Shortcomings of the Low impedance Restricted Earth Fault function as applied to an Auto Transformer

Anura Perera, Paul Keller

System Operator - Eskom Transmission

Introduction

During the design phase of new protection schemes to be used in the Eskom network, Model Power System (MPS) testing of the IEDs are conducted to verify that the IEDs are fit for purpose to be deployed on the Eskom network. These tests are conducted by the supplier of the IEDs and are witnessed by Eskom. MPS testing involves checking the performance of the IED connected to a real time simulator that is simulating a realistic representation of a part of the Eskom network. Various types of faults are simulated to toughly test the performance of the IED. The performance of the IED is evaluated taking in to account the correctness and its speed of its operation. During the MPS testing of the new transformer protection schemes Eskom identified some issues with the operation of the low impedance Restricted Earth Fault (REF) function. The problem was that for a simulated HV bushing earth fault of the auto transformer the REF function did not issue a trip command to the breaker.

Manufacturers promote the REF function as a complimentary function to the transformer differential function. However the utility expectation of the function is different; traditional – high impedance- REF is seen as a very sensitive unit protection function capable of detecting very low current faults. This expectation is justified as the differential function is set with a bias of typically 20% to cater for the error introduced by the transformer tap changer – for a 1000MVA transformer this translates to a 200MVA of fault current that the differential element is set not to see- and the expectation is that the REF will take care of these faults; albeit it will only see earth faults.

The source of the non-operation was identified to be the directional check that is done in the low impedance REF. In the application of the low impedance REF to an auto transformer the HV and the MV zero sequence currents are summed and its direction compared to the direction of the transformer neutral current. The problem arises from the fact that for an auto transformer the direction of the neutral current can change based on the impedance ratios of the transformer and the source impedances and the fault position.

Restricted Earth Fault Protection

REF is a unit protection scheme for detecting earth faults. REF protection comes in two flavours; high impedance and low impedance. In the next two sections we shall briefly look at the two types of REF protection and their advantages and disadvantages.

High Impedance REF

The operating principal of the high impedance REF is to balance the sum of the residual phase currents –in the case of an auto transformer, the HV and the MV residual currents –with the output of a current transformer in the neutral. The CT connections of the scheme are show in Figure 1.

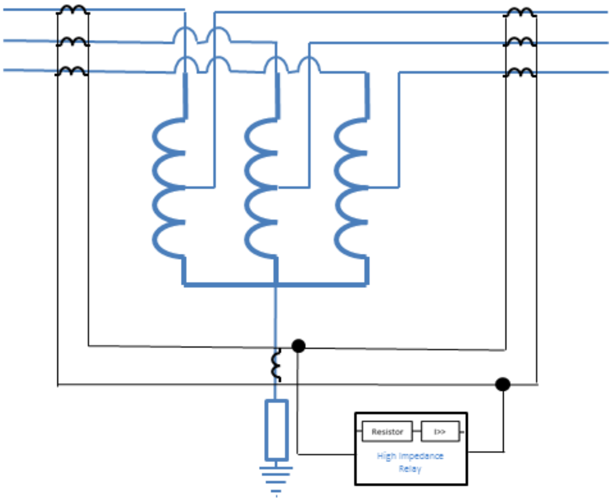


Figure 1-High Impedance REF CT connections

For external faults the sum of the measured residual current should be zero thus this protection should be stable. For internal faults, all the residual currents are measured – in addition to the phase residual currents the neutral current is also measured– therefore it is more sensitive than protection schemes that only measure phase currents. For impedance earthed transformer as shown in Figure 1 the whole winding could be protected with this protection. Even in cases – like in Eskom transmission- where the transformer is solidly earthed significant part of the winding is protected. Text books [Reference 1] claim that this protection is sensitive to the last turn of the neutral. The high impedance relay is typically an instantaneous over current relay (a current detector) with an operating level of typically 20-50mA with a stabilising resistor - 500 to 2500 Ohm - connected in series. The setting for a REF relay is a voltage level, which is the resistor value multiplied by the operating current level. For example for an operating current of 20mA and a resistor value of 2000 Ohm will result in an operating voltage of 40V. Typically, the operating current of the relay is fixed and the required setting is achieved by changing the resistor value.

