A TRANSMISSION UTILITY'S EXPERIENCE TO DATE WITH TRANSFORMER PROTECTION SYSTEMS

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Abstract

This paper investigates a number of design, operation and lifetime management experiences of transformer protection systems installed on National Grid Electricity Transmission (NGET) networks. The paper will consider the policy, application design and operational experiences under the following categories particularly since the move to numeric protection:

Policy and application design
Operational experience to date
A bespoke transformer protection scheme solution
Maintenance and post commissioning support

Examples of protection mal-operations during transformer energisation are discussed in the paper. A bespoke transformer overall protection scheme is presented for application of the scheme on a transformer banked with a long cable circuit (> 5km).

1 Policy and Application Design

In 2000 NGET changed its policy on transformer protection systems. This was to make use of numeric protection relays as part of an overall strategy known as Substation Information Control and Protection (SICAP).

A decision was made to move to using single numeric unit transformer protection relays on both auto and two or three winding transformers with primary windings at 400kV, 275kV and 132kV. Mechanical and Back up protection systems have remained separate and unchanged with the exception of integration in modern numerical relays where possible.

Prior to this change NGET had traditionally employed transformer main unit protection schemes utilising either a duplicated high impedance system on auto transformers, or a single biased differential with separate high impedance Restricted Earth Fault (REF) relays.

The introduction of numeric transformer protection systems has enabled more complex protection algorithms to be used such as more flexible differential characteristics and cross-blocking. It has also allowed integration of protection functions into single numeric protection relays, rather than using separate devices per function which was previously the case. Further enhancements are the self supervising nature of numeric relays, and the provision of fault and event records in each relay - allowing for more detailed visibility of reasoning behind protection operations or mal-operations.

1.1 Auto Transformer Protection Application Policy

The protection application policy for auto transformers prior to 2000 was as per Figure 1. Some of the back up protections such as 2OCI EI may be omitted depending on the LV voltage, and mechanical protections are not shown. Each function uses a physically separate relay.

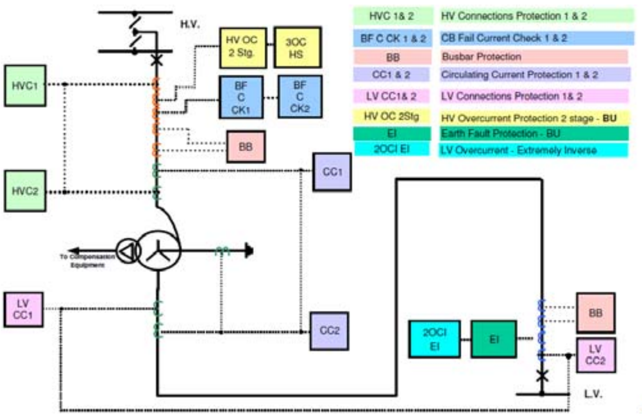

Fig 1: Legacy application scheme for an auto-transformer

The policy after 2000 can be summarised in the following paragraphs.

- A single numeric biased differential unit protection relay to cover for phase and earth faults is now used rather than two high impedance protections. In addition an additional REF protection is required using the same relay and using a different algorithm.

- Buchholz protection and Winding Temperature protection is provided as previously, initiating tripping directly via the first tripping system. However in addition tripping to both trip systems and alarms are provided via the “opto input” of a numeric relay.

- Three phase high set overcurrent and two stage backup overcurrent is identical but implemented in a single numeric relay rather than individual devices.

- LV earth fault protection and LV overcurrent is identical but implemented in a single numeric relay rather than individual devices.

- In general all protection devices now trip via both trip systems which was not previously the case.

1.2 Two or Three Winding Transformer Protection Application Policy

The protection application policy for two or three winding transformers prior to 2000 was as per Figure 2. Each function uses a physically separate relay.

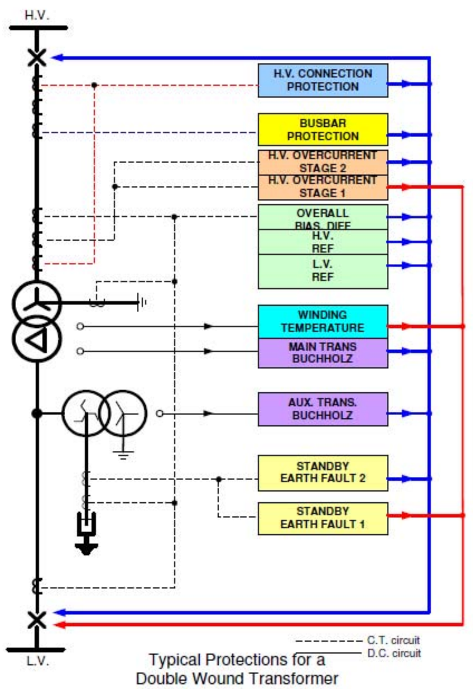

Fig.2: Legacy application scheme for a two-winding transformer

The policy after 2000 can be summarised in the following paragraphs.

