8TH SOUTHERN AFRICA
REGIONAL CONFERENCE

14 - 17 NOVEMBER 2017

“ **Electricity Supply to Africa and Developing Economies …. Challenges and opportunities.”**

Preferential Topic: Technology solutions and innovations for developing economies

Pre-emptive tripping of distribution power transformers for decaying auxiliary DC supply

Stuart van Zyl[1], Thomas Jacobs

Group Technology, Eskom

South Africa

Summary

Loss of the auxiliary DC supply to a substation can render it unprotected against certain network faults and at risk of catastrophic infrastructure failure, notably power transformer and MV indoor switchgear failure. This is especially applicable to HV/MV distribution substations in South Africa as the low resistance MV neutral earthing philosophy renders MV earth faults practically un-detectable from upstream HV substations. MV phase faults may also not be detected from the upstream substation(s). This paper describes a protection philosophy that has been applied in Eskom Distribution’s Gauteng Operating Unit since 2010 and which is being considered for nationwide implementation in Eskom Distribution. The philosophy prescribes the tripping of power transformer MV-side circuit-breakers once the substation’s auxiliary supply decays to a critical-low threshold.

Keywords

decaying DC, fail-safe design, substation auxiliary supply.

1. Introduction

Power system protection is defined as:

> *“Provisions for the detection of faults and other abnormal conditions in a power system, for enabling fault clearance, for terminating abnormal conditions, and for initiating signals or indications” [IEV 448-11-01].*

Power system protection is achieved via protective relays which operate the tripping coils of primary circuit-breakers using an auxiliary substation DC supply. The DC supply to Distribution substations is provided via a single battery bank which is sized with sufficient

[1] The author may be contacted via stuart.vzyl@eskom.co.za

stand-by capacity so as to keep the protection system operative for a reasonable time following loss of supply to or failure of the battery charger. A minimum stand-by time of 12 hours is provided to Eskom's Distribution substations which have Supervisory Control and Data Acquisition (SCADA) connectivity and which are situated within a 200km radius of a DC Technical Support section [6]. Loss of DC supply to a substation renders its protection system and circuit-breakers "solid" – unable to operate.

As will be seen in Section 2, loss of the auxiliary DC supply to a substation may render it unprotected against faults on its busbars, primary plant equipment and outgoing feeders. Many of these faults are undetectable from remote upstream substations. The occurrence of such an undetected fault will often result in the catastrophic failure of the solid substation's power transformer(s), Neutral Electromagnetic Couplers (NECs) and/or MV indoor switchgear. Collateral damage to neighbouring plant is common, not to mention the extreme safety risk to persons in the vicinity. Restoration times following such failures normally span days.

In Eskom's experience, the most frequent cause for loss of auxiliary DC supply to a substation is the loss of the AC supply to the battery charger, or (less common) failure of the battery charger. This gives rise to a gradual decaying of the substation DC voltage as the batteries discharge over time due to their standing loads. The alternative of a sudden, complete loss of DC to the entire substation is very rare given the design of the DC distribution system with multiple levels and branches of DC circuits.

Faults with substation DC systems are reported as priority alarms to the SCADA system and are normally responded to immediately by technicians who remain on 24-hour stand-by. Communication break-downs in the SCADA or human systems do occasionally occur, however, and there have been cases where technicians do not arrive on site before it is too late.

This paper describes a protection philosophy which aims to avert the catastrophic failure of primary plant due to the occurrence of faults whilst the substation protection is "solid". Section 2 describes the risks associated with "solid" distribution substations, whilst Section 3 considers different risk mitigation measures, including the option of pre-emptive tripping of MV/secondary-side circuit-breakers of power transformers: tripping the circuit-breakers whilst it remains possible to do so, and before a primary system fault that will be undetectable can occur. Section 4 describes Eskom's design philosophy for low voltage DC tripping, whilst Section 5 describes regulatory and other implications of the philosophy.

The philosophy has been applied successfully in Eskom Distribution's Gauteng Operating Unit since 2010, and is being considered for nationwide implementation in Eskom Distribution.

2. Detection of faults from remote upstream substations

This section describes the extent to which typical South African Distribution network fault conditions are detectable from the remote upstream substation(s) in the case that the local substation's protection is solid due to DC supply failure. In identifying faults which are practically undetectable from remote upstream substations in such scenarios, a requirement for local remedial action during critical substation DC failure is established.

