Analysis of a Transformer Differential Relay Over-trip on an External Fault at National Grid

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Introduction

On April 1st, 2010, National Grid experienced a fault on 23kV bus at WH substation. As a consequence of this fault, one of the substation 115/23 kV step-down transformers connected to the un-faulted bus experienced an over- trip by the transformer differential relay. The protection system shall work properly to identify and isolate faults quickly and minimize the impact on interrupting service to customers. Correct and rapid fault clearance and power outage minimization are of concern to utilities and regional Independent System Operator. Base on a disturbance investigation, this paper presents an analysis of the event utilizing fault records, from digital fault recorders and relays, and short circuit simulation to determine what happened and why the 115/23kV transformer differential relay responded to the close-in external 23kV bus fault. The fault records captured by disturbance monitoring equipment and relays and the short circuit simulation provided valuable data which gave an insight into the nature of this disturbance. The fault records provided analog and digital data which allowed an efficient investigation and accurate diagnosis of this event.

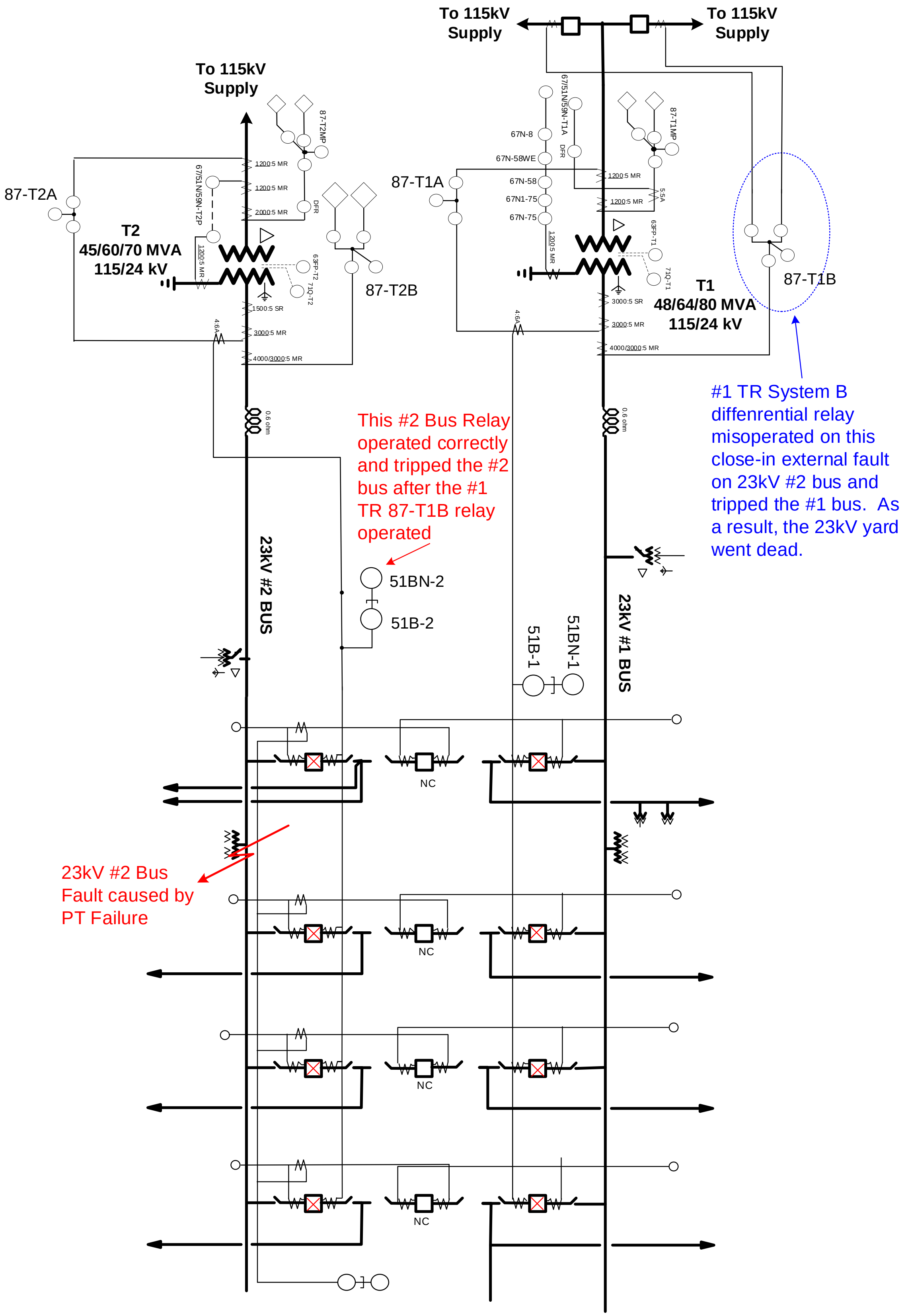
System Overview and Incident Summary

23kV yard of substation WH is supplied by two 115/23 kV delta/grounded-wye step-down transformers which are connected to each 23kV bus. The 23kV portion of the switch-yard is arranged in four bays with a breaker and a half scheme with tie breaker normally closed.

Each transformer is protected by two transformer differential relays, relay A and relay B with different relay maker, wrapping around 115kV circuit breaker's bushing CTs and 23kV transformer outer bushing CTs. Each 23kV bus is protected by differentially connected bus overcurrent relays, wrapping around 23kV transformer inner CTs and all 23kV bus breaker's bushing CTs. The simplified system relay one-line diagram is shown in Figure 1.

On April 1st, 2010 at 6:00 AM, a fault occurred on the 23kV #2 bus at WH substation due to the bus potential device (PT) failure. Because of this bus PT fault, one of the115/23kV #1 transformer differential relays, relay B (87-T1B), on the un-faulted bus side responded to this external bus fault before the #2 bus differential relay (87-B2) operated, which tripped all 23kV #1 bus (un-faulted bus) breakers incorrectly. The #2 bus differential relay operated with a short time delay and tripped all 23kV #2 bus breakers correctly to isolate the #2 bus fault. Up to this point, the entire 23kV yard went dead.