- A single numeric biased differential unit protection and REF relay to cover phase and earth faults respectively, is now used rather than a separate biased differential relay and separate REF relays.

- Buchholz protection and Winding Temperature protection is provided as previously, initiating tripping directly via the first tripping system. However in addition tripping to both trip systems and alarms are provided via the “opto input” of a numeric relay.

- Three phase high set overcurrent and two stage backup overcurrent is identical but implemented in a single numeric relay rather than individual devices.

- Standby earth fault protection stage 1 is identical and implemented in a single numeric relay. Stage 2 must be implemented in a separate relay but not in the biased differential and REF relay.

- In general all protection devices now trip via both trip systems which was not previously the case.

The policy for specialist applications such as three winding trackside transformers is similar but other functions are required which have not been stated above.

2 Operational Experience to Date

The performance of high impedance overall protection applied to auto-transformers is generally very reliable due to the protection scheme being relatively simple. In addition, and most importantly, this design is immune to the inrush currents which occur during transformer energisation. NGET has experienced very few mal-operations of the high impedance schemes in the last 10 years. One disadvantage of the legacy high impedance scheme is that it has no self supervision or fault recording facilities, making it very difficult to determine the cause of a mal-operation.

The majority of mal-operations observed in the last 3 years relate to overall protection applied to two-winding transformers, in particular during transformer energisation. The mal-operations of this type of low impedance biased numeric differential protection are listed below:

2.1 Mal-operations on energisation of a transformer

The mal-operated relays employ second harmonic detection technique to identify inrush current and block operation during transformer energisation. The blocking logic is normally phase segregated, but it can be set to cross-blocking for a limited short time. In one specific case in 2009, during energisation of a 100 MVA 400/33 kV two winding transformer (winding connection YN0d11), the overall protection operated due to one phase having insufficient second harmonics for the relay to block operation. The recorded transformer HV current waveforms (inrush currents) are shown in Fig.3 below:

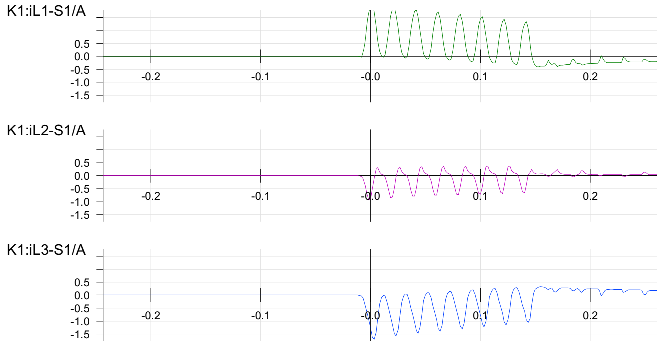

Fig.3: Inrush currents recorded during transformer energisation (x axis is time in second)

The 2nd harmonic in red phase current (iL1) was below the setting 15%, hence the red phase differential protection has to rely on the cross blocking from yellow and blue phases. As the cross blocking was only set to block for 60 ms (i.e. 3 cycles), when it resets, the red phase differential protection operated.

The solution to the problem was to increase the cross blocking delay and reduce the 2nd harmonic pickup threshold as shown below.

Setting	Old Setting	New Setting
2nd Harmonic Restraint	15%	12%
Cross blocking delay	3 cycles	10 cycles

It must be noted that increasing the cross blocking delay too much will result in a long tripping time for internal low current faults with harmonics present.

2.2 Mal-operations due to resonance between a cable circuit and a transformer

NGET has a significant number of mesh substations. At these sites a feeder is normally banked with a transformer as shown in Fig.4 below. These substations are often located in cities and the feeder can be a long cable circuit (>20 km).