For an internal fault, the fault current is only seen by some of the CTs; HV and the MV CTs of the faulted phase plus the neutral CT. For the REF to operate, the voltage of the CT secondary side needs to get to the setting value. Besides the operating current, the magnetizing current for the other CTs also needs to be provided by the CTs seeing fault current. This should be borne in mind when calculating the sensitivity of the High Impedance REF protection.

The disadvantage if using High Impedance REF is that because the CTs are physically summed, they need to have the same CT ratio. Further, as there is almost no filtering done in the current detector of the REF relay, to avoid mal operations in transient conditions – like transformer inrush and inception and clearing of external faults - the dynamic behaviour of the CTs also need to be matched. Finally, one needs a set of dedicated CTs for this function.

Low Impedance REF

Fundamentally, the operating principal of the Low Impedance REF is to use the vector sum of the currents- HV, MV and the neutral - as the operating quantity and some factor of the algebraic sum of all input currents or one of the input currents – typically the current from the CT that is working the hardest, i.e. having the highest secondary current - as the bias quantity in a differential element. As in the High Impedance REF case, for external faults the zero sequence currents would add up to zero. However, because the CTs are not ideal devices and for external faults they could be measuring large currents, the relay could end up with a false differential zero sequence current. Since the same measurements are used to calculate the bias current, for external faults the bias current will also be high thus reducing the sensitivity of the Low Impedance REF element making it stable for external faults. Protection text books suggest that this is sufficient security for a Low Impedance REF element.

However, the relay manufactures seem to do an additional directional check. Although the calculations done in the various relays are different, they all fundamentally look at the direction of the transformer neutral current and the phase residual current. In some relays if the current magnitudes are too small to measure the angle, the directional check is forgone. In all of them, if the directional check indicates an external fault values the Low Impedance REF trip is blocked. In doing the directionality check the assumption made by the relay manufactures seem to be that for all earth faults the transformer neutral current flows into the transformer. As will be shown later, this assumption is not always true.

The advantages of using Low Impedance REF are, since each CT input is wired to the relay the currents can be scaled numerically in the relay; it is not necessary to have the same CT ratio for all REF inputs, one does not need dedicated CT inputs for the REF function, the auxiliary security functions available in the relay such as CT saturation detection, directionality checks –if you get it right- can be used to desensitize or block the REF protection, and finally the sensitivity and the security of the function is in the hands of the protection engineer; unlike in the case of high impedance REF which depend on external factors such as the magnetizing characteristics of CTs.

Application of Low Impedance REF

We will examine the application of low impedance REF protection to a transformer with 2 separate earths and to an auto transformer where the HV and MV winding share a common star point and earth.

Transformer with 2 separate star points

In applications where 2 star points are available, the REF application consists of 2 REF functions. One REF for the HV winding and a separate REF function for the MV winding. The HV REF function will compare the HV neutral current to the residual current from the HV phase currents, and the MV REF will compare the MV neutral current with the residual current from the MV phase currents. Figure 2 shows the application to a 3 winding transformer with 2 separate earths.