2.1 MV earth faults at HV/MV substations

Medium Voltage networks in South Africa are mostly resistively earthed so as to limit earth fault currents to the range of 360A per supply transformer. The Star-Delta winding configuration of the power transformer gives rise to the scenario whereby a single phase earth fault on the MV side of the transformer reflects as a phase-to-phase fault on the HV side. This scenario is shown in Figure 1 for a YNd1 power transformer with an MV side Neutral Electromagnetic Coupler with Resistor (NEC/R).

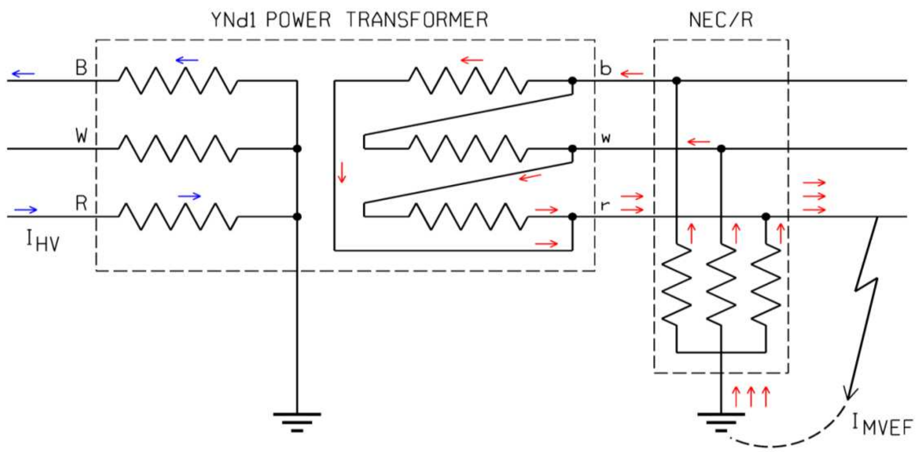

Figure 1: Current distribution for an MV earth fault on a typical Eskom HV/MV power transformer

The fault current that is seen in two phases from the HV-side of the power transformer (I_{HV}) for an MV-side earth fault (I_{MVEF}) is calculated using Eq. 1:

$$I_{HV} = \frac{I_{MVEF} \times N_2}{3 \times N_1} \qquad \text{Eq. 1}$$

Where N_1 and N_2 refer to the power transformer primary and secondary winding turns ratios.

For a 132/22kV power transformer (N1 = 76.2, N2 = 22) with a 360 A MV earth fault, I_{HV} is calculated to be 34 A or 7.7 MVA. For a 132/11kV transformer this figure is 17 A or 3.9 MVA. From Figure 1, it is important to note that the current distribution on the HV side of the transformer will only be detected by phase over current protection, and not by any HV residual earth fault protection element. The MV side earth fault, seen from the HV side of the transformer, is indistinguishable from unbalanced load and is below normal minimum over current protection pick-up settings.

2.2 MV phase faults at HV/MV substations

The detection of MV-side phase faults at a substation by the HV feeders of a remote upstream substation may be achieved using back-up zones of impedance protection relays, or by time delayed over current protection. In reality, measurement and setting limitations renders this impractical for all but close-in and bolted-type MV faults, and detection is marginal at best.

2.3 Secondary-side faults at HV/HV substations

These substations typically include auto-transformers which do not de-couple earth faults on the secondary-side network from the primary-side network as in the example in Section 2.1. That is, secondary-side network phase and earth faults may be detectable from the remote HV substation, but protection limitations may prevent the remote substation from providing back-up to the complete length of all secondary-side feeders at the downstream substation.

2.4 Causes and implications of a “solid” substation

The most common cause of loss of DC supply to a substation is the gradual discharging of the batteries following a loss of AC supply to the charger. AC fail alarms are either not received at SCADA, or are not actioned timeously. The sudden loss of DC supply to a large part of a substation (e.g. due to the tripping of a miniature circuit-breaker) is uncommon owing to the design of the DC distribution circuits.

