Benefits of Combining Four Transformer Differential Schemes for Autotransformer Protection

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Abstract -- **The electrical connection between the primary and secondary windings of an autotransformer allows for the use of differential protection schemes that are unique to autotransformers. However, these unique transformer schemes have their own limitations. A combination of using traditional transformer differential protection as well as schemes unique to autotransformers allows for more complete and redundant protection. This approach allows the engineer to have the benefits of different types of differential elements while securing the system against the weaknesses of each type. A recent autotransformer protection project made use of four different types of differential protection, implemented with a transformer and a bus relay, for a 1,120 MVA 500/230/13 kV autotransformer. This paper examines the basics of autotransformers as well as the benefits of using multiple types of differential protection. Each scheme's design and settings limitations are also discussed in order to demonstrate the benefits and feasibility of implementing these schemes.**

I. INTRODUCTION

Autotransformers are often key parts of the bulk electric system connecting important parts of the grid at different voltages. They are also extremely expensive, with a 500 kV to 230 kV bank, made up of single-phase units, costing up to $1000 per MVA per phase. These transformers can be difficult to replace due to the lead times and difficulty of transporting such large transformers. For these reasons, protecting large autotransformers is extremely important. When designing and setting protection for these units, the goal is to set the protection to be as fast operating and sensitive to faults as possible without causing mis-operations.

One of the fastest forms of protection available is differential protection. There are multiple different types of differential protection that can be used to protect an autotransformer, some conventional, others much less so. A combination of four of these schemes can provide faster and more comprehensive protection than any one scheme on its own. These four differential schemes can be divided into a primary and backup relay to provide redundancy without having identical protection in each relay. The result is fast and comprehensive autotransformer protection. In this paper we discuss these four schemes and their application.

II. AUTOTRANSFORMER BASICS

Understanding how autotransformers differ from basic transformers is important to understanding how some of these protective elements work and the benefits of using them. Autotransformers are unique due to the common winding, N_C, that is shared by both the primary and secondary sides of the transformer (Figure 1). The difference in the number of turns between the primary and secondary side of the transformer is determined by the size of the series winding, N_{SE}, which is unique to one side of the autotransformer [1]. Because of the common winding of the autotransformer, there is an electrical connection between the primary and secondary sides that does not exist in conventional transformers. This electrical connection allows current to flow from one side of the transformer, through the series winding, to the other side of the transformer as can be seen in Figure 2.

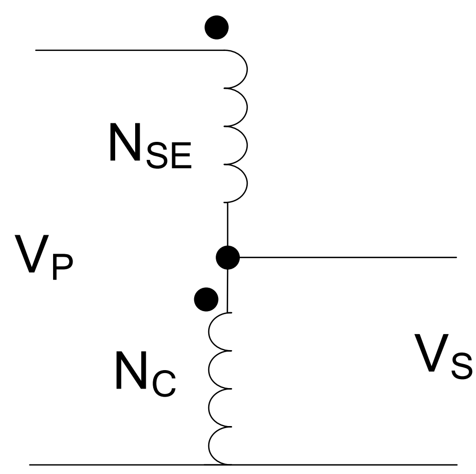

Figure 1 – Autotransformer Windings

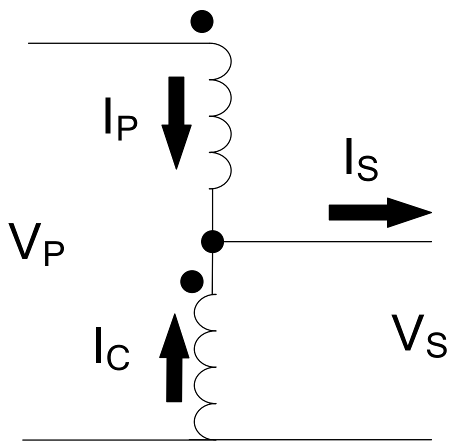

Figure 2 – Autotransformer Windings

This results in something known as apparent power advantage. The apparent power advantage exists because power can flow from the primary to the secondary of the transformer through the electrical connection. The power transferred through this electrical connection is not relying on the windings magnetic coupling. Due to the transformer's windings, power is also transferred from the primary to the secondary via magnetic coupling (transformer action). Therefore, the total power transfer through an autotransformer is the sum of the electrical and magnetic power transfer [1]. Because autotransformers are not relying entirely on magnetic coupling (transformer action) to transfer power, they can have smaller windings than a conventional transformer while having the same MVA rating as a conventional transformer [1]. This advantage increases as the difference between the primary and secondary voltages decreases. For this reason, autotransformers are more commonly used when there is a small difference between the primary and secondary voltage.