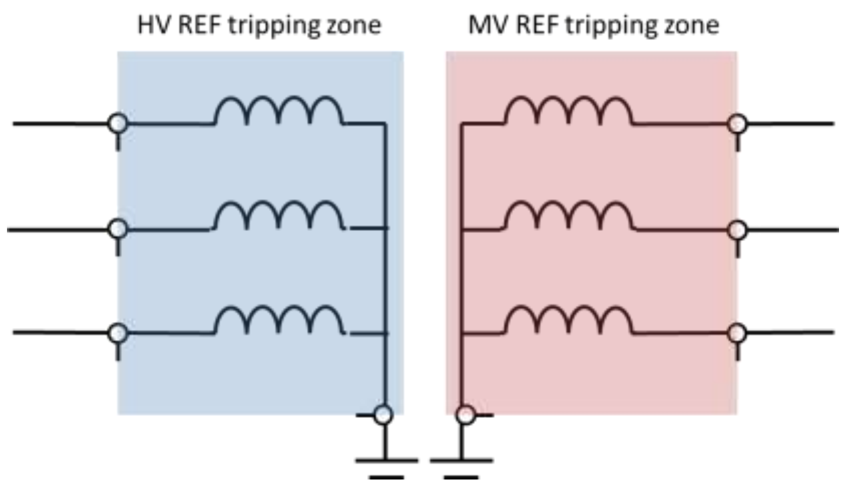


Figure 2-Low Impedance REF application when 2 earths are available

The directional check employed by most relay manufacturers works very well on applications where the REF functions are separated between the HV and the MV. The key to the success of the directional check is that for faults on the HV side of the transformer, the current in the HV neutral will always be towards the transformer. For faults in the tripping zone the neutral current will be towards the transformer and the faulted phase current will also be towards the transformer. For a fault outside the tripping area, the neutral current will still be towards the transformer but the faulted phase current will be away from the transformer (as measured by the connected CTs). The HV neutral current can thus be used as a reference current to compare the phase currents against, and thus a directional determination can be made. The same principle of operation applies for faults on the MV side because the HV and MV earths are separated.

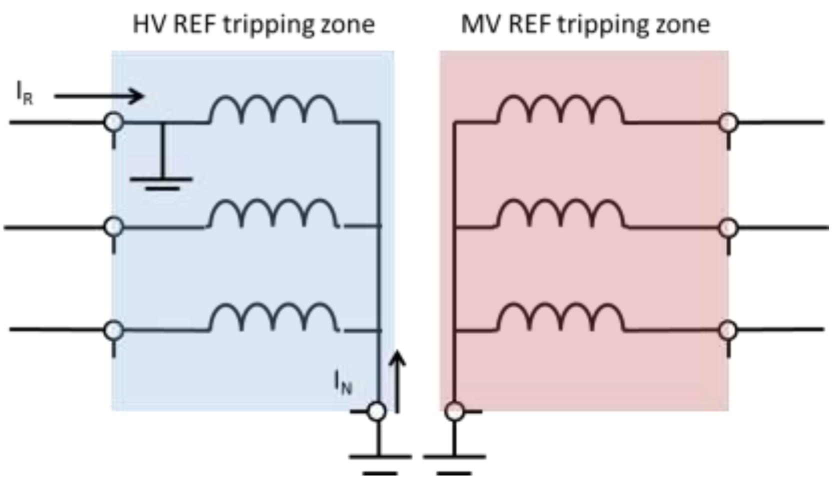


Figure 3-Current direction for a HV in-zone fault

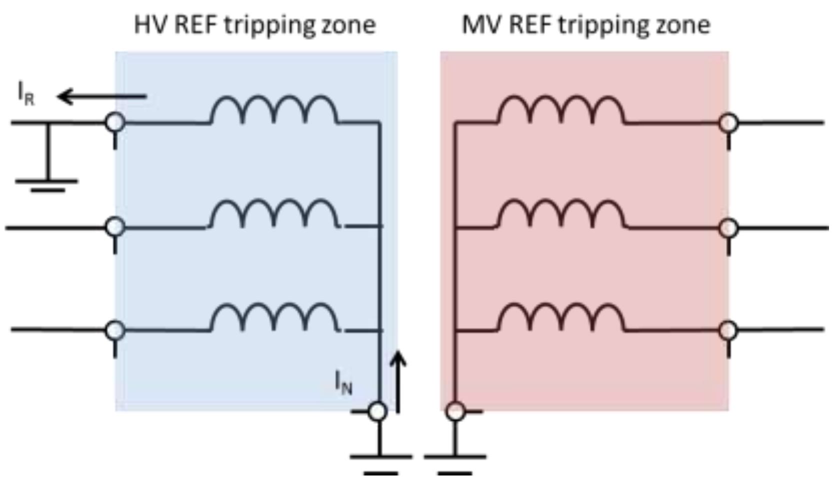


Figure 4- Current direction for a HV out of zone fault

Transformer with a common earth – auto transformer

When the low impedance REF is applied to a transformer with a common earth between the HV and the MV, all currents must be evaluated. A single REF function is used that sums the HV residual current (calculated from the 3 phases on the HV side), MV residual current (calculated from the 3 currents on the MV side) as well as the neutral current to determine the differential component. The neutral current is effectively the vector sum of the HV neutral and the MV neutral as referred to a transformer with 2 separate earths.

