Tutorial on Protection of Three Single-Phase Transformers

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***Abstract*— At the design stage of a new power substation, one of the decisions to be made is whether to select a single three-phase power transformer or a bank of three single-phase transformers. At Churchill Falls Terminal Station 2, of the Lower Churchill Project, a bank of three single-phase 3x280 MVA 735 kV power transformers was selected because of the required capacity.**

During the transformer protection relay configuration stage, the protection engineers typically encounter relays designed towards protecting the more standard three-phase transformers. In order to adequately protect the bank of three single-phase power transformers, and ensure both security and dependability, some measures have to be taken to adapt the existing relay parameters to the reality of the primary equipment.

This paper will briefly cover the pros and cons of using a bank of single-phase transformers. It will then address the main protection functions used for large utility electric power transformers, and how the protection setting calculations and actual relay settings are affected when protecting three single-phase transformers.

***Index Terms* — Current Differential Protection, Power Transformer, Protection Relay, Single Phase**

I. Introduction

As part of Nalcor Energy's Lower Churchill Project a new substation was constructed in order to connect the Upper Churchill Falls 735 kV substation to the new Muskrat Falls Generation Station and Muskrat Falls Converter Station of the LIL (Labrador Island Link). Churchill Falls Terminal Station 2 included a 735 kV connection to the existing Churchill Falls Terminal Station, five 735 kV breakers, two sets of three single phase autotransformers and six 315 kV GIS breakers. There are two 315 kV 245 km transmission lines connecting Churchill Falls Terminal Station 2 to Muskrat Falls Terminal Station 2.

Churchill Falls Terminal Station 2 was commissioned and successfully energized in early 2018.

Three 735kV-315kV autotransformers (280 MVA each) with a 13.8 kV tertiary winding for station service supply were installed. The capacity required for this connection between Churchill Falls and Muskrats Falls using single phase autotransformers were part of the station design.

The autotransformer primary protection is a transformer differential element with redundant protection functions that overlap the differential zones. The protective settings for the three single-phase auto-transformers required to adequately protect the asset are discussed in this paper.

There were a number of factors considered in the use of three single-phase transformers as opposed to a single three-phase transformer. Given the capacity requirement, the bank was rated at 840 MVA, the insulation requirements at 735 kV, also the physical size of the transformers could prove challenging for transport and substation layout design. There are also single-phase transformers of a similar rating in the existing Churchill Falls Terminal Station.

II. Review of Transformer Differential Protection

After presenting a definition of Unit Protection, the principle of current differential principle in general, and of transformer differential protection in particular, are introduced.

A. Unit Protection of Power System Elements

For power system primary equipment, Unit Protection refers to equipment that has a very clear and defined zone of protection. Typically, the zone is circumscribed by the measuring current transformers.

One form of the Unit Protection is the Current Differential Protection. The Current Differential Protection basic principle is to verify Kirchhoff's law: the sum of the currents flowing into a node must equal the sum of the currents flowing out of that node. Whether the equipment is a busbar, a transmission line or a feeder; the sum of entering and leaving current must always be validated. When this is not true, typically a deviation of current to ground or to other parts of the power system is occurring in manners that are abnormal, and this situation must be stopped.

For most power system equipment, a simple phasor summation of the currents can be performed and the result must ideally be zero – practically it is not exactly zero due to measurement errors. The power transformer is a special case. Its primary function is to operate at different voltage levels which means that the current is proportionally different. Thus, strictly applying a phasor summation to the transformer currents would translate to non-zero results, incorrectly indicating a current deviation. Some measures need to be taken and they will be explained in the next Section.

Another phenomenon specific to power transformers is their effect on voltage and current phase results from their construction. In some instances, the outgoing transformer current is phase shifted with respect to the incoming current, resulting in an additional "error" when performing a simple phasor summation.

B. Power Transformer Differential Protection

1) Basics of Current Differential Protection

The relay performing Current Differential Protection on a power transformer must perform magnitude and phase compensation in order to provide adequate safety and security. In order to ease the process for the end users, modern electronic relays integrate widely accepted and simple method consisting in entering the power transformer parameters (MVA, winding connections, winding voltages) as well as the current transformer ratios. With this information, the relay can automatically determine a reference winding and calculate the magnitude and phase compensation factors in addition to the zero-sequence compensation (when applicable). Shall the user encounter a non-typical scenario, all of these compensations can be entered manually by the protection engineer.

