

3.6.11.5 Parallel Control

3.6.11.5.1 Philosophy

When power transformers fitted with on-load tap changing equipment are operated parallel, they should have some form of control which forces the respective tap changers to maintain the same tap position with respect to one another. The parallel control provided shall be sufficient to cater for all possible operating configurations, having multiple zones that can be created in a double bus bar arrangement.

3.6.11.5.2 Rationale

There are various ways of achieving this form of control and from Eskom transmission's perspective this is achieved through the master/follower and/or circulating reactive current method.

3.6.11.5.3 Master/Follower method

The parallel transformers should have identical winding characteristics in order to avoid circulating current at the same tap.

One of the tap change controllers is selected as a “master” while the others are set as “followers”. When a command is received via supervisory control or from the voltage regulating relay to raise or lower the tap position of the transformer bank, the master initiates the raise/lower process and the “followers” follow the master by means of interlocking contacts and a raise/lower bus-wire system. The interlocking function must allow for any one of the units to be selected as the master and must prevent more than one unit to be selected as master. In addition to the interlocking function arrangement, the parallel check timer inhibits further tap changes in parallel transformers if they are at different tap position.

3.6.11.5.4 Design requirements

The interlocking function must allow for any one unit to be selected as the as the master and must prevent more than one unit being selected as the master at any given time. In addition to the interlocking arrangement, Eskom transmission require that a parallel check feature be incorporated such that if any of the tap changers move out of step, then after a set time has elapsed, the master unit is locked out and prevented from performing any other tap changes.

Odd and Even contacts from each tap changer are connected in series and the moment that the circuit is broken, parallel check timer is initiated. When this timer has timed out and out - of - step condition still exists, then the tap change lock out relay is operated.

3.6.11.5.5 Circulating Current method

Certain applications do not suit the master/follower method of parallel control. For instance should the on-load tap changers?

- which are in parallel, be dissimilar in respect of their number of tap positions,
- or their tap step voltages,
- or should the transformer impedances be somewhat different,

Then master/follower control method is not optimal. Under these conditions, then the method used is that of minimising the circulating current that flows.

This can be done by deriving the circulating current in secondary form from the CTs and then artificially adding or subtracting a compensating voltage to the respective voltage regulating relay so that the transformer operating in parallel are driven towards the same tap position.

3.6.11.6 Voltage Regulation

3.6.11.6.1 Philosophy

Bus bar voltages in the power system network should be held within the acceptable limits either manual or automatic operation of the tap changers on the power transformers. When set on automatic, a voltage regulating relay is required to control the tap changers.

3.6.11.6.2 Voltage Regulating Relay

The voltage regulating relay shall control the on-load tap changer, when selected to the auto operating mode. The voltage regulating relays receive voltages from the MV bus bar voltage transformers (VTs). They provide control of the on load tap changer in order to maintain the secondary voltage to the acceptable limits. The voltage regulating relay determines whether the secondary voltage needs to be regulated based on the statutory limits set to the relay. It issues a signal to the on load tap changer to change taps in the correct direction.

The operating characteristics of the voltage regulating relay is such that it waits for a time delay before issuing a control signal to the on-load tap changer. This prevents excessive wear on the OLTC due to short-duration voltage fluctuations. The setting of the voltage regulating relay consists of a voltage set point and a width of “dead band” around the set point.

Under-voltage and over-voltage blocking facilities shall be provided to inhibit the operation of the voltage regulator when supplied voltage falls below, or rises above set limits.

3.6.11.6.3 Design requirements

Raise and lower commands must be performed by potential free, make contacts rated for trip duty. It is required that a potential alarm contact be provided for the case when the voltage relay and tap changer failed to bring the supplied voltage to within the set-point dead-band within 10 minutes.

Indication of raise/lower; manual/auto operation shall be provided either as separate indications or integrated within the regulating relay.

3.6.11.7 Line Drop Compensation (LDC)

LDC is commonly used to compensate for the voltage drop along a line or cable due its load current in order to control the voltage at the remote end in the system. This can be achieved by adding or subtracting various resistance and reactance values (simulating the line impedance) directly in the voltage measurement circuit in numerical relays. It is more appropriate to calculate the volt drop along the line and automatically adjust the measured voltage to provide necessary compensation.

It is Eskom transmission practice not to use this function or feature, but can be provided as an optional feature in the scheme.

3.6.11.7.1 Rationale

Transmission stations are normally not supplying the load directly; it is then not requirement to have this feature as this requires that the transformer voltage be regulated according to load midpoint and not according to the transformer LV bus bar voltage.