Figure 5 shows the application of low impedance REF to an auto-transformer.

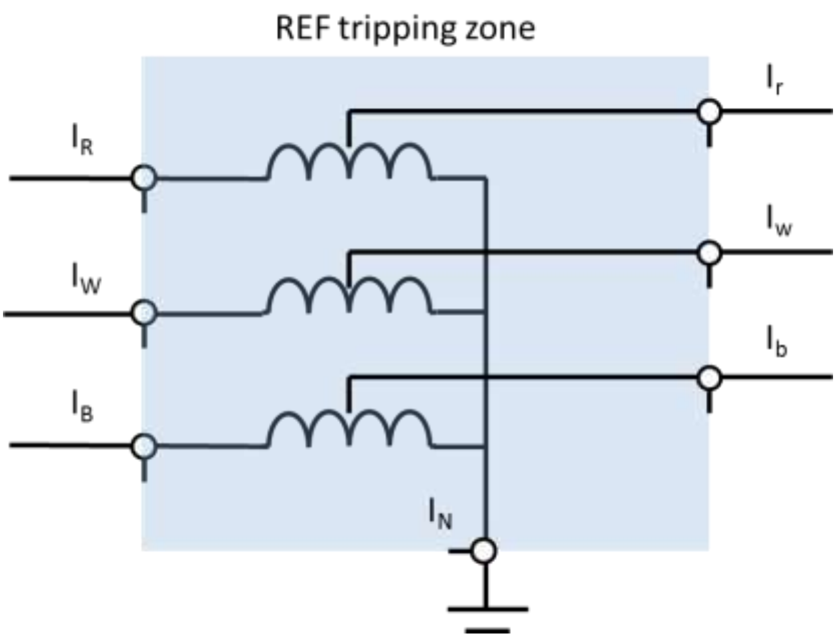


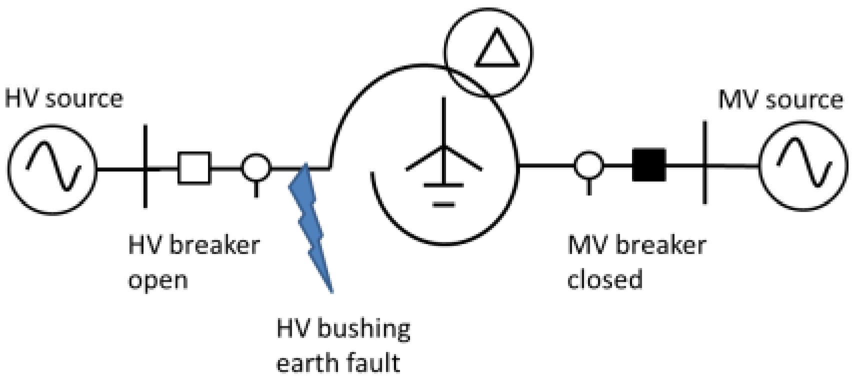
Figure 5-Low impedance REF applied to an auto-transformer

Direction of neutral current in an auto-transformer

We already saw that for a transformer with 2 separate earths, the direction of the neutral current on the HV side is always towards the transformer for faults on the HV side. Similarly the direction of the MV neutral current is always towards the transformer for faults on the MV side.

In an auto-transformer where only one earth is present, the direction of the neutral current can be towards the transformer or away from the transformer. One of the tests for which the low impedance function failed to operate was an earth fault on the HV bushing of the transformer with the HV circuit breaker open. The following calculations will show that the direction of the neutral current can change depending on the strength of the MV source impedance. The first calculation is done with a strong MV source i.e. small MV source impedance and the second calculation is done with a weak MV source i.e. large MV source impedance.