To reduce the complexity of the compensations performed, a simple case is presented below. Considering a power transformer of 100 MVA, 115 kV - 34.5 kV connected in YY0, the relay would perform the following steps. (To ease the understanding of the magnitude compensation, this example considers identical high-side and low-side CTs with a ratio of 1800:5). An actual real scenario is presented later on in Section III.

Step 1 – Calculate the rated current of each winding with

$$I_{rated} = \frac{S_{rated}}{\sqrt{3} \times V_{nom}}$$

which is:

$$I_{ratedHigh} = \frac{100\ MVA}{\sqrt{3} \times 115\ kV} = 502.0\ A$$

$$I_{ratedLow} = \frac{100\ MVA}{\sqrt{3} \times 34.5\ kV} = 1673.4\ A$$

Step 2 – Select the reference winding, based on the CT margin, as the winding that has the CT that is most likely to saturate. The margin for each winding is calculated as:

$$I_{margin} = \frac{\text{CT Primary Current}}{\text{Nominal Current}}$$

$$I_{marginHigh} = \frac{1800}{502} = 3.58$$

$$I_{marginLow} = \frac{1800}{1673} = 1.08$$

The winding with the lowest CT margin is selected as the reference winding.

Step 3 – Calculate a magnitude compensation factor as:

$$k_{winding} = \frac{I_{winding} \times V_{nom_{winding}}}{I_{reference} \times V_{nom_{reference}}}$$

which, for each winding, is

$$k_{High} = \frac{1800 \times 115}{1800 \times 34.5} = 3.33$$

$$k_{Low} = \frac{1800 \times 34.5}{1800 \times 34.5} = 1.0$$

Given the construction of the YY0 transformer in this example, phase compensation is not necessary. Similarly, zero-sequence compensation is not required.

Step 4 – The differential protection operates with the magnitude-, phase- and zero sequence-compensated signals. In the simplified example above, the compensated currents are calculated as:

$$\begin{aligned} I_A^c &= k_{winding} \times I_A \\ I_B^c &= k_{winding} \times I_B \\ I_C^c &= k_{winding} \times I_c \end{aligned}$$

In the example above, the compensated high-side nominal currents would be (for phase A only at nominal load)

$$I_{A_{high}}^c = 3.33 \times 502 = 1671.6$$

While the low-side would be

$$I_{A_{low}}^c = 1.0 \times 1673.4 = 1673.4$$

It becomes clear that the compensated currents can now be compared, or vectorially summed, as for a more standard differential protection.

Using the compensated currents, the protection relay can calculate the differential and restraint currents. While there are variations among relay manufacturers, the basic principle is the same. A differential current provides an indication of how many amperes are not flowing through the primary or secondary winding of the transformer and is obtained by a vector sum of all currents, on a phase-by phase basis.

The restraint current provides an estimation of the magnitude of the currents flowing through or in the transformer and is used to adjust the relay sensitivity through the use of a percent differential characteristic, as shown in the Fig. 1 below. As can be seen, the beginning of the percent differential characteristic is flat, to account for measurement error (and possibly tap changer) when the transformer is lightly loaded.

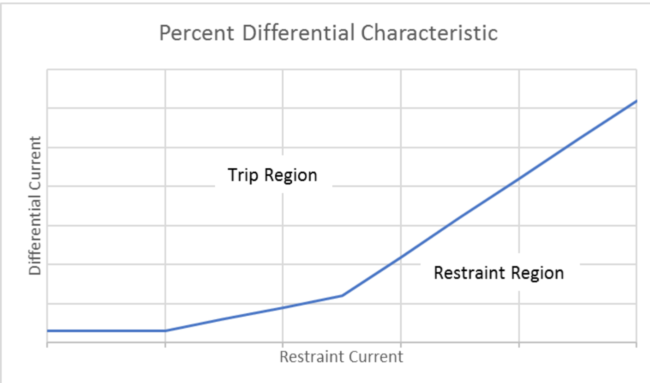

Fig. 1. Transformer Percent Differential Characteristic

It should be noted that each relay manufacturer introduces its own peculiarity and, as such, it is crucial to have a thorough understanding for a given relay model of a given manufacturer. The relay instruction manual is the first reference that should be reviewed (some examples can be found at [2]-[4]).

2) A Note on Phase and Zero-Sequence Compensation, and Harmonic Restraint.

The simplified example above demonstrated the basic principle of transformer current differential protection. In addition to the magnitude compensation shown above, there are transformer configurations where phase compensation and/or zero-sequence compensation are required.

