Challenges Replacing Electro-Mechanical Transformer Differential Relays

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Abstract – This paper will explore some of the challenges associated with replacing electromechanical transformer protection relays with microprocessor-based relays. The paper will first explore how electro-mechanical relays accommodated magnitude compensation, zero sequence removal, phase compensation, harmonic restraint and unequal CT performance and then explore these same challenges with microprocessor-based relays. The paper will then discuss challenges around retrofitting microprocessor-based relays and configuring them to accommodate the retrofit.

I. INTRODUCTION

All Differential protection makes use of Thevenin node rule to provide a defined zone of protection that does not over-reach the zone of protection. This makes the differential an effective protection scheme for important assets because it can trip fast and securely. The differential zone is created by measuring all the currents connected to the zone of protection and then creating a differential operate quantity with the vector sum of these currents. In theory, with an ideal configuration, these currents would sum to zero. Unfortunately, the current transformers that comprise the differential zone of protection will not be perfect devices and can have unequal performance. This unequal performance would cause operation of the differential if it isn't restrained in some way. Most differential schemes make use of a sloped differential characteristic, like Figure 1 below, to accommodate unequal current transformer performance. The sloped differential characteristic is comprised of a restrain quantity along the bottom axis and a operate quantity along the vertical axis. The restraint quantity is typically the maximum current that flows through any current transformer connected to the zone of protection. The differential is the operate quantity that is the vector sum of the currents connected to the zone of protection. The sloped differential characteristic helps accommodate unequal CT performance by requiring the differential current to be a sloped percentage of the restraint current to operate. In this way, when through fault currents are high, it allows for more error in the CT performance.

Power transformers pose a unique challenge to differential protection schemes because, unlike most differential schemes, they employ differential protection across the transformer rather than across a conductor. For example, in Figure 2 below, the CT locations are as shown in X and Y. The actual current that flows through X will flow out of the winding neutral connection at Z, but current is measured at Y. Since the differential is measuring across the transformer the differential relay will have to compensate for the difference in current across the transformer.