Loss of the DC supply to an HV/MV substation renders it unprotected against MV earth faults occurring anywhere from the power transformer MV bushings down to the first auto-recloser or fuse installation on each outgoing MV feeder. An earth fault in this zone, which could span an exposure area of tens of kilometres, will only be detected from the HV network once it has developed into a close-in phase fault, typically upon failure of the NEC/R or power transformer due to the sustained earth fault current. A number of Eskom substations and MV feeders have suffered extensive damage due to this failure mechanism.

A phase fault in the "exposure" area described above would similarly be required to evolve into a close-in fault before it became detectable from the remote upstream substation. Again, the fault evolution would often entail catastrophic failure of the solid substation's power transformer(s). MV indoor switchgear has also been prone to catastrophic failure in such circumstances.

A risk assessment was conducted regarding the implications of loss of DC supply to substations of different types, the results being presented in Table 1.

Table 1: Risk assessment per substation type

Substation Type	Probability of Loss of DC	Probability of Primary Fault	Consequence	Overall Risk
HV/MV substation – utility MV network	Medium	High (MV Overhead)	Catastrophic failure	**High**
HV/MV Industrial substation – Customer MV network	Low Medium[1]	Low Medium (MV Cable)	Catastrophic failure	**Medium**
HV/HV substation	Medium	Medium / Low	Catastrophic / Network failure	**Medium / Low**
HV switching station	Medium/ High	Medium / Low	Network outage	**Low**
MV switching station (AIS indoor)	Medium/ High	Low Medium (MV Cable)	Catastrophic failure	**Medium**
		High (MV Overhead)		**High[2]**

NOTE 1: Customer uses independent DC to Utility for network protection.

NOTE 2: MV indoor substations supplying overhead feeders would mostly include transformation and would thus be classified as "HV/MV substation – utility MV network".

3. Avoidance of undetected faults due to substation DC failure

There are three main design options for the avoidance of the risk of undetected primary network faults due to substation DC supply failure:

3.1 Use of redundant DC supplies

This design option, employed as standard in Transmission substations, limits the likelihood of a solid substation by including redundant DC systems with independent AC supplies for battery charging. This design approach is particularly well suited to the dual-main protection philosophy that is applied as standard to Extra High Voltage (EHV) networks. It is not considered to be cost effective for Distribution substations.

3.2 Use of an emergency auxiliary energy supply

A number of manufacturers offer energy storage devices which can be applied to the tripping coils of specific circuit-breakers in conjunction with self-powered protective relays (e.g. powered by Current- or Voltage Transformer signals) so as to provide basic protection even in the absence of the substation auxiliary DC supply. The energy storage devices typically employ power capacitors which are discharged into the circuit-breaker tripping coils by the self-powered relay when a power system fault is detected. These devices provide back-up protection in all DC failure scenarios. When deployed close to the circuit-breaker in question they also provide emergency protection in the case of control cable theft. These devices are, however, expensive and may have limited operational lives, especially in a high temperature environment.

3.3 Use of a fail-safe design (pre-emptive tripping)

Protection systems for safety critical applications may make use of a fail-safe design whereby the circuit-breaker includes a under-voltage trip release – a "dead man's switch" – which releases tripping of the circuit-breaker when the auxiliary supply to the device is lost (either due to operation of the protective relay, or due to failure of the auxiliary supply)[2]. Such systems are, however, insecure as inadvertent disruption of the DC supply, even for the shortest period, will result in the tripping of the primary circuit-breaker.

A more secure variation of the fail-safe design, specifically catering for the decaying DC scenario is to trip the circuit-breaker after the substation auxiliary voltage has achieved a sustained low voltage level for a given security time. The time delay prevents the circuit-breaker from being tripped for a complete loss of DC (as there is no DC supply with which to trip the circuit-breaker).

4. Design philosophy for low voltage DC pre-emptive tripping

The philosophy of applying pre-emptive tripping is proposed as a last-resort preventative measure to avoid catastrophic substation failures arising from network faults which remain uncleared due to loss of DC supply to the substation protection. The philosophy is specifically proposed to cater for the "decaying DC" scenario, and does not cater for a sudden and complete loss of DC to the entire substation.