If the windings do not align in terms of phase, and only the magnitude compensation is performed, then a false differential current will appear, even during normal conditions. This is the result of the sum done with vectors that have a phase separation. This phase separation needs to be compensated for.

Additionally, if a winding does not allow the circulation of zero-sequence current (e.g., a delta-connected winding), then a ground fault would allow the zero-sequence current to appear on one side of the transformer but not on the other side. This would also present a false differential current to the relay, even in the case of external faults. As such, the zero-sequence current must also be compensated for.

Further explanation on these two compensations are outside the scope of this article and the reader is referred to other references for more details [1].

Also outside of the scope of this document is the harmonic restraint. It is possible to detect transformer energization by measuring the 2^{nd} harmonic of current, as well as overexcitation by measuring the 5^{th} harmonic.

C. Considerations when Configuring a Transformer Relay for Three Single-Phase Transformers

Most commercially available current differential relays for power transformer protection were designed to protect three-winding transformers. The relay transformer parameters are designed as such and, as seen above, are used to compute the compensation factors.

It is important to fully understand the specific model of a given relay manufacturer. This is also true when it comes to configuring the transformer differential relay. For instance, manufacturer M1 uses the nominal power of the transformer simply to determine the winding that will be used as a reference. The current compensation factor is then calculated based on the CT ratios and nominal voltages. On the other hand, manufacturer M2 makes direct use of the nominal power to calculate the compensation factor. The methodology used has to be considered when configuring the relay.

Continuing with the case of the simple YY0 transformer presented above, the compensation factor was already calculated for a relay from manufacturer M1.

Observing how a relay from manufacturer M2 operates, the compensation is calculated as:

$$k_{winding} = \frac{1000 \times S_{rated}}{\sqrt{3} \times V_{nom} \times CTR}$$

where
S_{rated} = Transformer maximum MVA (MVA)
V_{nom} = Terminal line-to-line voltage of the winding (kV)

When calculating the compensation factor, the following results are obtained.

Table 1 Compensation Factors

Winding	Relay M1	Relay M2		Relay M3	
	1-ph or 3-ph	1-ph	3-ph	1-ph	3-ph
High	3.33	0.81	1.39	6.21	3.59
Low	1.0	2.68	4.64	1.86	1.08

For comparison purpose, the Table above also displays the results for a relay from manufacturer M3, although the paper will not go into the calculation details.

This difference is important between 1-phase form and 3-phase form when it comes to the setting calculation since it is effectively expanding the axis of the differential characteristic graph.

As can be seen from these two sample relays, one relay would be affected by whether the transformer parameters are entered as a three-phase transformer or as three single-phase transformers, while the other relay would not be affected. Both relays will protect the asset adequately as long as the protection engineer is aware of the differences and account for them.

III. Solution Proposal

In the solutions proposed below, the simple transformer example from above is left aside in order to present the real case of the Churchill Falls Terminal Station 2 auto-transformers.

A. Transformer Protection – Three-line AC Diagram

Figure 2 shows the three-single phase transformers that are to be protected with transformer differential relays at Churchill Falls Terminal Station 2.

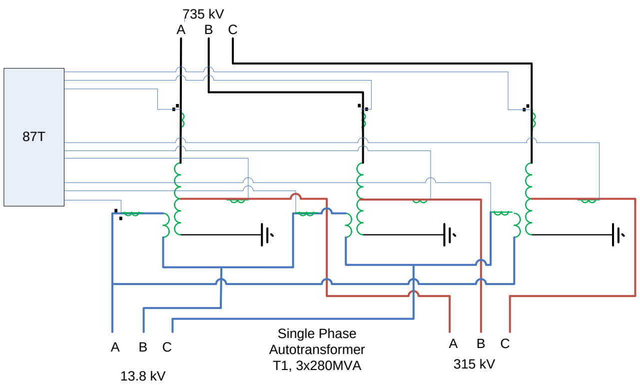

Fig. 2. Transformer Three-line Diagram for Differential Protection

Please note the tertiary CTs are inside the Delta. If the tertiary CTs are outside the tertiary, then the transformer can be protected in the same manner as more standard three-phases, three-winding transformer. There will be magnitude and angle compensation by the 87T, with straight-forward settings. However, the solution below is to address the tertiary CTs that are located inside the Delta. Some relay settings need to be tricked to ensure the 87T will provide adequate protection for the transformer.

B. Transformer Parameters

Table 2 below lists the transformer parameters that are used to calculate the transformer differential settings. The transformers are protected with redundant differential relays from different manufacturers. To simplify the discussion, only the setting calculation for manufacturer M3 is discussed.