3.6.11.7.2 Design requirements

None

3.6.12 Shunt Reactor Protection

3.6.12.1 Introduction

Shunt reactors provide inductive reactance to compensate for the effects of high charging current of long transmission lines. There are two basic shunt reactor configurations which is dry and oil-immersed types. Dry-type reactors can only be used up to 34.5 kV and are often installed on the transformer tertiary winding. Oil-immersed shunt reactors are the most compact and cost-efficient way to compensate reactive power generation of long-distance, high voltage power transmission lines. Oil-immersed reactors can be classified into two configuration designs and that is coreless and gapped iron-core type. Oil-immersed shunt reactors can be constructed as either single-phase or three-phase units and are very similar in external appearance to that of conventional power transformers. They are designed for either self-cooling or forced cooling.

Shunt reactors may be continuously in service and are used on EHV or HV lines. Switched shunt reactors are applied in the underlying system and near load centres.

They differ in size, type, construction, and application. Their capacities range from 3 MVA to over 400 MVA, at voltage levels from 4.6 kV to 765 kV. They can be connected in three different ways, namely:

- Directly to the transmission line circuit;
- To the tertiary winding of a transformer bank which is part of the line;
- To the high voltage bus bars.

When a long high voltage transmission line is switched on, the initial energizing current is capacitive due to capacitive coupling between phases and between the line and ground. This produces Vars and causes the voltage along the line to rise progressively. In order to reduce this capacitive effect, line reactors are installed so that the rise in voltage is reduced when line is energised.

When the line is in service, the line reactor also compensate for line capacitance, absorbing Vars and thus facilitating voltage control.

3.6.12.2 Shunt Reactor Switching

When switching - in a shunt reactor, the magnitude of the energising current is very large; this is due to transient phenomenon related to saturation of the shunt reactor magnetic circuit. This current is in principle similar to the transformer inrush current.

This current can have significant DC offset component with long time constants which results in unequal CT saturation, thereby a large differential current results in the secondary relaying circuits. The gapped core type reactor has an inrush current which can contain a large DC component of long duration and a large amount of harmonic currents. A coreless type reactor has inrush current which can also have DC component but with a small amount of harmonic currents. It is therefore essential to consider the magnitude and the nature of the inrush currents when selecting the relay protection system for shunt reactors.

3.6.12.3 Voltage Surges during Reactor Switching

Research has shown that with specific grounding arrangements at the reactor, successive burst of induced high voltage at high frequencies can result during reactor switching operations.

3.6.12.4 Type of Faults

Shunt reactor may be subjected to various type of faults such as flashover of external bushings, earth faults on the windings or connections (phase faults if the three phases are mounted in one tank), core faults, inter-turn faults and overheating of the winding as a result of excessive loading or failure of the cooling equipment.

3.6.12.5 Shunt Reactor Primary Protection

The protection system should include as a minimum requirement the following protection relays:

- Differential protection relays
- Restricted earth fault protection
- Buchholz trip
- Surge pressure trip
- Neutral Reactor Buchholz trip
- Buszone trip
- Circuit Breaker Pole discrepancy
- Pantograph Pole discrepancy
- Breaker Failure trip
- IDMT Over-current and Earth fault
- Instantaneous Over-current and Earth fault
- Master trip
- Circuit breaker Charge fail
- Anti-pump timer

In principle the scheme philosophy is similar to that applied to transformers:

- Duplicated protection systems.
- Speed of protection operation a priority.
- Master tripping
- Cross - tripping.
- Breaker - fail tripping.
- Bus zone tripping
- On - line testing and trip blocking.

3.6.12.6 Shunt Reactor Tripping

3.6.12.6.1 Philosophy

- For a line reactor fault, where a reactor breaker is included in the scheme, the reactor breaker shall trip. If this reactor breaker fails to clear the fault, it must initiate a 3 phase trip with ARC Lock out at the local and the remote end of the line.
- For a line reactor fault, where a reactor breaker is not included in the scheme, a 3 phase trip with ARC lock out must be initiated at the local and the remote end of the line. If the local feeder breaker fails to open, the scheme should initiate a local bus strip operation.

The bus bar reactor will always have circuit breaker included in the scheme.

- For a bus bar reactor fault, the reactor breaker shall trip. If this reactor breaker fails to clear the fault, it should initiate a bus strip operation and tripping of the zone on which the reactor is connected.

3.6.13 IEC 61850 Implementation

The IEC 61850 communication protocol will be implemented at bay level for now. The present migrated transformer and reactor schemes has IEC 61850 implemented this way. It is only applicable to vertical communication to the RTU 560 and as an option for D400 station RTU. Basically all the alarms to the control centre had been configured using IEC 61850.

Tripping shall remain routed via the hard-wiring.

4. Authorization

This document has been seen and accepted by:

Name and surname	Designation
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5. Revisions

Date	Rev	Compiler	Remarks
Oct 2015	1	V Jansen van Rensburg	First issue

6. Development team

The following people were involved in the development of this document:

- Vincent Jansen van Rensburg

7. Acknowledgement

Not applicable.