4.1 Tripping philosophy

The following options exist as to which substation circuit-breaker(s) to trip upon critical low DC supply.

a) <u>Trip one secondary-side feeder</u>

A single secondary-side feeder circuit-breaker could be tripped. Customers affected by the outage would report loss of supply to the call centre, providing a separate communication path to substation SCADA communication that there is a problem at the substation. This has the least impact on network SAIDI (see below) of the two approaches but has the significant disadvantage that the operator will visit a substation that is live, possibly without functioning protection and with a substantial network exposure area to power system faults.

b) <u>Trip all transformer secondary-side circuit-breakers</u>

This is the preferred approach in high risk applications since it aims to reduce the exposure to secondary-side network faults that would become undetectable following further DC voltage decay: the secondary-side busbars and outgoing feeders are disconnected. The transformer's primary-side circuit-breakers are not tripped as this would lead to the loss of the substation auxiliary AC supply (provided via the NEC/Rs or auxiliary transformers connected to the transformer tertiary winding), and would greatly complicate restoration of DC and subsequent re-energisation of the loads.

---

[2] See "under-voltage release" in [1].

4.2 Functional specification for protective device/system

The following functional design requirements apply to the implementation of low DC tripping in Eskom:

1) Trip when station DC voltage level reaches 80% of nominal (+ 2% margin) for 60 seconds. The trip level is determined by the lower threshold of the auxiliary power supply to protective relays: 80% of nominal [2]. This defines the voltage level below which protective relays are no longer guaranteed to be operative. Circuit-breaker tripping coils are specified to still operate at 70% of nominal auxiliary voltage [1], and even considering voltage drops on cabling between the relay room and circuit-breaker represent a less onerous condition than the relay's auxiliary power supply threshold. A time delay of 60 seconds is applied to the trip output to prevent nuisance operation due to voltage dips, or during relay power-up/down.

2) Do not trip for complete loss of DC (<40%). There should be insufficient energy for trip coil operation anyway.

3) Measurement accuracy of ± 2Vdc, immune to AC interference. The undervoltage element must not operate in the event that a 230Vac signal is superimposed on the DC signal.

4) The DC tripping threshold and time delay settings should be fixed settings, or set via computer software, helping to avoid inadvertent adjustment.

5) Distributed system: independent DC voltage level measurement by each transformer protection scheme.

6) Trip signal shall be of the self-resetting type (resetting once the DC voltage level returns above the trip threshold). The low DC trip indication shall be latched.

7) DC low voltage tripping shall operate one or both tripping coils of the designated circuit-breakers. The circuit-breakers shall be interlocked from closing whilst the low DC trip signal is active.

4.3 Applicability to different types of substations

Table 2 describes the applicability of the low DC tripping philosophy at Eskom's Distribution substations of different types.

Table 2: Low DC tripping philosophy application per type of substation

Substation Type	Implement Low DC tripping?	Comment
HV/MV substation – utility MV network	**Yes**	
HV/MV Industrial substation – customer MV network	Partial/No	With agreement of the applicable customer, it is recommended that the least significant load transformer is tripped. Alternatively, cross report a Utility DC low alarm to the customer without implementing low DC tripping.
HV/HV substation	**Yes**	
HV switching station	No	
MV switching station	No / **Maybe**	Dependent on risk of loss of auxiliary AC supply (reduced by using a power VT or on-board auxiliary transformer). Risk increased in the event that the station supplies MV overhead feeders.

The low DC tripping philosophy is implemented as a standard feature of new power transformer protection schemes. Legacy transformer protection schemes that include DC voltage level monitoring capability are to be set for low DC tripping during major maintenance.

Special projects to retrofit hardware for low DC tripping are not envisaged as standard, but may be considered in networks which experience poor SCADA system/communication reliability and which are thus deemed to be at increased risk of DC-related substation failures.

5. Implications

5.1 Hardware and installation cost

Some brands of numerical protection relays offer DC voltage level measurement capability of suitable accuracy and immunity to noise for tripping purposes. In such cases, low DC tripping may be implemented at almost zero hardware and installation cost. In cases where the numerical transformer protection relay does not offer such capability, adding the feature via an external measurement device may cost up to R13k.

5.2 Legal/Regulatory

The following pieces of legislation/regulation are applicable to the low DC tripping philosophy:

1) Regulation 7(1) of the Electrical Machinery Regulations of the Occupational Health and Safety Act [3] requires: "An employer or user shall provide all electrical machinery with controlling apparatus and protective devices which shall, as far as is reasonably practicable, be capable of automatically isolating the power supply in the event of a fault developing on such machinery".