Table 2 Single-Phase Power Transformer Parameters

Transformer Rated MVA at ONAF2	840 MVA (3x 280 MVA)
HV Rated Voltage (V_{HV})	735 kV
LV Rated Voltage (V_{LV})	315 kV
Tertiary Rated Voltage(T_{LV})	13.8 kV
Transformer Winding Connection	YNa0-D11
HV CT Ratio (CTR_{HV})	2000-1000:1 A
LV CT Ratio (CTR_{LV})	4000-2000:1 A (87TA CT uses 2000:1 TAP)
Tertiary CT Ratio (CTR_{TV})	2000-1000:5 (Interposing CT 5:1 for 87TA relay only)
Neutral CT Ratio (CTR_{N})	2000-1000:1 A
Neutral CT Ratio (CTR_{N-GR})	600:5 A
HV Rated Current (IR_{HV})	660 A
LV Rated Current (IR_{LV})	1540 A
Tertiary Rated Current (IR_{TV})	725 A

C. Two Possible Solutions

Below are presented two methods to treat the transformer. For each method, the relay setting calculation are detailed.

1) Solution 1 – Treat as a Three-Phase Transformer

Since the auto-transformer is connected with YNa0-D11, but the tertiary CTs are inside the Delta connection, set the CT connection compensation to be 0/0/0 or 12/12/12 for terminal CT1, 2 and 3 respectively.

Calculate the Magnitude Compensation Values

The protection relay from manufacturer M3 will calculate the magnitude compensation factor ($K_{winding}$) values automatically using the MVA, winding voltage and CT ratio per the following formula when the CT connection is wye. Please note the $K_{winging}$ has to be calculated based on the three-phase transformer parameters. (S_{T_REF}=840MVA; V_{HV}=735kV, V_{LV}=315kV, $V_{TV}=\sqrt{3}$*13.8=23.9kV). In the specific case of the Nalcor single-phase autotransformers, the tertiary CT is located inside the Delta winding connection. Thus, there is no angle compensation required and the tertiary voltage has to be set like a wye-connected transformer, which means the L-L voltage for the relay setting will be 23.9kV.

The HV CT ratio is selected as 2000:1, LV CT ratio set to 4000:1, tertiary CT ratio set to 2000:5 and then the calculated $K_{winding}$ values as below:

$$K_{winding_n} = I_{norm\_ctp} \Big/ \frac{S_{T\_REF} \cdot 1000}{\sqrt{3} \cdot V_m}$$

$$K_{HV} = 3.031$$

$$K_{LV} = 2.597$$

$$K_{TV} = 0.099$$

$$0.05 \leq K_{winding} \leq 15$$

The K_{TV} is very close to 0.05, but still in the settable range. Changing the CT ratio may not be necessary.

Calculate the Differential Pickup Value

Since there is no tap-changer, tap error is not considered. Therefore, set the 87 pickup higher than the maximum error caused by the steady-state CT error and transformer excitation current. Therefore, set the 87 pickup to 0.15 pu.

Calculate the Slope Values (K1 and K2)

Set the K1=30% for maximum error caused by CT and relay measuring errors during a through fault condition and K2=80% for possible CT saturation for a higher current through fault.

Calculate the Hi Set Instantaneous Differential Value

The unrestrained differential element must be set to higher than the large inrush current peak value (1750 A as obtained from the transformer manufacturer), which is 2.7 times the transformer HV rated current. Set to 6 pu.

Therefore, set: 87 pickup to 0.15 pu
87 Slope 1 to 30%
Is2=1.0 pu
87 Slope 2 to 80 %
87 Hi Set pickup =6 pu

2) Solution 2 – Treat as Single-Phase Transformers

Calculate the Magnitude Compensation Values

To protect single-phase transformers, the parameters have to be entered differently. The relay from manufacturer M3 can calculate the $K_{winging}$ values automatically using the MVA, winding voltage and CT ratio per the following formula when the CT connection is wye. Please note the $K_{winging}$ has to be calculated based on the single-phase transformer parameters (ST_{REF}=280 MVA; V_{HV}=424.4 kV, V_{LV}=181.9 kV, V_{TV}=13.8 kV) due to the tertiary CT being located inside the transformer delta connection. The protection relay is designed for a three-phase transformer. Therefore, when calculating the $K_{winding}$, $\sqrt{3}$ is included in the formula below.

$$K_{winding_n} = I_{norm\_ctp} \Big/ \frac{S_{T\_REF} \bullet 1000}{\sqrt{3} \bullet V_m}$$

$$K_{HV} = 5.242$$
$$K_{LV} = 4.5$$
$$K_{TV} = 0.171$$
$$0.05 \leq K_{winding} \leq 15$$

The K_{TV} is very close to 0.05, but still in the settable range. Changing the CT ratio may not be necessary. The remaining parameters can be set the same as in Solution 1.

