Methods and Benefits to the Application of Ultra-High-Speed Transformer Protection

Roy Moxley, Stefan Nohe, - Siemens

Introduction -

In the spring of 2016, a fault occurred in a large single phase auto-transformer on the transmission system of a major US electric utility. The fault was cleared in a time that met standard operating speeds of both relaying and the circuit breaker but a tank failure occurred that caused the spill of a large amount of oil. Significant damage to the core and coils of the transformer also occurred.

As a part of ongoing efforts to improve the performance of the overall protection system it was decided to replay the transformer fault into a relay with a different operating algorithm than the two that were used to protect the transformer. Results showed that the different relay operated from 8 - 20 ms faster than either of the two installed relays. Analysis of the fault energy shows that with that faster speed there would have been 15 - 30% less energy dissapated into the fault. Inspection of the ruptured tank and the physical damage to the transformer suggest that with that reduction in energy there may have been significantly less damage, resulting in lower cleanup and repair costs.

The paper discusses the fault, the playback, and the operating principles of the relay under investigation. Transformer damage and standards are discussed. The relationship between speed and security for different operating principles is evaluated and economic and engineering tradeoffs are considered to assist engineers in making protection decisions.

Transformer fault and analysis –

In the case of this transformer failure we have both the evidence of the failed unit, fault studies and fault records. Examination of the transformer revealed the fault point to be inside the unit near the low voltage connection. This is verified by a comparison of the voltages on the high and low side of the transformer shown in figures 1 and 2.

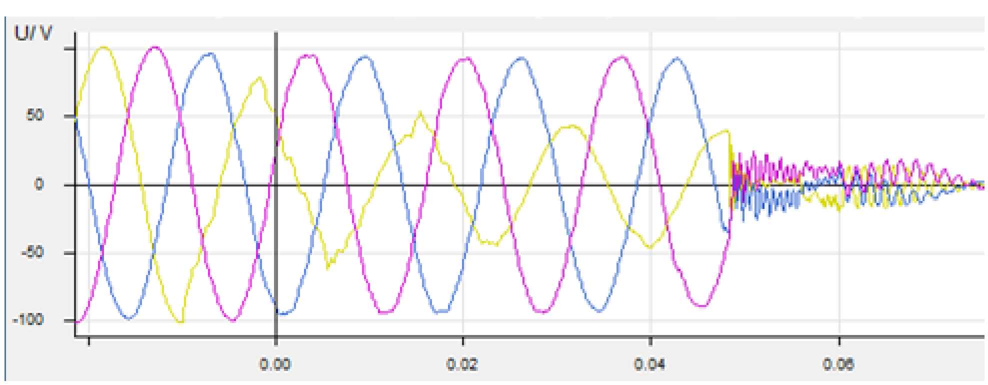

Fig. 1 Transformer High Side Voltage

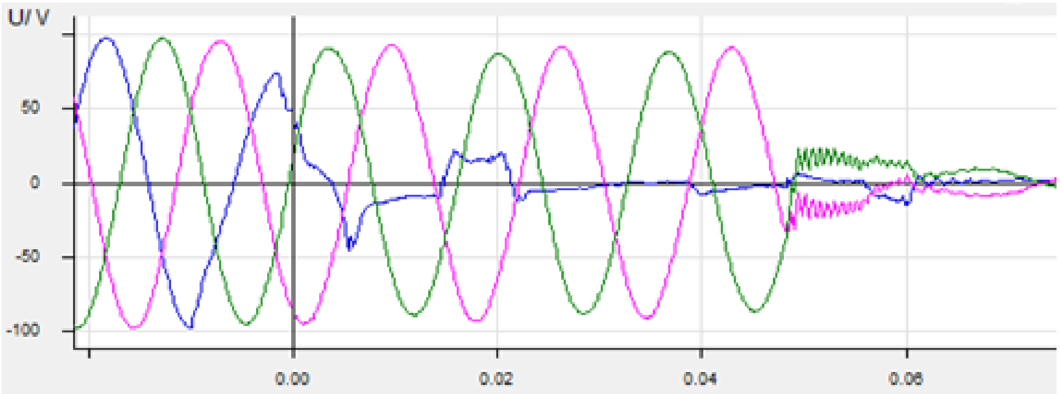

Fig. 3 Transformer Low Side Voltage

We can see the high side voltage on the faulted phase dropping to about 50% voltage (roughly matching the high to low side voltage ratio), while the low side voltage drops very low. Based on the event record it appears there was a total of 7900 Amps of fault current from the high side (summing the two breakers), and 46,000 Amps from the low side. The fault voltage on the low side shows 78 kV. This aligns fairly well with a fault study showing 17260 amps for a bolted ground fault at the H1 bushing. Assuming the transformer impedance was the cause of the voltage being only 50%, not zero, this would also lead to 50% of the possible fault current actually flowing.