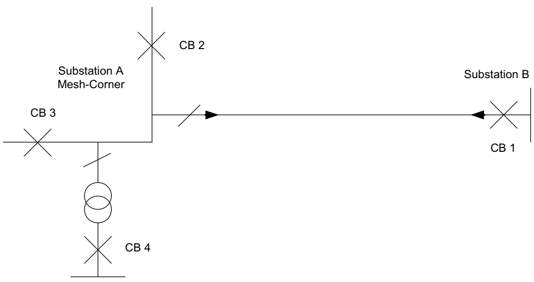

Fig. 4: A feeder banked with a transformer at a mesh substation

If the transformer shown in Fig. 4 above is a two-winding transformer, then the overall biased differential protection is applied. In NGET's experience, if the banked circuit is a long cable circuit (>5 km), when the cable circuit and the transformer are de-energised, the charged cable capacitance can resonate with the reactance of transformer HV winding, it can generate a large resonant current flowing through the transformer HV winding and cable. The resonant current can last as long as 500 ms after the Circuit Breakers (CB) are opened and the maximum peak of the resonant current can be as high as 1200 A (a 180MVA 275/66 kV transformer banked with a 21km 275kV cable). As this current is only present in the transformer HV winding, it is seen by the relay as a differential current and hence it can cause the overall biased differential protection to mal-operate.

Fig. 5A shows an overall protection mal-operation on de-energising a 180 MVA 275/33 kV transformer (winding connection YN0yn0) banked with a cable circuit. The relay tripped at 0 ms as shown in the figure soon after the CBs were opened (CBs opened at –0.04s). The currents recorded were transformer HV current (IA, IB, IC) and HV neutral terminal current (IG). Fig.5B shows the resonant currents of the same event which lasted more than 0.5 s. The mal-operation of the overall protection affected the delayed auto-reclose sequence, causing the transformer to be incorrectly auto-isolated.

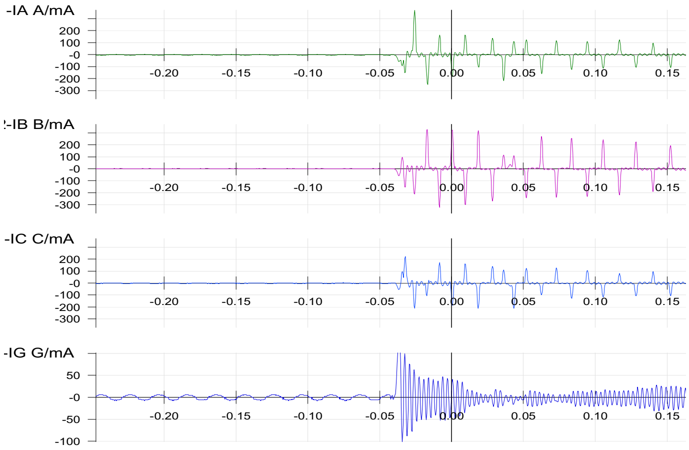

Fig.5A: Transformer HV currents (IA, IB, IC) and HV neutral terminal current (IG) recorded (x axis is time in second)

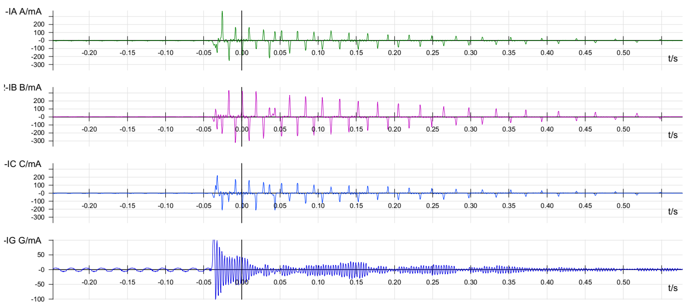

Fig.5B: Resonant currents of same event as shown in Fig.5A above (x axis is time in second)

The temporary solution implemented was to raise the relay setting. A permanent solution was later developed to solve this specific problem and this is discussed in section 3 below.

2.3 Mal-operation due to significant harmonics during transformer energisation

In 2009 an REF function in a numeric transformer protection relay mal-operated following energisation of a 180 MVA, 275/66 kV two-winding transformer (winding connection YN0yn0). The transformer HV and neutral currents recorded by the relay are shown in Fig.6 below. The relay tripped at 0.073 s and the currents after 0.16 s shown in the diagram were the resonant currents after the CBs were opened.