III. CONVENTIONAL TRANSFORMER PROTECTION

There are two types of differential protection that are used commonly on autotransformers and conventional transformers: Amp-Turn Balance and Restricted Earth Fault. These schemes are common because the Current Transformers (CTs) that are required are typically provided on the bushings of three-phase transformers.

A. Amp-Turn Balance

Amp-Turn Balance differential protection is the most common type of transformer differential protection. It only needs two sets of CTs, one set each on the primary and secondary sides of the autotransformer to create a differential zone (Figure 3). If the autotransformer has a loaded tertiary, a third set of CTs can be added to the tertiary outside of the delta to increase the sensitivity of this differential (Figure 4). But this CT placement does not create a differential based on Kirchhoff's Current Law because the relay does not see the current that leaves the windings through the neutral. Instead, the relay compares the currents on the primary and secondary of the transformer using multipliers, known as taps, to scale the currents to account for differences caused by the transformer turns ratio. The relay then multiplies the measured currents by a matrix to account for any phase shift from the primary to the secondary windings. Autotransformers do not have a phase shift between the primary and secondary, but a matrix shift should still be used to prevent mis-operations caused by external faults [4].

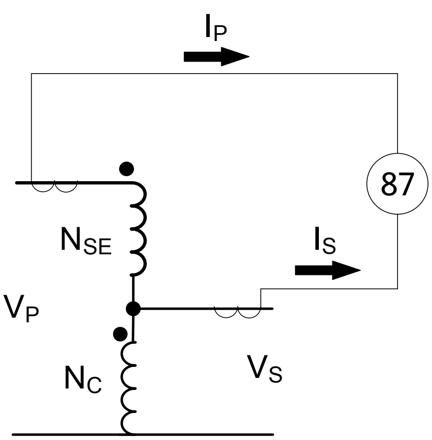

Figure 3 – CT Locations for Amp-Turn Balance Differential

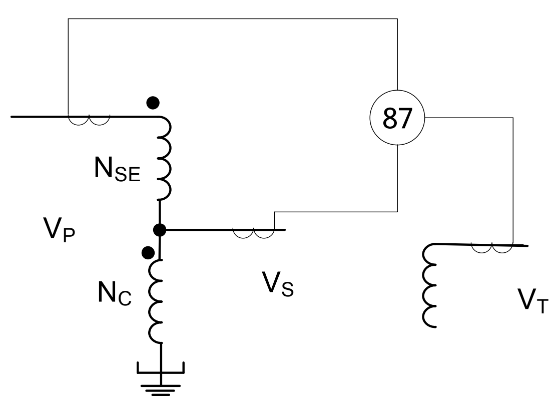

Figure 4 – CT Locations for Amp-Turn Balance Differential with Loaded Tertiary

This differential scheme protects the primary and secondary windings as well as having the ability to detect faults in the delta tertiary winding [2]. Additionally, it provides protection for turn to turn faults because they appear to the relay as a change in the transformer turns ratio between the primary and secondary windings. This imbalance occurs because a turn to turn fault effectively reduces the number of turns in the faulted winding.

The Amp-Turn Balance differential has some large limitations. This element needs to account for tap changers because they effectively change the transformer's turns ratio. This is done by adding additional margin to the differential slope. As a result, the element will be less sensitive to internal faults. Additionally, the element is not very sensitive for faults close to the neutral, because the slope cannot be set sensitively enough to detect them without risking false trips. This element also has zero sequence compensation that makes it less sensitive to single line to ground faults because it reduces the current seen by the relay by a factor of one over the square root of three, and it prevents the relay from determining which phase was faulted [3]. A negative sequence differential element, based on this Amp-Turn balance scheme, can be used to make the relay more sensitive to turn to turn faults because it does not see balanced load current as restraining current [5].