This gives a total fault current of 53,900 Amps at 78 kV for 70,000 kWsec per cycle, or 35,000 kilojoules per half cycle, assuming the arcing at the fault location is resistive. The point of measuring energy in terms of half cycles is that circuit breakers can only interrupt at a current zero; or every half cycle. This makes half cycles the “quanta” of energy for a fault.

As shown in figure 4 the relays in the transformer protection scheme operated in about 28 ms for the fault. This was as expected and within the design standards for the utility involved. Notice also that the fault current is rising steadily during the duration of the fault. This is consistent with the fault type, inside the transformer, burning through paper insulation and becoming a more metalic fault. This also explains the collapse in the voltage as the fault progresses. This also makes it more important to interrupt the fault as quickly as possible. The increasing energy and damage involved in the fault both make repair more difficult but increase the possibilty of consequential damage such as an explosion or as in this case a tank rupture (with no explosion). The rupture involved about 18 inches of a lower corner of the tank. This caused 30,000 gallons of oil to spill. Even with no fire, the cleanup cost was significant, even when compared with the cost of the transformer (still covered by warranty).

Because there was no evidence of burning around the tank split or fire involving the spilled oil, it was suggested by equipment engineers inspecting the transformer that the split occurred just as the fault was interrupted; again pointing out that even a short time gained could have been very significant in terms of cost savings.

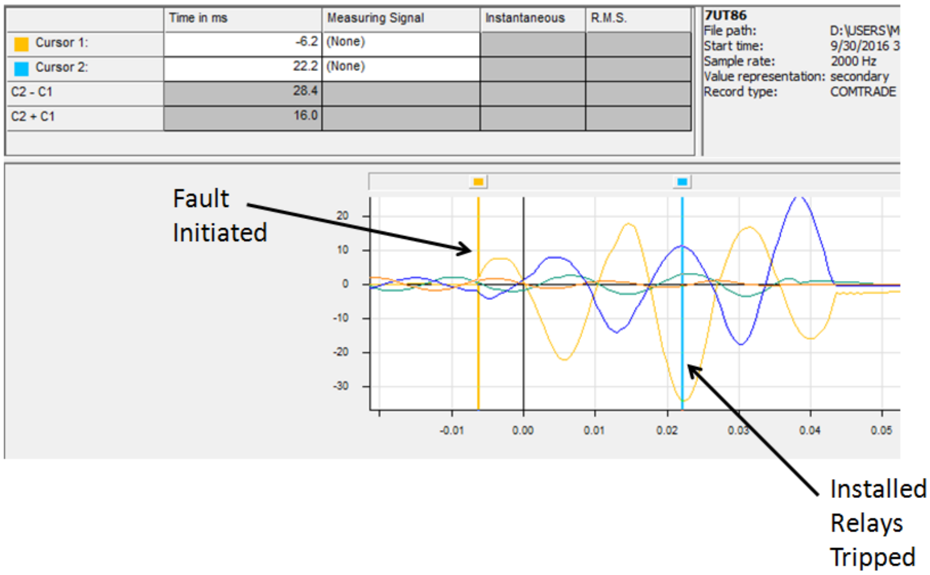

Figure 4. Fault currents and trip times

Relay Response and Algorithms -

Transformer differential relays have some inherent delay to ensure that the apparent “fault” is not in fact inrush during energization or sympathetic inrush when a nearby transformer is connected. This delay is typically for evaluation of harmonic content in the current that is typically involved in inrush. There is a problem with this delay when there is harmonic content in the measured fault current of an actual internal fault. Figure 5 shows the harmonic content during the fault period.

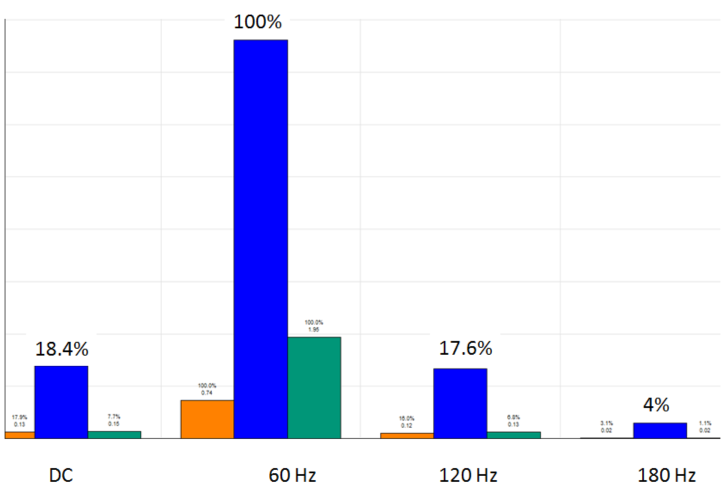

Fig. 5 Harmonic content of the current

The high level of second harmonc, over 17% in this case is probably not present in the primary current but is caused by a partial saturation of the CT. Note that there is significant DC current on the phase with the high harmonic level. The objective then is to arrive at a system to speed up tripping without misoperating on transformer inrush or with CT saturation.