As seen from the calculations in Solutions 1 and 2, when the CT is located inside of delta of the tertiary winding, the nominal voltage used to calculate the $K_{winding}$ must be input into the relay $\sqrt{3}$ times the voltage (as if treated like a three-phase transformer, which is 23.9kV and 13.8 kV respectively.) It can be selected depending on the protection engineer's preference.

IV. Other Protection Functions

In the previous sections, the focus was mainly on the transformer current differential function, which is the function that presents the biggest challenges for adequately protecting the three single-phase transformers. Additionally, other protection elements contained in the same multi-function relay, should be used to complement the differential, such as the overexcitation (or V/Hz) and restricted earth fault protections.

A. Overexcitation

Because transformers are typically operated near the inflexion of the iron saturation curve, relatively small increases in voltages can result in large exciting currents in the transformer which can lead to damage to the asset. Given that the voltage divided by the frequency is proportional to the flux in the transformer, the ideal protection element against such damage is the volts per hertz function.

Considering the IEEE Std C57.12.00 [5] which allows the transformer to be operated up to 10% above the rated secondary voltage, this becomes a good criterion to set the overexcitation protection element [6].

Figure 3 below shows the overflux limit curve for the transformer as well as the Overexcitation protection element curve protecting adequately the transformer.

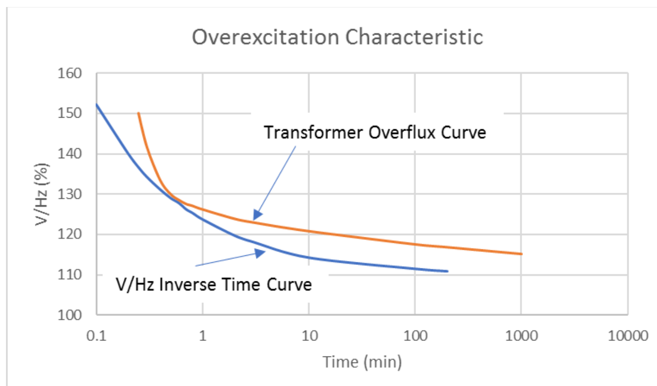

Fig. 3. Transformer V/Hz Protection Curve

B. Restricted Earth Fault

A ground fault occurring near the neutral point of a wye-connected winding can result in fault current below the pickup level of overcurrent or differential elements. Such a fault can degenerate and lead to more serious ground faults or phase-to-phase faults if not detected and cleared on time.

The restricted earth fault element can mitigate this low sensitivity by comparing the winding phase current with the current circulating through the winding grounding impedance. While the current differential element provides protection typically for the top 70% of the winding, the restricted earth fault can cover the bottom 35% of that winding.

The operating signal is typically of the form

$$I_{op} = |I_G + I_N| = |I_G + (I_A + I_B + I_C)|$$

and to ensure the safety of the operation in front of CT saturation conditions, this operating signal is compared to a restraint signal defined in order to prevent misoperations during external ground or external phase-to-phase faults. An example of restraint signal from manufacturer M1 is

$$I_{rest} = max\{I_{R0}, I_{R1}, I_{R2}\}$$

where

$$I_{R0} = |I_G - I_N| = |I_G - (I_A + I_B + I_C)|$$

and I_{R1}, I_{R2} are respectively the positive- and negative-sequence currents.

The operation of the protection element occurs when the operating current is larger than the restraint current multiplied by a slope factor.

V. CONCLUSION

When the specific application encountered by the protection engineer does not match exactly the typical scenario envisioned and documented by the relay manufacturer, a thorough understanding of basic principles and specifics of the equipment is required. In protecting three single-phase transformers, settings for the transformer current differential have to be entered carefully to adapt to protection relays designed to protect three-phase transformers. It can be accomplished in more than one ways, but it first must be well understood.

Multi-function protection relays are able to protect the transformer from conditions not easily detected by a current-only protection element. For instance, from overvoltage that could cause heating and insulation damage, which can be detected with an overexcitation function. Also from low magnitude ground fault current that could easily trip the transformer in case of a ground fault near its neutral point.

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