Immediately after the operations, the #1 transformer was tested with no problem being found, but why the #1 transformer differential relays, relay B (87-T1B) misoperated on this 23kV #2 bus fault. A question brought investigation team's attention. Why did one #1 transformer differential relay (87-T1B) over-trip only, although the settings for both differential relays (i.e. 87-T1A and 87-T1B) on #1 transformer are the same?



This #2 Bus Relay operated correctly and tripped the #2 bus after the #1 TR 87-T1B relay operated

#1 TR System B diffenrential relay misoperated on this close-in external fault on 23kV #2 bus and tripped the #1 bus. As a result, the 23kV yard went dead.

23kV #2 Bus Fault caused by PT Failure

Figure 1 The Simplified System & Relay One-Line Diagram at WH Substation

Investigation and Analysis

First, the disturbance investigation began with collection and review of relay settings and targets, Sequence of Events (SOE) data and fault records captured by the digital fault recorder (DFR) and the operated transformer differential relay at the substation WH. Based on the relay settings, reported relay targets and the captured fault records, it was confirmed that:

1. As seen in Figure 2, the C Phase of the 87-T1B relay's operating current exceeded the restraint current a little bit. That explained why it operated.

2. The relay setting for the 87-T1B was reviewed and confirmed to be correct.

3. Settings on differential function for both 87-T1A and 87-T1B relays are the same. It was confirmed that the 87-T1A relay did not sense this close-in external fault as per design.

4. As per our recollection and experiences, there could be a potential issue inside this type of relay which caused this un-expected operation. Therefore, it was suspected that the over-trip associated with CT saturation, but we could not figure out whether external main CTs or relay internal auxiliary CTs got saturated on this close-in external fault.

5. It seems that the 87-T1B relay saw some DC offset at the start of fault. Based on the fault records, the relay saw about 8 cycles of DC offset for this bus fault before the bus relay operated.