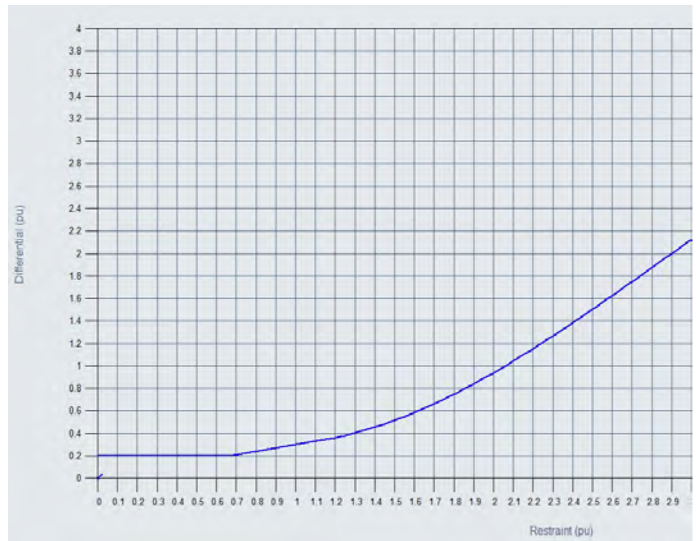

Figure 1 – Sloped Differential Characteristic

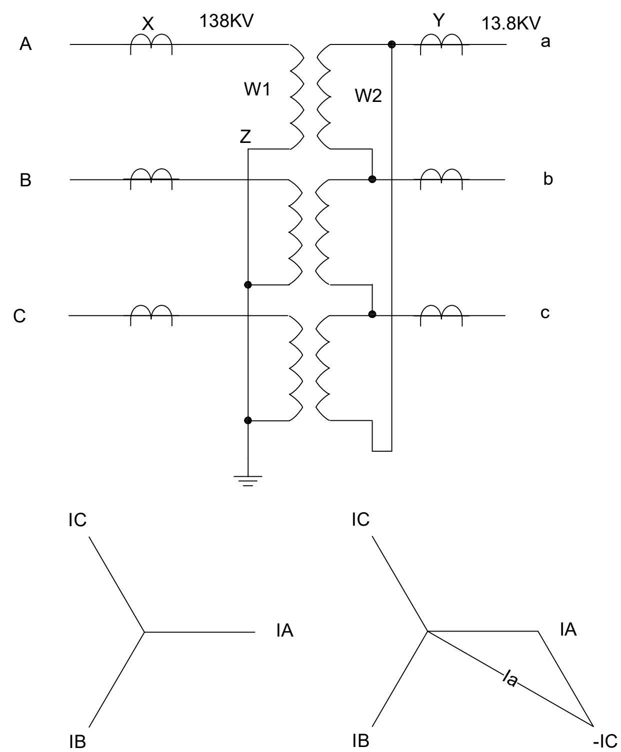

Figure 2 -Typical Transformer Connection

In the transformer shown in Figure 2, the voltage transformation ratio is 138KV to 13.8KV. Power flow is maintained across the transformer, so that the transformation ratio also applies to the currents. If 10 amps is flowing into the 138KV winding 100 amps will flow out of the 13.8KV winding. The relay will need to accommodate this magnitude compensation in some way.

The delta to wye conversion of the transformer in Figure 1 will introduce a phase shift. In Figure 1 W1 is in phase with w2, but the CT location that is measuring current for the relay is reading a combination of the winding currents. For example, the A phase CT current will be equal to the A phase W2 current minus the C phase W2 current. If A phase current is equal to 1per unit at 0 degrees and C phase is equal to 1 per unit at -240 degrees, the resultant vector that the relay will have to presented to it will be equal to the square root of thee at an angle of -30 degrees. This 30-degree phase shift must be accounted for or it will cause an error in the differential.

Additionally, the ground connection of the 138KV winding on Figure 2 will be able to supply ground current to the 138KV system. The delta connection of the 13.8KV winding will block that ground current. The fact that the 138KV winding can see this ground current and the 13.8KW winding cannot, would cause operation of the differential if the ground current isn't removed.

Electromechanical differential relays took the form of Figure 3 below. In Figure 3, the OP coil represents the operate coil of the relay and provides operate or closing torque on the relay. The R coils are restraint coils and provided opening torque of the relay. Electromechanical relays implemented a sloped differential characteristic because the operate torque had to be a percentage of the restraint torque to close the contacts.

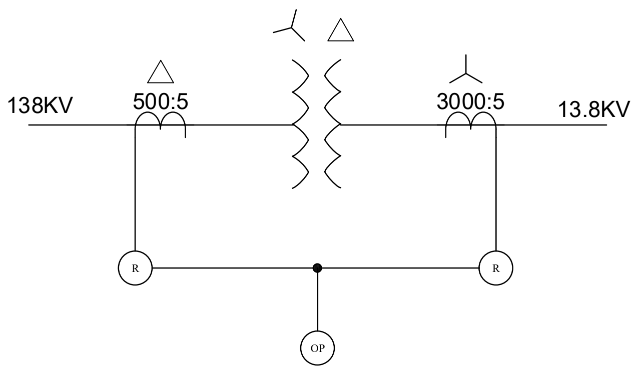

Figure 3 – Electro-Mechanical Relay Transformer Differential

The delta connected CTs remove the zero-sequence currents from the secondary connections of the CTs that are connected to the grounded wye transformer winding. Phase compensation was accounted for in the electromechanical relays by wiring the transformer delta winding CTs in wye and the transformer wye winding CTs in delta. This delta connection of the CTs would shift the currents by thirty degrees which would rectify the thirty-degree shift of the transformer delta winding. This secondary current would also be increased by the square root of three because of the delta connected CTs and that issue could be rectified by the choice of CTs and tap setting.

In electromechanical relays magnitude compensation was taken care of with CT settings as much as possible. In Figure 3, if 10 amps is flowing into the 138KV winding 100 amps will be flowing out of the 13.8KV secondary winding. The current on the secondary of the 138KV CT will be 173ma ((10amps/100)*Sqrt(3)). The current on the secondary of the 13.8KV winding will be 166ma(100amps/600). The difference in current could be accounted for with a tap point setting and the percentage of differential setting.