The most significant weakness of this element is that it sees inrush currents, caused by transformer energization, as an internal fault. To prevent the relay from tripping during energization, most relays detect second and fourth harmonic content, common in inrush currents, and either blocks or restrains the differential element. While these blocking and restraining functions increase the relays security, they also decrease its sensitivity and slow down the relay's operation. Additionally, it is possible for faults to have harmonic content that delays the relays operation due to the relay's blocking or restraint.

B. Restricted Earth Fault

Restricted Earth Fault (REF) protection is another type of transformer differential protection. It is a zero-sequence differential element that provides full coverage of the transformers common and series windings. For that reason, it is commonly applied in the same relays as a traditional transformer differential element to make up for the Amp-Turn balance element's inability to detect faults close to the neutral point and its reduced sensitivity to single line to ground faults. This element is unable to detect turn to turn faults because the element sees the increased current going both into and out of the differential zone, and therefore sees them as through faults.

The REF element's differential zone is composed of CTs on the primary and secondary windings of the autotransformer as well as a single neutral CT (Figure 5). The relay creates a differential zone using calculated values of zero sequence current on the primary and secondary side of the transformer and the directly measured zero sequence current from the neutral CT.

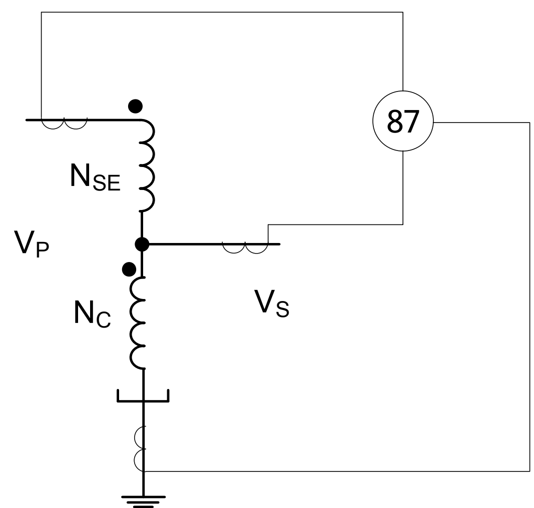

Figure 5 – CT Locations for a Restricted Earth Fault Element

If the autotransformer has a delta tertiary winding, it will not be protected by this element. Zero-sequence current will circulate in the tertiary, and as a result, a CT inside the delta would be required to monitor that current. Such a CT could not be incorporated into the REF element on its own because the current it sees would not flow through any of the other CTs in the differential zone and would be seen by the relay as an internal fault.

IV. Unique Differential Schemes

When protecting large autotransformers, we can take advantage of the electrical connection between the primary and secondary windings to implement an element that cannot be applied to traditional transformers. These protection schemes also take advantage of CTs that are typically only available on large banks that are composed of three single-phase units.

A. Phase Segregated Common and Series Winding Differential

The first of these unique schemes is the Phase Segregated differential element. They are unique to autotransformers because it makes use of the electrical connection between the common and series windings. This connection allows the use of Kirchhoff's Current law around that node to form a differential zone [2]. The first two branches leaving the node are already seen by the CTs that are typically in place on the primary and secondary bushings of a conventional transformer. But there is a third path from the node: through the common winding to the neutral. For this differential scheme to work, there must be a CT for each phase on the neutral side of the winding to see the current flowing through the third branch leaving the node. The locations of the CTs needed for this scheme are shown in Figure 6. This type of differential looks at each phase separately, which effectively gives each phase of the transformer its own differential zone.

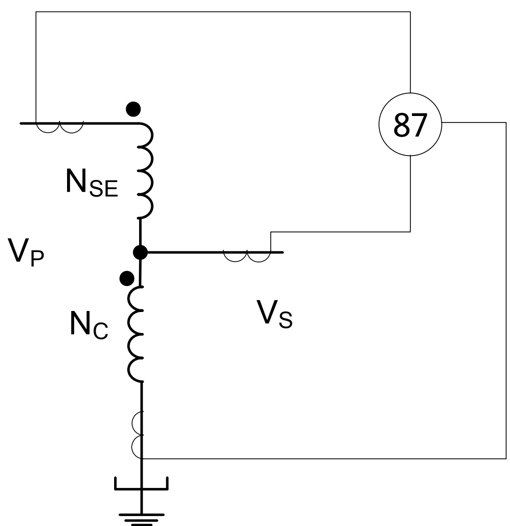

Figure 6 – CT Placements for Phase Segregated Differential

This differential scheme has numerous advantages. Because the relay is seeing all the current flowing in and out of the node for each phase, there is no need for the zero-sequence reduction that is done by the Amp-Turn Balance differential [4]. This allows the element to be much more sensitive to single line to ground faults and allows the relay to determine which phase has faulted, which is especially valuable for banks composed of single phase units.