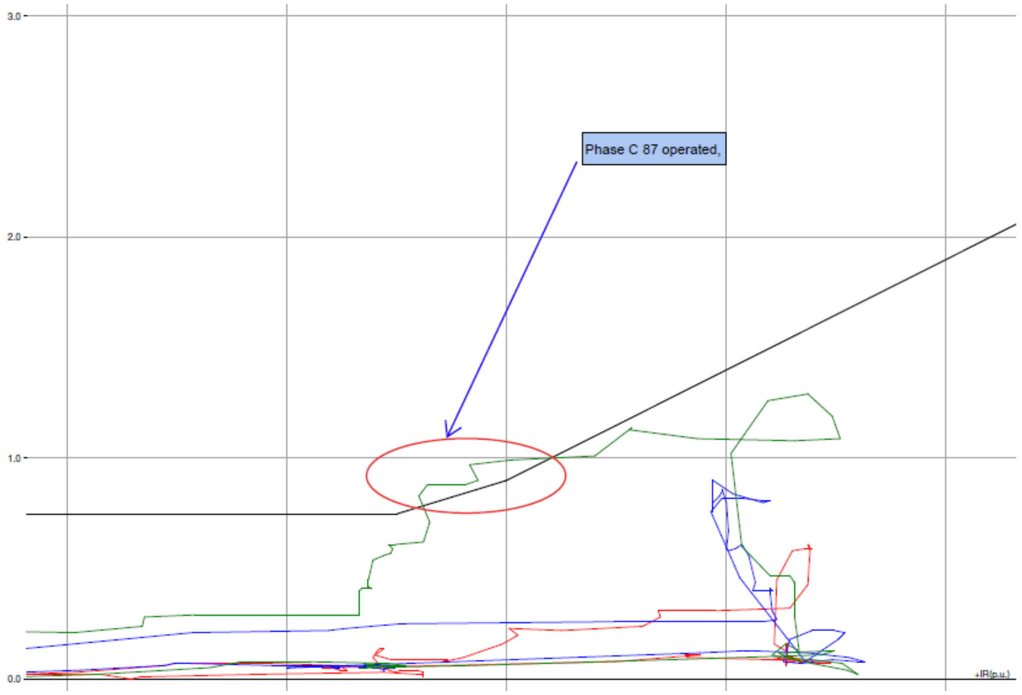


Figure 2 The C Phase of the 87-T1B Relay Fault Record – Differential Trajectory (IO-IR plane)

Note: This is a trajectory of differential fault going back through slope 2. This is a condition of CT saturation. This is a C Phase operation.

6. The 23kV #2 bus differential relay is an electro-mechanical type of overcurrent relay with inverse-time characteristics, and the misoperated 87-T1B is a microprocessor type of sloped percentage restraint differential relay. That explained why the #1 transformer differential relay, 87-T1B, responded to the external bus fault prior to the operation of the bus relay.

The relay vendor was contacted, and the captured records and our observations were shared with them. They further analyzed the fault records, the in-house investigation team's findings and observed the following:

1. Exponential DC offset on all the input currents on both 115kV and 23kV side as seen in Figure 3. It appears that secondary current with DC offset was transformed by the main CTs and contributed to the misoperation. These offset current waveforms seem to be more pronounced for faults on nearby buses.

2. By further analysis of the fault records, it was noticed that the same type of differential relay on #2 transformer, 87-T2B, sensed less significant DC offset current in their mail CTs, therefore it did not respond to this external fault.

3. A simulation of the CT performance as observed was done using a CT saturation program. The parameters of the main CTs used were adjusted to match the response seen during the misoperation. The results can be seen in Figure 4 for the 115kV side currents experienced. The error for the 115kV side current of DC offset was quite marginal.

4. The offset simulation was then run for the 23kV side where fault current was approaching 12kA in magnitude, the result is illustrated in Figure 5. As shown in Figure 6, while the fault level was reduced to 5kA, the CT response for this fault level is much closer to the ideal.

5. Due to DC offset and CT saturation, the differential trajectory (IO-IR plane) entering tripping zone during the fault recovery. Refer to Figure 2.