Microprocessor-based relays can accommodate magnitude compensation, phase compensation, and zero sequence removal with calculations performed inside the relay. These calculations eliminate the need for delta connected CTs on the Wye winding and allow the simpler connection of both CTs wired in wye.

The microprocessor relay performs magnitude compensation by calculating the transformer, transformation ratio using settings of rated voltage of each winding. The relay will then calculate primary current and apply the magnitude compensation factor to the higher voltage winding to equalize the magnitude of the two connected currents. Phase compensation and zero sequence removal in a microprocessor-based relay is accomplished with settings that describe the phase relationship of the two windings and whether there is a ground source in the zone of protection. The relay will use those settings to calculate a compensation factor for the current. Consider Figure 2 where the 13.8Kv winding currents lag the 138KV current by thirty degrees. The compensation is as shown in Equation 1 below.

$$I_A{}^P[w] = \frac{1}{\sqrt{3}} I_A[w] - \frac{1}{\sqrt{3}} I_C[w]$$
$$I_B{}^P[w] = \frac{1}{\sqrt{3}} I_B[w] - \frac{1}{\sqrt{3}} I_A[w]$$
$$I_C{}^P[w] = \frac{1}{\sqrt{3}} I_C[w] - \frac{1}{\sqrt{3}} I_B[w]$$

Equation 1 – Compensation equations

II. Retrofit Challenges

Microprocessor-based relays allow for flexibility in CT connections since they can do phase compensation, zero sequence removal, and magnitude compensation with calculations on wye connected CTs. Often it is not practical to make use of this flexibility in a retrofit application when microprocessor-based relays are replacing electro-mechanical. For example, electro-mechanical relays relied on delta connected CTs to remove zero sequence current and to account for the phase shift of a delta to wye transformer. If the delta connections of the CT are made up at the transformer or circuit breaker in the switchyard, it is very likely that only three wires are brought to the control house. In that situation, it would require a new cable to be installed across the yard, in addition to changing the CT wiring to wire the CTs in wye. Often it is not practical to install this additional cable to replace the relay.

Microprocessor-based relays can be set to either apply phase compensation or ignore it and allow phase compensation and zero sequence removal to be accomplished with the CT connections. If it is impractical to change to wye CT connections in an electro-mechanical retrofit application, then the relay should be set to allow the CTs to accommodate the phase compensation and zero-sequence removal. In those situations, the current presented to the relay will be greater than expected by the square root of three. This larger current must be considered, or it will cause mis-operation of the differential. There are two ways to account for this current: accounting in the rated voltage winding settings or accounting for in the CT settings. Increasing the rated voltage of the winding by the square root of three would cause magnitude compensation to account for the larger delta currents, but this is not the recommended method. The better method is to decrease the CT ratio of the delta connected CTs by the square root of three. For example, if the CT ratio of the delta connected winding is 2000:5 then the ratio should be set to 1155:5 to correct the ratios for the larger delta connected currents. If 2000 amps are flowing through the primary of this CT, 5 amps are flowing out of the secondary. Since the relay is located beyond the delta connections, the relay will have 8.66 amps injected into it. Since the ratio is 1155:5 the relay will calculate 8.66*1155/5=2000amps.

Decreasing the CT ratio by the square root of three on the delta connected winding will “normalize” the current and reflect the magnitude of the CT primary current. However, these currents will lag the primary current by 30 degrees. If this delta connected current is used in metering, it will cause erroneous metering values in power metering because of the angular difference in voltage and current.

Electro-mechanical transformer differential relays were typically phase segregated with a relay per phase. These relays typically had a filter that was tuned to twice the fundamental and the output of that filter provided restraint torque to prevent differential operation on transformer inrush. The filter was tuned to the second harmonic and the filtered current would provide restraint torque. These circuits were typically built so that when the second harmonic content was 20% of the differential operate current, the relay would restrain. In many applications a twenty percent restraint, per phase, is not sufficient to prevent mis-operation. Modern microprocessor-based relays can restrain all three phases based on the average content of the second harmonic or if two out of the thee phases have second harmonic content higher than the setting. In retrofit applications, restraint on two out of three or on the average level of second harmonic should be used.