Similarly, a magnitude adjustment, typically made with a multiplier known as the tap, is not needed to compensate for the transformer turns ratio. As a result, it is not necessary to have extra margin in the settings when there is a load tap changer. These differences allow the element to be set more comparably to a bus differential element than a transformer differential element, resulting in much greater sensitivity.

Another benefit of seeing all the current in and out of the node, is that the differential elements do not need blocking or compensation to account for inrush currents [2]. Without the extra processing needed for harmonic blocking or restraint, the differential can identify a fault condition faster than an Amp-Turn balance differential. This lack of harmonic compensation also removes the possibility of the relay having delayed operation due to harmonic content in the fault. The result of these benefits is an element that can detect and operate for a fault faster than any traditional transformer differential protection.

One of the weaknesses of this differential element is an inability to detect faults in an auto-transformers delta tertiary winding. Though the tertiary is magnetically coupled to the other windings, any increase in current that is generated in the series and phase windings will pass completely through the differential zone and be seen as an external fault by the relay. Another weakness is its inability to detect turn to turn faults. This limitation exists because the increasing current caused by the turn to turn fault goes through both sides of the differential zone and sums to zero. If a fault occurs within a single phase of the transformer between its turns, these elements will not detect it until it has developed into a larger fault that includes ground or another phase.

B. Phase Segregated Delta Tertiary Differential

Autotransformers frequently have delta tertiaries that are used to limit third harmonic voltages caused by uneven loading and magnetizing currents [2]. In many cases the tertiary is loaded as well, with loads such as station service transformers, reactors, or capacitors. These delta tertiary windings can be protected in several different ways, including a delta specific differential element. This element requires CTs to be inside of the delta, typically on the bushings, and monitors each leg of the delta individually. For that reason, this method of protection is effectively restricted to autotransformers composed of single-phase units. Figure 7 shows the locations of the CTs for a delta winding differential element.

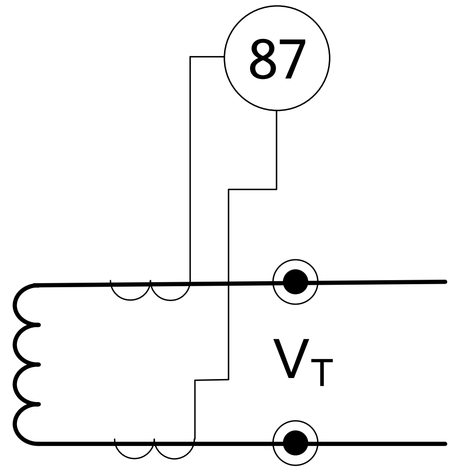

Figure 7 – CT Locations for Delta Tertiary Differential Protection

Like the Phase Segregated Differential, the Delta Differential makes use of CT locations that are not often found on autotransformers that are not single-phase units. The other similarity is that the Delta Differential is effectively three differential zones based on Kirchhoff's Current Law, one for each phase. A benefit of looking at each phase individually is getting a clear indication of the phase that has faulted [2]. This type of differential also has the weakness of the Phase Segregated Differential element: an inability to detect turn to turn faults.

V. Application

A typical protection scheme for an autotransformer is composed of two relays. The reason for using two relays is redundancy and typically they are not the exact same relay to avoid common mode failures. The relays may be from two different manufacturers, or they may be different versions of transformer relays from the same manufacturer. Because the reason for the second relay is redundancy, these relays typically employ the same basic functions and setpoints with the end goal of identical operation of the two relays.