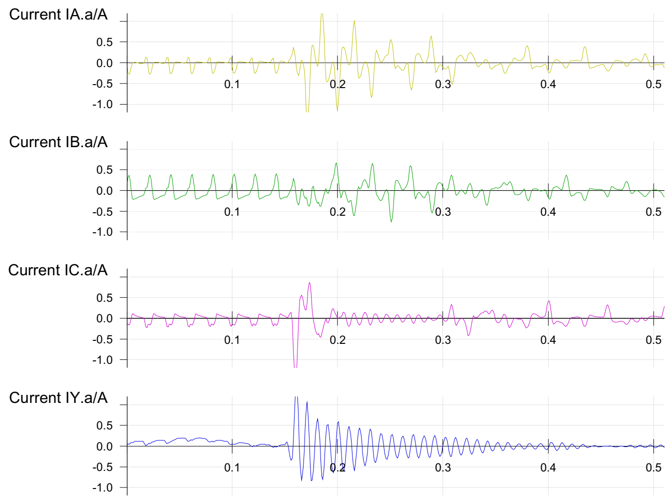

Fig.6: Transformer HV currents (IA, IB, IC) and HV neutral terminal current (IY) recorded (x axis is time in second)

The off-line analysis of the captured data showed that the differential current exhibits a significant increase due to the increasing DC component of the star-point current IY. This is likely to occur if a transformer is banked with a cable circuit. With stabilisation method "maximum phase current", the trajectory of the differential and restraining currents enters the tripping characteristic for about one period and the REF function tripped at 73 ms.

The mal-operation was due to the specific design defect of the REF function. The REF function did not use Fourier filtering (or similar fixed basic frequency) techniques. This allowed operation over a wide range of frequencies, as required for generator protection during start-up or for protection of filter circuits.

In order to avoid REF operation under such measurement conditions, a temporary solution was implemented to raise the minimum operating current from 15% to 20% of transformer full load. The permanent solution would be to modify the REF algorithm for utilising Fourier filtering, or disable the REF function in the relay and replace it with a different REF protection.

2.4 Mal-operation due to inadequate voltage threshold on optical coupler inputs of a numeric relay

In 2009 a number of mal-operations occurred on a numeric transformer protection relay. The immediate cause was identified as incorrect trip commands issued by the relays due to the transient energisation of the relay's optical coupler inputs. The optical coupler inputs were connected to transformer mechanical protection devices (Buchholz, winding temperature trip etc).

Examination of site event logs identified that the timing of the transient optical coupler energisation was coincidental with the timing of the transformer automatic tap change operations. Investigation concluded that the direct cause of incorrect tripping was due to a combination of factors including:

- Failure of the relay to meet the required technical specification
- Non centre tapped 110V DC supplies used for optical inputs
- Battery earth faults
- Long multi-core cables containing both optical coupler input and AC circuits

The optical coupler inputs associated with the relay failed to meet the minimum operate voltage threshold (operated at 19V, it should be 75V) and the capacitive discharge test (150V, 1μF).

To minimise the risk of similar mal-operations, this specific type of relay has been modified with a new optical coupler input card.

2.5 Spurious operations of Buchholz protection

Several Buchholz protection mal-operations have been observed during the past 3 years. These occurred coincident with cooling pumps starting.

3 A Bespoke Transformer Protection Scheme Solution

A bespoke transformer protection scheme solution has been developed specifically to solve the problem discussed in 2.2 above. The solution consists of two overall protection functions; one is a high set element and the other is a low set element. The high set element is instantaneous operation and has an applied setting greater than the maximum RMS resonant current. The low set element has a more sensitive setting (typically 20%) with a 500ms time delayed output to ensure that the relay remains stable throughout the resonance period. Fig.7 below shows both elements applied on a 180MVA 275/66kV transformer (winding connection YN0yn0) which is banked with a 21 km 275 kV cable. The high set element was set to operate at 1.8x transformer full load instantaneously as shown in Fig.7A and the low set element was set to operate at 20% of transformer full load but with a time delay of 0.5s as shown in Fig.7B. Both elements are biased differential with 2nd harmonic restraint. Operation of either element will trip the transformer HV and LV circuit breakers. These settings were determined by simulation studies and injecting the simulated current waveforms into the relay to find the optimum values. This solution has been in service in NGET systems for more than 4 years and to date the performance is satisfactory.