III. CASE STUDIES

Zero-sequence removal is important for transformers that have delta to wye conversion because the grounded wye winding can provide zero-sequence current outside of the zone of protection. An example of this is shown in Figure 4 below. The waveforms from Figure 4 represent a generator step up transformer that is wye connected on the transmission system side and delta connected on the generator side of the transformers. During the event capture of Figure 4, the generator breaker was open and the generator was out of service for maintenance, when a system fault occurred on the transmission system and the transformer provided ground fault current for that system fault. The flow of current can be seen by examining the phase currents of the transformer and the ground current in the waveforms and phasor diagram of Figure 5. In Figure 5, the phase currents are all in phase producing zero-sequence current that is equal to the positive sequence current. This zero-sequence current flows into the transformer and out of the ground connection as shown in the phasor diagram of Figure 5. If the zero sequence current is not removed from the differential calculation, it would cause a differential operation because the current is not seen on the delta side of the winding where the other set of differential CTs are located. The equations shown in equation 1 above, not only provide phase compensation but also remove zero-sequence current. As an example of this zero sequence removal, consider the compensated differential current of a phase. The compensated value of A phase current is a combination of A phase current minus the C phase current. Since A and C are in phase and of equal magnitude, the compensated value would be zero, effectively removing the zero sequence component and preventing mis-operation.

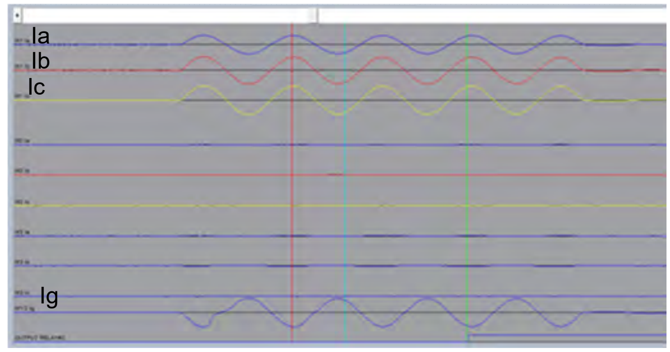

Figure 4 – Waveforms of Transformer Zero-sequence Current.

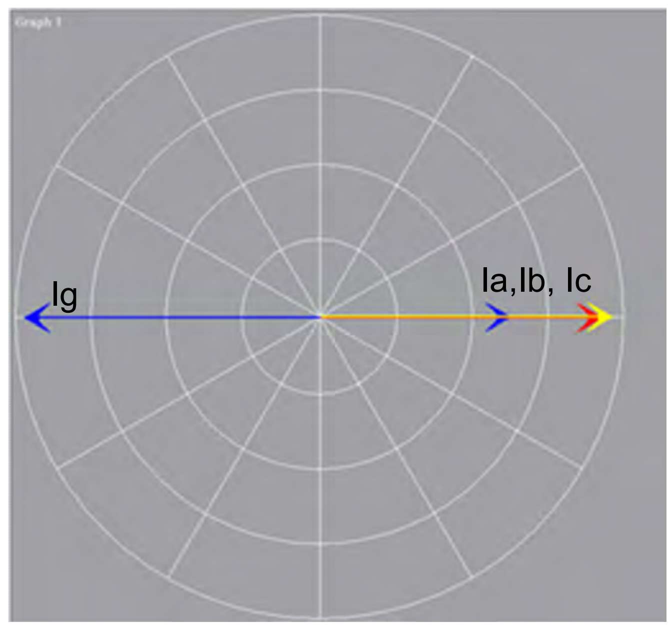

Figure 5 – Phasors of Transformer Zero-sequence Current.

Figure 6 below is the oscillography capture of the second harmonic content during a transformer energization. During this energization, A phase produced a high level of second harmonic while B and C phase produced very little. A phase second harmonic was equal to 64 percent of the fundamental while both B and C phase produced 7.5% of the fundamental. This relay was set to block second harmonic per phase just like an electro-mechanical relay and tripped on differential on B and C phase. Setting this relay to block differential on the average level of second harmonic content would have resulted in an average value of 26% and the relay would have restrained with a block threshold setting of 20%.