HV earth fault, HV breaker open, Strong MV source



The network above was used to calculate the currents for a HV bushing fault. The following parameters were used. All impedances are in per unit on a 100 MVA base. All network resistances are ignored; hence all impedances are inductive reactances.

Transformer:

765kV : 400kV : 33kV
$Z_{HV1} = Z_{HV2} = Z_{HV0} = j0.00836$ pu
$Z_{MV1} = Z_{MV2} = Z_{MV0} = -j0.00116$ pu
$Z_{LV1} = Z_{LV2} = Z_{LV0} = j0.09104$ pu

MV source:

$Z_{S1} = Z_{S2} = Z_{S0} = j0.01$ pu

Sequence Networks for the above system:

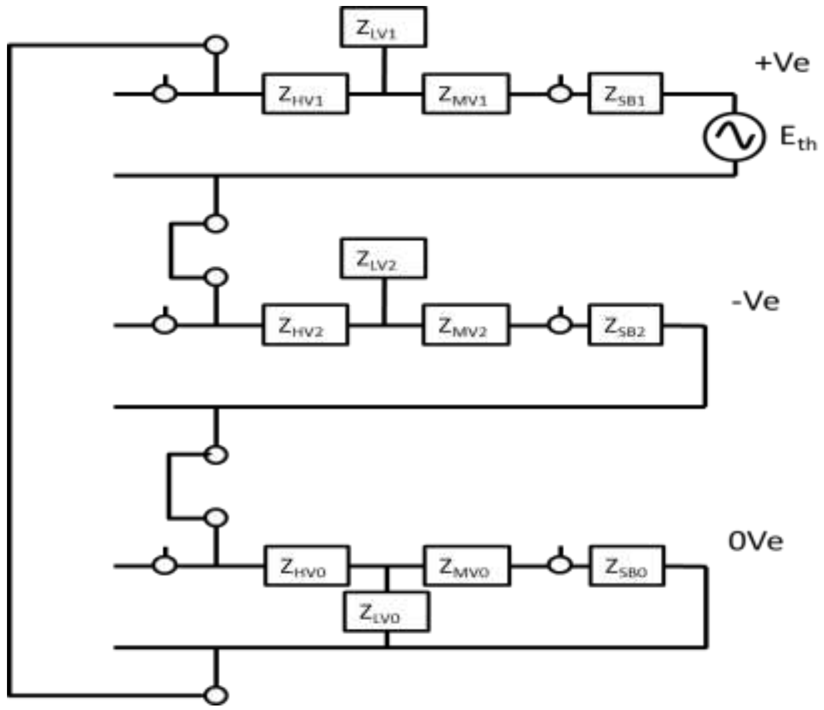


Figure 6-Sequence networks for the test case

Using sequence component theory we can calculate the currents through the HV and MV CTs and then determine how the current would distribute in this network. Figure 7 shows the distribution of currents. It can clearly be seen that the current in the neutral of the transformer is not towards the transformer, but away from it. The directional check used in the low impedance REF will incorrectly classify this fault as external.

Note: The LV winding is not represented in this drawing.