6. In-sufficient margin in the Slope 2 region during this external fault with saturation due to DC offset.

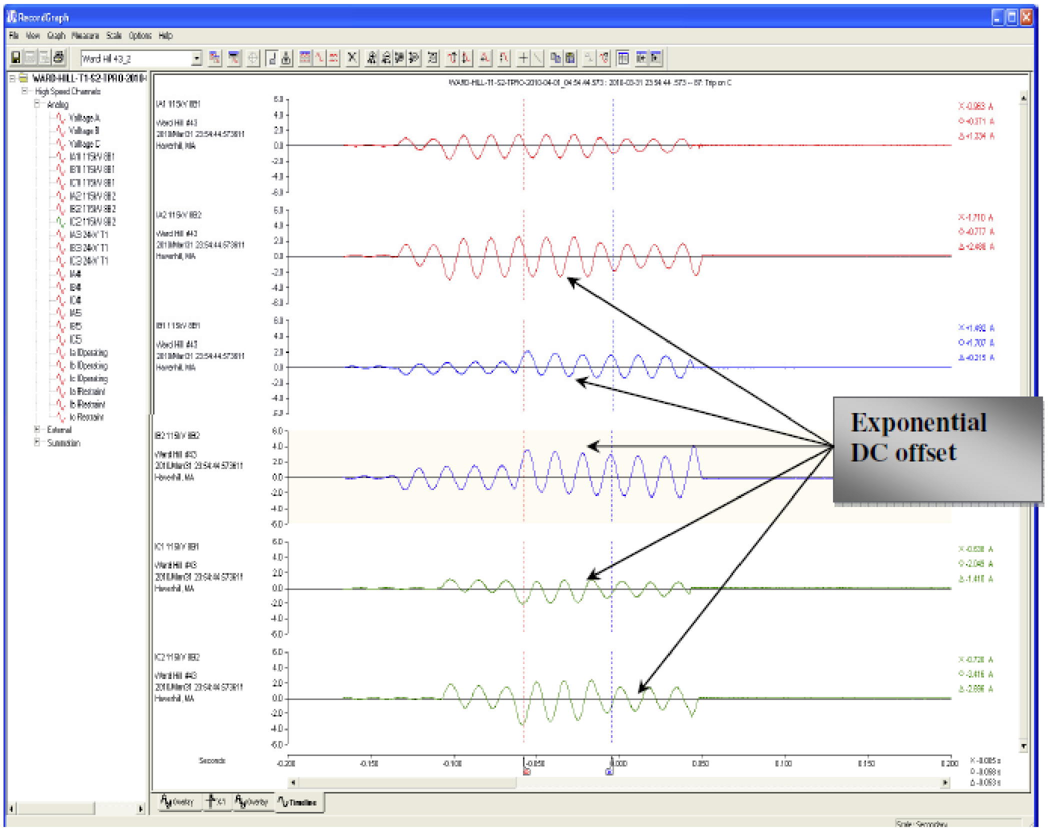


Figure 3 The Misoperated 87-T1B Relay Fault Record – Exponential DC Offset on All Input Currents

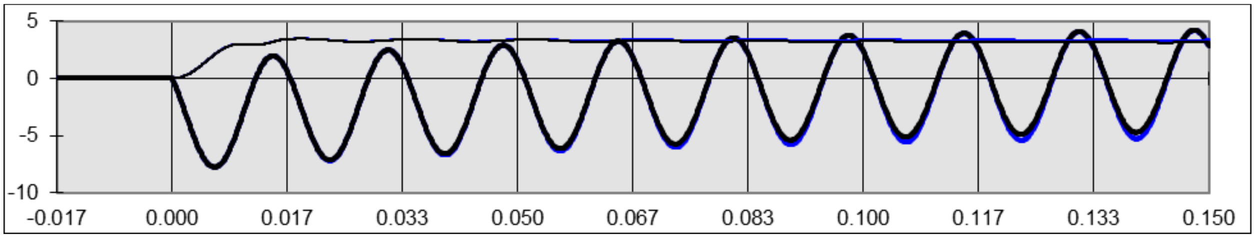


Figure 4 The Offset Simulation for 115kV Side Current by IEEE Version of CT Saturation Calculator