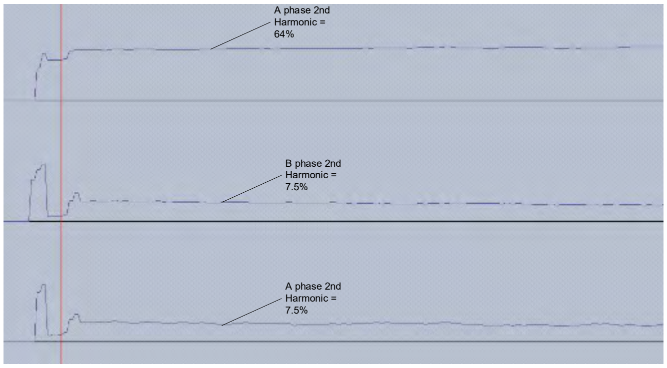

Figure 6 – Harmonic Content During Energization

Figure 7 below shows the phasors diagrams for CTs on the transformer primary and secondary where phase compensation is accomplished with the CT connections. In this case the angular difference between the CT secondary primary current and secondary currents is 180 degrees rather than the 210 degrees that would be expected for a transformer with a 30 degree phase shift. In this case the relay must be set for external compensation with CTs or set with an angular difference of 0 degrees.

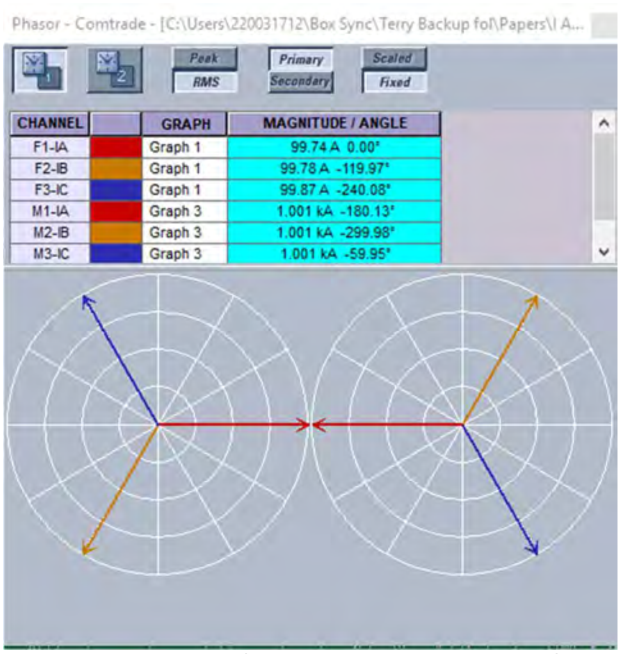

Figure 7 – Transformer Phasors with External CT Compensation

When the transformer is put into service the wiring needs to be verified prior to putting the differential protection element in service. Because the calculations depend on the phase relationship between the current inputs and the rotation of the phases, it is recommended that the transformer have some load so that proper operation of the differential can be confirmed.

IV. CONCLUSIONS

Microprocessor-based relays allow more flexibility in the wiring and settings of the transformer differential relay but retrofitting those relays may pose a challenge since it may require an additional cable to be installed from the relay location to the current transformer location. In those situations, the microprocessor-based relay can mimic the electro-mechanical relay, but an understanding of how the electro-mechanical relay and the microprocessor relay accommodate unequal current transformer performance, unequal phase relationships, magnitude compensation, and zero-sequence removal are necessary for success of the project.

Examining the methods that electro-mechanical relays use to perform transformer differential and comparing the electro-mechanical compensation to microprocessor-based compensation aids in understanding phase compensation, zero sequence removal, and magnitude compensations applied to transformer differential.

V. REFERENCES

[1] J. L. Blackburn, *Applied Protective Relaying, Principles and Applications*, New York, NY: Marcel Dekker, Inc. 1987.

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[3] GE Technical Note GET-8430, *T60 Connection Winding Monitoring.*