2) Clauses of the Distribution Code: Network Code [4]:

- Clause 6(1) "The Distributor's protection system shall be appropriately designed and maintained to ensure optimal discrimination, safety and minimum interruptions to customers."
- Clause 7.2.1 (3) "All investments must be the least lifecycle cost technically acceptable solution, that is, shall provide for standard supply:
  - a) Minimum quality requirements in terms of NRS 048.
  - b) Minimum reliability and operational requirements as determined by this code and by the NERSA."

The proposed fail-safe design philosophy whereby the plant is de-energised immediately prior to a situation arising whereby it will be rendered unprotected is an established design practice for safety critical applications. The design is a final safety net to prevent catastrophic plant failure with multiple system and/or human failures having to occur before a low DC trip is initiated. It is thus not in contravention of the above laws/regulations. Contrarily, it can be argued the design philosophy promotes the requirements for optimal network safety and reliability at least lifecycle cost.

5.3 System performance

Low DC tripping, in causing loss of supply to networks has an impact on the key network performance index: System Average Interruption Duration Index (SAIDI).

SAIDI is calculated as [5]:

$$SAIDI = \frac{\sum customer\ interruption\ durations\ per\ annum}{Total\ number\ of\ customers\ served}$$

SAIDI is dependent on the number of customers affected and the duration that they are interrupted. A catastrophic substation failure that occurs as a result of an uncleared network fault typically causes outages to entire networks for a number of days. By avoiding such an event, low DC tripping is seen as a means to safeguard a utility's SAIDI performance. Low

DC tripping and the short-duration network outages that it would cause (to the detriment of SAIDI) are completely avoidable should normal utility business practices be followed.

5.4 Emergency response (black-out restoration)

The proposed low DC tripping philosophy has no impact on system restoration after a black-out. Loss of DC supply to substations due to sustained and widespread loss of AC will result in substation transformer secondary-side circuit-breakers being tripped at the end of their DC stand-by times, but the self-resetting nature of the trip signals will allow SCADA control to close back the circuit-breakers immediately after the AC auxiliary supply is restored (by restoration of HV supply to the substation).

6. Conclusion

HV/MV distribution substations in South Africa are at particular risk of catastrophic failure due to network faults occurring whilst the substation is unprotected due to loss of its auxiliary DC supply. This is due to the impracticality of fault detection by the remote upstream substations. HV/HV substations are also at risk, though mostly at a lower risk level.

Whilst a number of options exist to mitigate this risk, Eskom Distribution's Gauteng Operating Unit adopted a fail-safe design solution whereby primary plant circuit-breakers are tripped following a sustained critical-low auxiliary DC voltage level at the substation. In responding only to critical low decaying DC scenarios, the philosophy has proven to be completely secure against nuisance operation, and has operated in rare events to safeguard the substations concerned. The philosophy is presently being considered for nationwide implementation by Eskom Distribution.

7. Bibliography

[1] IEC 62271-1, *High-voltage switchgear and controlgear – Part 1: Common requirements*

[2] IEC 60255-1, *Measuring relays and protection equipment – Part 1: Common requirements*

[3] Occupational Health and Safety Act and Regulations

[4] South African Distribution Code: Network Code

[5] NRS048-6, *Electricity Supply - Quality of Supply – Part 6: Measurement and reporting of medium-voltage network interruption performance.*

[6] Eskom Standard DSP 34-1299, *Minimum Reliability and Capacity Requirements of Essential DC Power Supplies for Various Equipment at Distribution Sites.*

8. Acknowledgement

Jock Rizzotto of Eskom Distribution Northern region first proposed a pre-emptive low DC tripping philosophy in 2008. He was supported by Christo van Zyl.

This paper draws from draft Eskom Standard 240-128725069 "Pre-emptive tripping of Distribution Power Transformers for decaying auxiliary DC supply" which was compiled by the authors and members of Eskom's SCOT working group PA-W-72 under the convenorship of Osie Oosthuizen. Paul Gerber and Peter Almeida of Eskom Distribution's Gauteng Operating Unit were instrumental in the development and deployment of low DC tripping in that business unit.