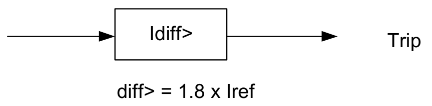

Fig.7A: High Set Overall Protection element with instantaneous operation

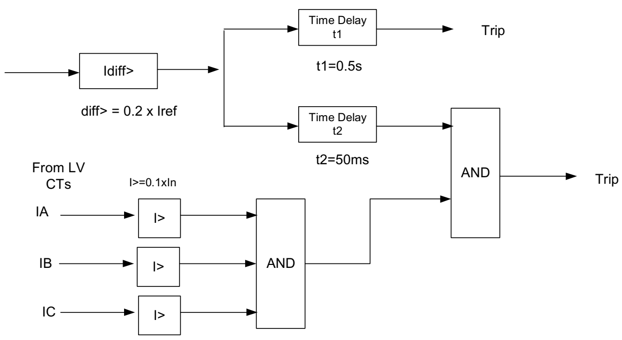

Fig.7B: Low Set Overall Protection element with time delayed operation

As the resonance cannot occur when the transformer is energised, a special logic was implemented in the low set element as shown above to speed the operation of the low set element if it operates when the transformer is on load. It can be seen from above logic that if the load current is detected in the transformer LV CTs (i.e. the transformer is on load) and when the low set element operates, the trip signal would only be delayed for 50 ms instead of 500 ms. The 50 ms delay time is required to make sure that when the transformer LV and HV breakers are opened (i.e. the Idiff> element is about to operate under resonant condition), the overcurrent element IA, IB, IC will reset before the timer t2 operates so that the trip signal can only be initiated with the timer t1 delay. As the t1 is set to 0.5s, the trip signal will not be initiated if the Idiff> operation is due to the resonant current, because it cannot last for more than 0.5s.

In addition to the above overall protection, there is normally a separate sensitive REF protection on transformer HV and LV winding which is immune to the resonant current.

3 Maintenance and Post Commissioning Support

Transformer electrical protection maintenance is as per feeder protection maintenance detailed in reference [1]. The transformer mechanical protection maintenance is aligned with the main transformer maintenance activity. Gas detection devices (Buchholz) are injected with air to confirm satisfactory operation of trip and alarm functions. Winding temperature instruments (WTI's) are checked for correct temperature calibration across the full operating range using a 'dry air test block'. Where applicable, WTI's are also electrically injected to confirm correct temperature gradient 'hot spot' compensation.

Prior to 2003 support for transformer protection systems was provided in-house by NGET staff. From this time onwards the majority of transformer protection installations and replacements have been carried out under National Integrated Control and Protection (NICAP) projects. Due to the complexity and diversity of these solutions the extent to which National Grid staff can effectively diagnose and repair issues is limited. Manufacturer support is required in the event where NGET staff cannot repair an issue with a NICAP installation and restore it to service. As part of an overall protection support strategy NGET has put in place Post Delivery Support Agreement (PDSA) with each of the supplier or installers in order to ensure that an efficient return to service is achieved for any issue affecting the NICAP protection systems. The agreements require the supplier to manage the investigation, repair and return to service of the affected equipment.

4 Conclusions

The performance of high impedance overall protection applied to auto-transformers is reliable due to the protection scheme being relatively simple. In addition, and most importantly, this design is immune to the inrush currents which occur during transformer energisation. NGET has experienced very few mal-operations of the high impedance schemes in the last 10 years.

The majority of transformer protection mal-operations which NGET experienced recently relate to overall biased differential protection applied to two-winding transformers, in particular during transformer energisation with inrush currents. Although the protection can be set to cross blocking using second harmonics, this may delay the protection operation if the transformer is switched onto a single phase to earth fault. To maintain the relay's stability during transformer energisation whilst achieving a fast operation if the transformer is switched onto a single phase to earth fault is still a challenge to relay manufacturers.

If a two winding transformer is banked with a long HV cable circuit (> 5 km), when the transformer is off loaded with the cable circuit, resonant currents can flow between the cable and the transformer HV winding. In NGET's experience the maximum peak of the resonant current can be as high as 1200A lasting for 500 ms. As the resonant current is seen by the transformer overall protection as differential current, it can cause it to mal-operate. The standard overall protection scheme for a two-winding transformer is therefore not suitable for this type of application.

To overcome the above problem, a bespoke protection scheme solution has been developed by NGET. The solution uses two numeric relays, one for the low set biased differential element and the other for the high set biased differential element. To reduce the cost of the hardware, it is recommended for the relay manufacturers to build two biased differential functions with second harmonic restraint in a single relay to cater for this type of application. The setting range of the two functions needs to be adequate for a wide range of applications.

Mechanical protection devices (Buchholz, winding temperature trip etc) can be connected to the optical coupler inputs of a numeric relay for tripping. However the minimum operate voltage threshold of the optical coupler inputs need to be tested and the capacitive discharge test needs to be carried out to make sure that the optical coupler will not operate if an earth fault occurs on the substation battery system or as a result of electrical interference.

References

[1] Wen An, N. Tart, D. Barron, M. Bingham, A. Hackett "A Transmission Utility's Experience to date with Feeder Unit Protection Systems", *DPSP 2012*.