Speeding Up Transformer Differential

In both the internal fault of figure 6 and the external fault of figure 7 the differential current goes above the restraint current in the case of a saturated CT. Note however in the case of the internal fault (figure 6.) the differential current is above the restraint current starting at time zero, or practically measured when the current goes above a setting threshold. With a high sampling rate, it is possible to have several samples measured before CT saturation can cause an apparent differential current to go above the restraint.

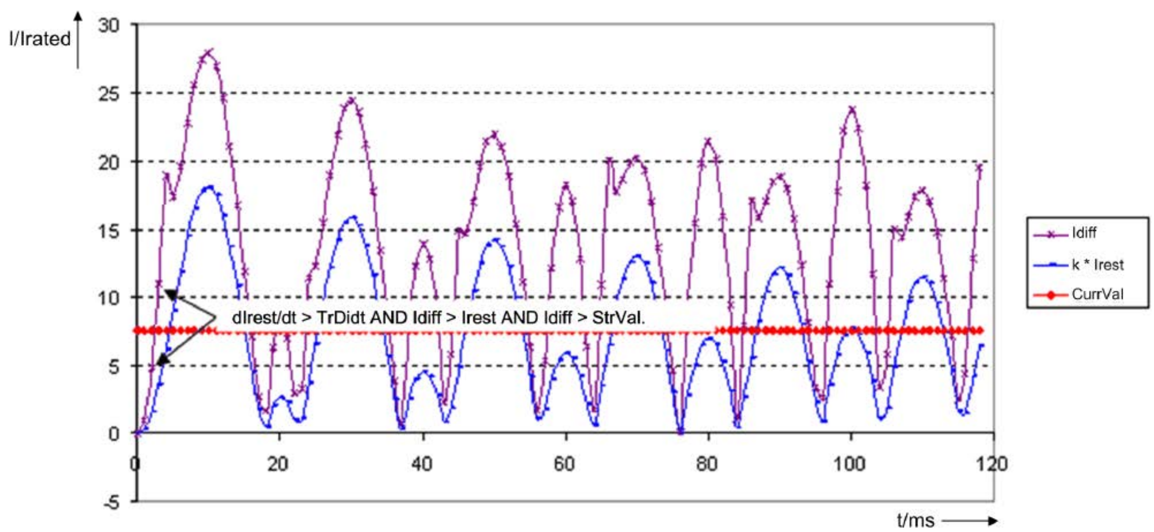

Figure 6. Internal Short Circuit with Transformer Saturation

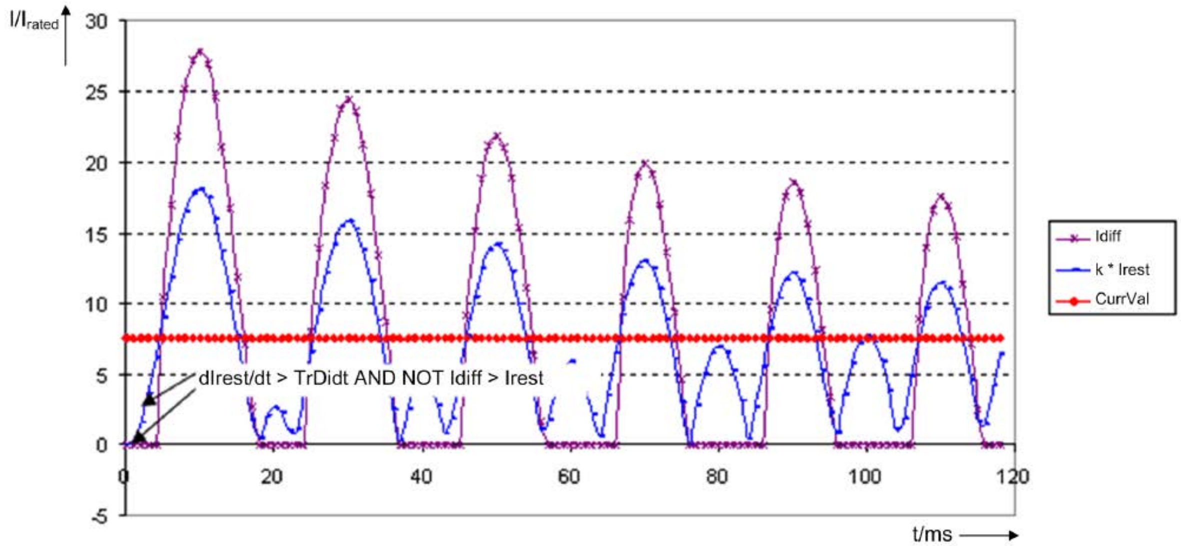

Figure 7. External Short Circuit with Transformer Saturation

For the transformer fault in question we can see the combined operate and restraint and relay pickup in figure 8.

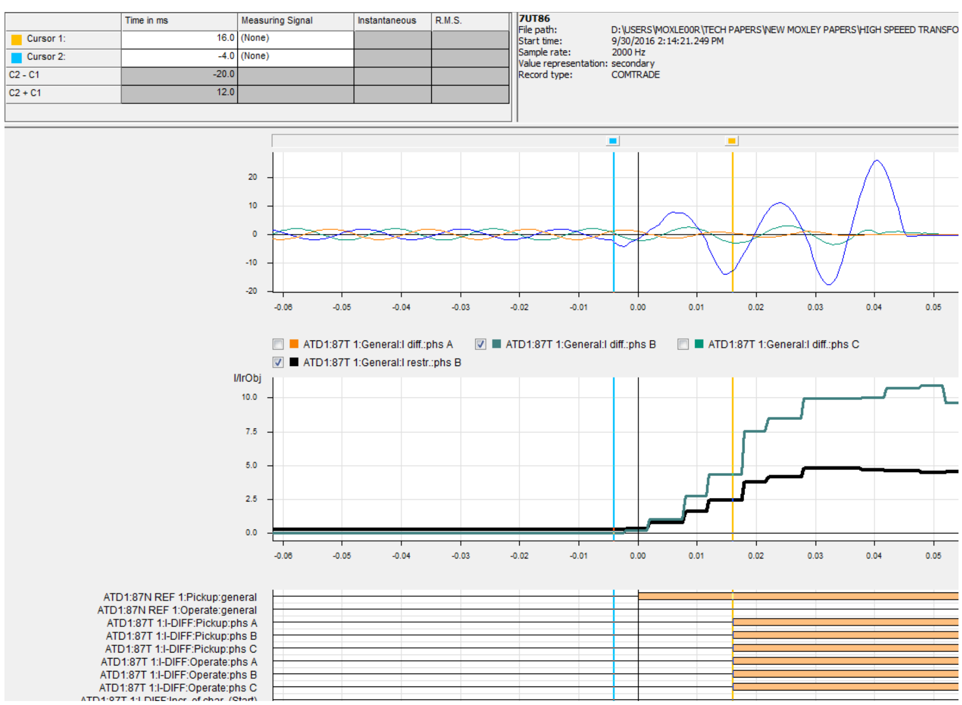

Figure 8. Operating Characteristic with Relay Pickup.

Here we see the differential rising faster than the restraint and the relay tripping 20 ms after the fault inception. If the fault had a faster rate of rise, such as would occur with a metalic fault from the beginning the tripping would have been even faster.

Even with the slow rate of rise, this principle is 8 ms faster than the fastest relay that saw the fault; even without special settings.

Consequences and Benefits of Faster Tripping –

Faster tripping provides real and measurable benefits. In the case of the failure example we are using we can make the following calculations of fault energy to determine if it is reasonable that a faster relay would have avoided the tank rupture.

Copper vaporizes at 1070 kilojoules / in^3. This means that for each half cycle of the fault about 32 cubic inches of copper was being vaporized. Assuming the winding was rated for about 3000A (CT rating) it would have a conductor cross section of about 2 inches [1].

The fault lasted for 3½ cycles. This gives total fault energy of about 245,000 kilojoules. During that time it would have vaporized about 114 inches of primary conductor. Of course that would have also involved paper, oil, and eventually core material. Reducing the interruption time to 3 cycles reduces the fault energy to 210,000 kilojoules, a reduction of almost 15%. Of course this is not an exact calculation as energy would have gone into producing the pressure that ruptured the tank and burning oil would have released additional energy. It is safe to say though, that because the tank rupture was small with the expelled oil not ignited, 30% faster relaying and 15% faster fault clearing could have prevented the rupture and would certainly have led to less damage. Physical and environmental cleanup of a spill on a large transformer can easily run into a million dollars. While fast tripping will not replace containment, in a case such as this it can save a million dollars.

References

[1] GE industrial systems data book