In order to make use of the four differential elements, it is best to split them across two relays. The problem with this approach is that it would require four relays to have full redundancy. The best solution to this problem is to split up these elements in a way that allows each relay to protect all three of the transformer windings and provides functionality that is as close to redundant as possible.

These goals can be achieved by using a transformer differential and bus differential relays. The transformer differential relay provides the traditional transformer differential protection: Amp-Turn balance and restricted earth fault. The bus differential relay provides the Phase Segregated differential protection for the series, common, and tertiary windings. A bus differential is an acceptable relay for the Phase Segregated differential elements because they don't require blocking for inrush currents or phase shift compensation across the transformer windings.

This scheme was recently applied on an autotransformer that is a part of the bulk electric system and has a short critical clearing time, making it important to detect and clear faults as quickly as possible. The autotransformer has a 500 kV to 230 kV 600/798/999/1120 MVA rating with a 13.8 kV delta connected tertiary winding. The transformer was composed of three single-phase units rated 200/266/333/373 MVA each. Figure 8 shows how the CTs were wired to the Transformer and Bus differential relays.

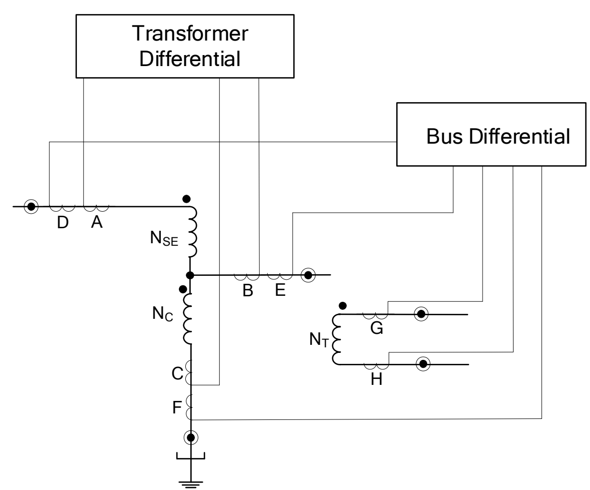

Figure 8 – CT Locations for Dual Relay Scheme

As mentioned previously, a transformer differential relay can be used for the first two differential schemes: Amp-Turn balance, and REF. The Amp-Turn balance scheme makes use of CTs on the primary and secondary transformer windings (CTs A and B).

The restricted earth fault element is inside of the transformer differential relay as well, so it can make use of CTs A and B as well. It also needs a single CT at the transformer neutral to form a complete zero-sequence differential zone (CT C). Because each single-phase transformer has CTs on the neutral bushing, three-phase CTs are summed together so that only the zero-sequence current is supplied to the relay (Figure 9), which is the equivalent of using a single neutral CT.

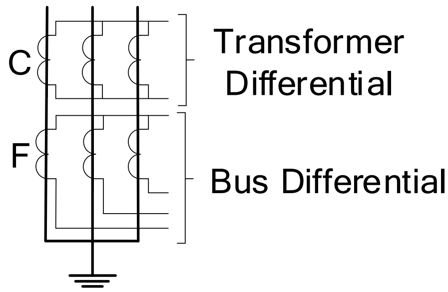

Figure 9 – CT Wiring for CTs at the Neutral

The Phase Segregated series and common winding differential makes use of CTs on the primary and secondary windings of the autotransformer (CTs D and E) as well as CTs at the transformer neutral (CT F). Unlike the REF element, the Phase Segregated differential requires a CT on each phase at the neutral point so that the relay can see the current for each individual phase at the neutral (Figure 9).

The final differential element to be used in this transformer is the delta tertiary differential. This differential zone makes use of the CTs inside of our transformer's delta tertiary (CTs G and H). These CTs are located on the tertiary bushings of each single-phase unit.

VI. Functionality

The transformer differential relay has comprehensive transformer protection completely on its own with both Amp-Turn Balance and Restricted Earth Fault elements. The Amp-Turn Balance differential can detect faults in the series, common, and tertiary windings. A negative sequence Amp-Turn Balance element is also enabled to provide sensitive detection of turn to turn faults. The Restricted Earth Fault differential allows the relay to detect faults close to the transformer neutral where the amount of fault current generated can be too small for the Amp-Turn Balance element to detect them on its own.