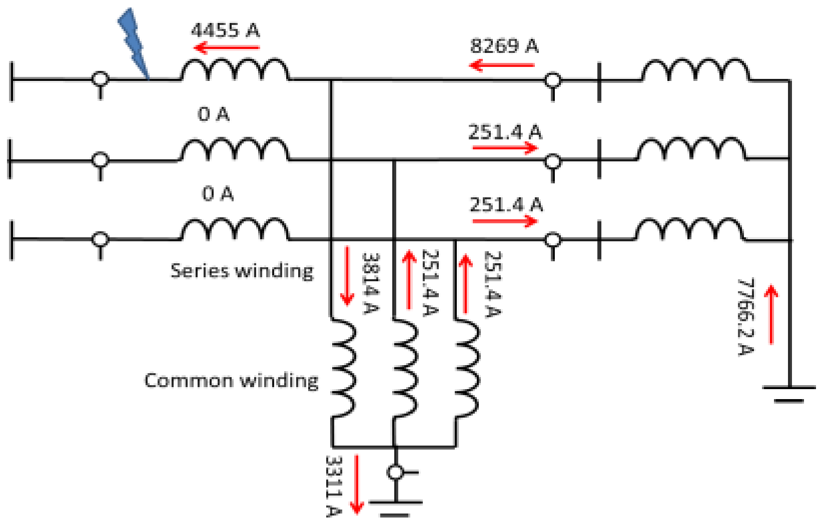


Figure 7-Current distribution for HV bushing earth fault with strong MV source

HV earth fault, HV breaker open, Weak MV source

For this scenario the value of the MV source impedance was increased. The following parameters were used:

Transformer:

765kV : 400kV : 33kV

$Z_{HV1} = Z_{HV2} = Z_{HV0} = j0.00836$ pu
$Z_{MV1} = Z_{MV2} = Z_{MV0} = -j0.00116$ pu
$Z_{LV1} = Z_{LV2} = Z_{LV0} = j0.09104$ pu

MV source:

$Z_{S1} = Z_{S2} = Z_{S0} = j0.1$ pu

Figure 8 shows the distribution of the current. It can be seen that the current in the transformer neutral is now towards the transformer as opposed to away as in the previous example. For this set of conditions/parameters the low impedance REF directional check will correctly determine the fault as internal.

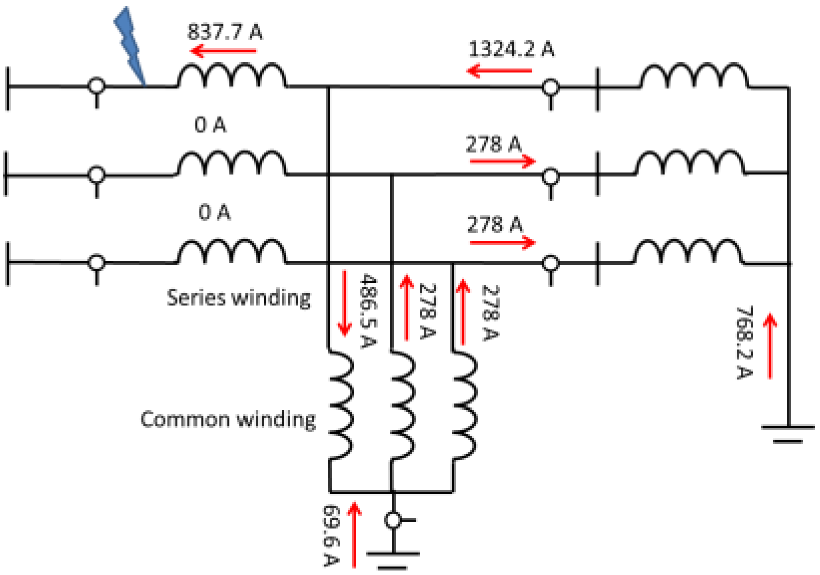


Figure 8- Current distribution for HV bushing earth fault with weak MV source

The same network and conditions were simulated in Matlab and the same results were obtained.

Conclusion

- From a utility perspective the REF function is not seen as a supplementary function to the differential function. The differential relay must often be de-sensitised; hence the greater reliance on the REF function to operate for low current earth faults.
- The use of a directional element in low impedance REF functions work well for applications on transformer with separate HV and MV earths. The assumption that the neutral current direction will always be towards the transformer can however not be made for transformers with a single earth (auto-transformers). This can result in the low impedance REF function

determining an incorrect direction and could lead to non-operation of the REF for internal faults.

- The direction of the neutral current for auto-transformers is determined by the ratio of the MV and HV source impedances as well as the winding impedances of the transformer. A strong MV source will cause the low impedance REF function to make an incorrect directional decision.

Recommendations

- The directional check should not be used as a criterion for the low impedance REF function to operate when applied to an auto-transformer.

References

1- NETWORK PROTECTION & AUTOMATION GUIDE, EDITION MAY 2011, ALSTOM GRID, ISBN: 978-0-9568678-0-3