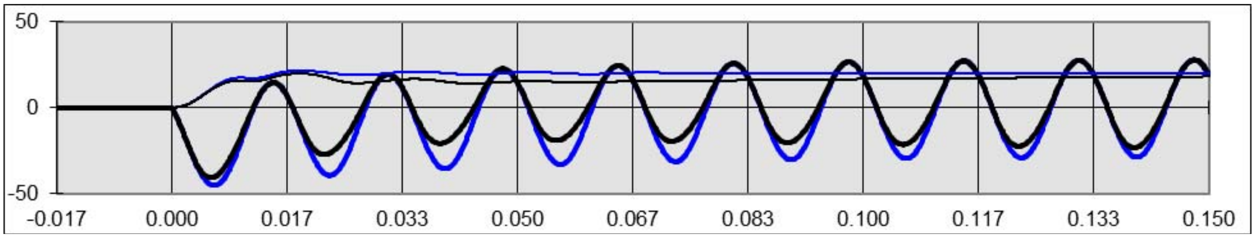


Figure 5 The Offset Simulation for 23kV Side Current @ 12kA by IEEE Version of CT Saturation Calculator

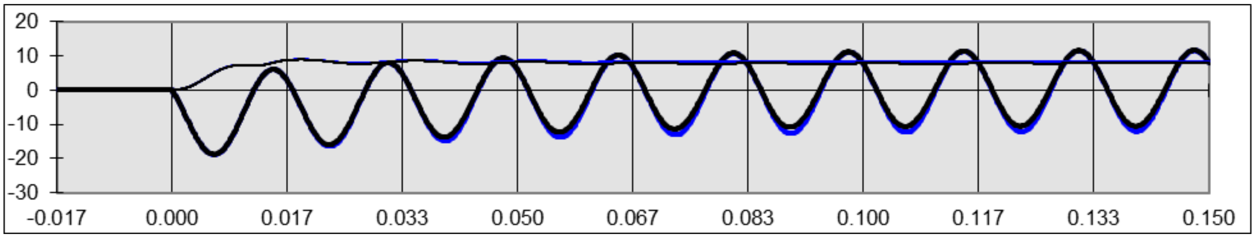


Figure 6 The Offset Simulation for 23kV Side Current at 5 kA by IEEE Version of CT Saturation Calculator

By summarizing and digesting above analysis results and findings from both in-house and the vendor, the two following key questions raised by in-house investigation team got explained as:

1. Why did not the #2 transformer differential relay B, 87-T2B (with the same model and same setting as on #1 transformer) respond to this fault, but #1 transformer differential relay B, 87-T1B did?

   It was revealed that a considerable amount of DC offset current during this close-in fault within the relay 87-T1B resulted in the inappropriate operation. And it was further confirmed that the #2 transformer differential relay, 87-T2B, sensed less significant DC offset current in its CTs, therefore, it did not operate on this external fault.

2. Why did not the differential relay A, 87-T1A, on #1 transformer respond to this fault? Is it possible there are some issues on the internal CTs for the 87-T1B?

   As per vendor's internal CT saturation simulation (Figure 4, 5 & 6) and analysis, it was determined that this relay internal auxiliary CT saturation and large amount of through DC offset current resulted in this inappropriate operation, i.e. the improper operation was due to the internal auxiliary CT saturation and DC offset effect.

In summary, the root cause for this 87-T1B relay misoperation is due to the relay internal auxiliary CT saturated. What is the solution? Is this type of transformer differential relay secure enough to continue using at National Grid system?

Short Term and Long Term Follow up Actions

There are approximately 20 plus this type of differential relays in National Grid system at the time of this misoperation occurred. To reduce the risk of this type of improper operation from re-occurring but remain these relays in service, the investigation team and the vendor mutually agreed to take two follow-up actions as:

1. Short term solution - to change the transformer differential relay slope setting characteristics to ride through this type of through fault. Temporary setting change request for all relays at National Grid system were issued from the in-house investigation team to testing group in two weeks. The testing team then made the setting changes in another week.