However, this traditional form of transformer protection can be relatively slow and lack sensitivity due to the harmonic blocking and/or restraint. The operating time of a transformer relay using harmonic restraint or harmonic blocking varies from as fast as half of a cycle to multiple cycles depending on the relay and fault conditions. Additionally, if the fault has second and fourth harmonic content, the relays operation could be further delayed by the harmonic restraint or harmonic blocking for a cycle or more. In this application, both harmonic blocking and harmonic restraint are used. Though this desensitizes and delays the differential, it provides extra security to ensure that the transformer does not have any unplanned outages. This reduced sensitivity is a tradeoff worth making in the transformer relay because it is being backed up by our Phase Segregated differential elements.

The Phase Segregated elements can be set in a bus differential relay because they do not require the turns compensation, harmonic blocking, harmonic restraint, or phase shift compensation that are typically required for transformer protection with an Amp-Turn Balance element. That also means that the relay does not need to be desensitized for tap changers or harmonic content. This results in a much faster relay element with more sensitive differential settings. The operating time of a low impedance differential element varies by relay model but can be as fast as half of a cycle with a slower operating time being around a single cycle. The lack of harmonic blocking or restraint also means that harmonic content on the fault won't delay the relay operating time beyond the bare minimum processing time that the relay needs. For faults that are not turn to turn faults, this relay can be expected to operate before the transformer differential relay by up to a few cycles, providing better protection of both equipment and personnel on this expensive and important piece of equipment.

In the event of a failure of the transformer differential relay, containing the Amp-Turn Balance and REF elements, this bus differential relay would still provide differential coverage of the entire autotransformer. This is because the tertiary differential protection makes up for the series and common winding differential's inability to detect tertiary faults. The result of combining these Phase Segregated differential elements is a bus differential relay that acts as a redundant transformer relay capable of backing up the traditional transformer differential relay.

A summary of the strengths and weaknesses of the four transformer differential schemes can be seen in Table 1. The second and third columns of the table show the protection provided by the transformer differential relay, while the fourth and fifth columns show the protection provided by the bus differential relay.

	Transformer Differential Relay		Bus Differential Relay	
Element	Amp-Turn Balance	Restricted Earth Fault	Phase Segregated Differential	Delta Tertiary Differential
High Sensitivity for Single Line to Ground Faults		✓	✓	
Faulted Phase Indication			✓	✓
No LTC Compensation Required			✓	✓
No Inrush Compensation Required			✓	✓
High Sensitivity for Faults Near the Neutral		✓	✓	
Protects the Series and Common Windings	✓	✓	✓	
Protects the Tertiary Winding	✓			✓
Turn to Turn Fault Detection	✓			

Table 1 – Protection Provided by Different Differential Schemes

VII. Conclusion

The use of redundant relays with different types of differential protection allows us to have a protection system that is more secure, more sensitive to faults, and faster than either of these relays would be on their own. This functionality is achieved by taking advantage of the complementary strengths of each of these relays to make up for the weaknesses of the other. The negative sequence Amp-Turn balance differential provides high speed turn to turn fault detection that the Phase Segregated differential cannot provide. The Phase Segregated differential provides faster and more sensitive protection for single line to ground, phase to phase, and three-phase faults than the Amp-Turn balance protection can provide.

Within each of the transformer's protective relays, the differential schemes used provide protection for all three of the transformer's windings. In the transformer differential relay, the restricted earth fault element helps to mitigate the Amp-Turn balance differential's inability to detect faults close to the neutral. In the bus differential relay, the delta tertiary differential helps to mitigate the Phase Segregated primary and series and common winding differential's inability to detect faults in the tertiary winding.

Using different types of relays, and different protection schemes within those relays, increases the likelihood that a relay will operate quickly during a fault event. These advantages can be very important when protecting very large, very expensive, autotransformers with short critical clearing times that are an important part of the bulk electric system.

VIII. References

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IX. Biography

Michael Garcia received the B.S. degree in engineering with an electrical emphasis from Texas Christian University, Fort Worth, TX, USA, in 2009. He is currently an Electrical Engineer with POWER Engineers, Inc., Lakewood, CO, USA. He has ten years of experience in protective relaying and system studies. Mr. Garcia is a licensed Professional Engineer in the state of Colorado.