2. Long term solution - the R&D team of the vendor proposed to upgrade the existing firmware/software and hardware by replacing internal auxiliary CTs with better quality product for this type of transformer differential relay to prevent this kind of misoperation from occurring again.

   Firmware Upgrade

   Sometimes a close-in external fault can cause considerable DC offset to the currents. If it is severe enough, the currents entering the differential relay using traditional slope characteristics comparison can be incorrectly interpreted as an internal fault and result in improper relay operation.

   It was told by the vendor that the new relay firmware would enhance the security for this type of traditional transformer differential relay and make it less sensitive to fault conditions involving DC offset waveforms as was experienced during this fault. General speaking, the new firmware is secure for external faults and is also sensitive for internal faults. Two new trip supervision features are added to the upgraded firmware:

   - Phase angle supervision of the traditional slope characteristics to provide additional security to the differential function, called as Delta Phase (DP).

   - Rate of Change of Differential Supervision (ROCOD) to compare first derivative of the differential operate (dIO/dt) and restraint (dIR/dt) quantities. If the positive rate of change of IO exceeds the positive rate of change of IR within the first cycle of a fault, ROCOD supervision will allow the differential function to assert if the fault goes into the trip area of the slope characteristics, in another word, it adds security and sensitivity to the differential trip. The DP and ROCOD logics are illustrated in Figure 7 and 8.

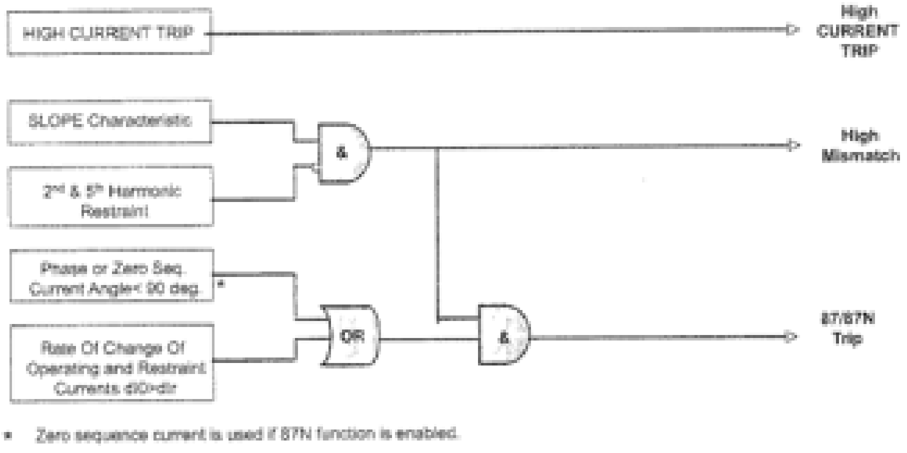


Figure 7 Differential Function (87) Logic with DP or ROCOD Supervision

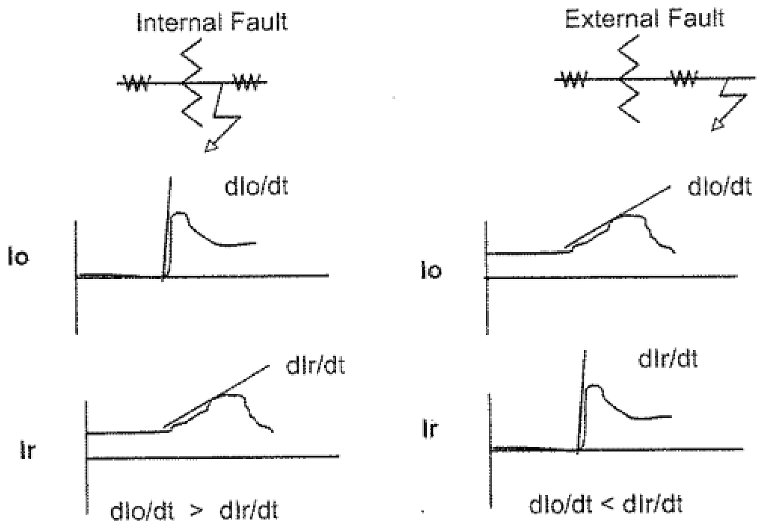


Figure 8 Rate of Change of Operating and Restraint Quantities

Hardware Upgrade

It is very likely that the internal auxiliary CTs go into saturation because they do not have enough iron core or enough turns. It is difficult to replace with bigger internal auxiliary CTs where there may be physical limitations for their existing relays. However, it is possible for their next generation of this type of relay. With a mutual agreement between National Grid and the relay vendor, it is decided to upgrade the internal auxiliary CTs on next platform design for this type of differential relay. The new generation of the relay with better quality of CTs has become available in four years after this event, and National Grid have been utilizing it since.

Corrective Action on Firmware Upgrade

An in-house evaluation on this new firmware was conducted by the investigation team, including review of the new addition logic on DP and ROCOD supervision and the vendor's lab simulation results. Next, we planned to perform a bench testing on this type of differential relays with the new firmware by in-house testing group. At National Grid, there is an in-house test procedure on transformer differential relays as:

- Test 1: 1 Phase test of Minimum Operating Current Differential Element Pickup (IOmin) at HV, LV & TV (no change from the existing test)

- Test 2: 1 Phase test of Unrestraint Differential Element Pickup (87 High Current) at HV, LV & TV (no change from the existing test)

- Test 3: 3 Phase test of Restraint Differential Element Pickup (87T) of Winding 1 to 2, 1 to 3, etc. (Note: at National Grid, a 2-winding test at each time is performed.)

It seems the new additions on ROCOD supervision needs to be tested but how? Do we have to revise the existing Test 3, the restraint differential element pickup test, while using this new firmware? By referring to Figure 7, it was figured that the test of RODOC feature can be as a new Test 4 by using the test results from the above Test 3 – Restraint Test with a minor change on the test plan. In the existing Test 3, instead of monitoring 87T function (OUTPUT 1) of the relay, monitor 87 High Mismatch (OUTPUT2). Then the new Test 4 with the 87T supervised by ROCOD can be performed as:

- Test 4: 3 Phase test of 87T trip with Slope + ROCOD + DP supervision at a balance point (i.e. an operation point) of the 87 High Mismatch pickup received from the Test 3 by ramping up winding 1 input current from (I input1 @balance point – 0.2 A) to (I input1 point + 0.2A) to monitor if the relay operates.

This in-house Test Plan (Test 3 and Test 4) for the 87 Trip Test with Slope + RPCOD + DP (i.e. the new firmware) is different from the introduced methodology in the revised manual from the vendor, which is much simpler and, from a practical perspective, involving less changes for the existing in-house testing plan for traditional transformer differential relays. This proposed in-house test plan and test results were sent to the vendor for comments with a positive feedback.

Given that the investigation team recommended to utilize this customized testing methodology at National Grid system after the firmware upgraded. All in-house engineers and testing technicians and the vendor accepted this customized testing plan. With this new test plan, only one test point needs to be added on the top of the restraint pickup point from Test 3, which makes the testing more efficient and, therefore, saves time and money! Up to this point, National Grid decided to accept this new firmware and upgraded the firmware for all in-serviced relays and test them with the new customized test plan to improve the system reliability. Furthermore, the test methodology was approved internally as the standardized test plan for this type of transformer differential relay at National Grid system.

Summary and Closing Thoughts

Briefly recapping what we have discussed as follows:

1. This paper discussed a case study on a sloped percentage restraint transformer differential relay over-trip on a close-in external fault due to severe DC offset current and relay internal auxiliary CT saturation.

2. It presents an analysis of this event utilizing relay setting and target information, fault records and relay vendor’s simulation results to determine what happened and why happened, in other word, what is the root cause of the transformer differential relay improper operation on the transformer connected to the un-faulted bus.

3. To prevent from traditional sloped percentage restraint transformer differential relay from misoperating on close-in external faults, what corrective action plan was implemented by working with the vendor to upgrade the firmware and hardware on the relay.

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