Experiences in commissioning and testing of differential protection for phase-shifting transformers

T. Hensler, F. Fink*, H. Mitter†

*OMICRON electronics GmbH, Austria, thomas.henlser@omicronenergy.com, †Vorarlberger Energienetze GmbH, Austria

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Abstract

Due to the increasing demand to control power flow within our networks nowadays more phase-shifting transformers (quadrature boosters) are installed. The most important protection principle for transformers is differential protection. An additional phase-shift has to be considered by the differential protection to fulfil the requirements for selectivity. Particularly for two-phase faults outside of the transformer an additional phase shift will introduce a differential current in the non-faulty phase. The protection relay has to handle this situation and this has to be verified during commissioning. The different relay manufacturers use different approaches how the relays will ensure stability for phase-shifting transformers. Depending on the actual phase-shift, which is usually signalled to the relay using binary inputs, the differential protection has to adapt. Different approaches for different types of phase-shifting transformers (e.g. one-core and two-core versions) are discussed and evaluated. For commissioning a relay for a phase-shifting transformer the correct behaviour of the protection has to be verified. Using a simulation-based test software, which is capable to simulate the detailed behaviour of the phase-shifts for the individual tap positions of the transformer, testing can be done in detail and conveniently.

1 Introduction

The energy transition has caused major changes to our electrical grid in the recent years. The integration of a lot of renewable energy sources changed the power flow considerably. Previously power was mostly transferred from higher to lower voltage levels. But today the distribution networks feed into the transport systems too. Additionally the market environment for power trading has changed in a lot of countries, e.g. all countries in the European Union, which causes even more dynamics for the electrical power flow.

Both the transport system operators (TSOs) and the distribution system operators (DSOs) want to control power flow as much as possible. By using a phase-shifting transformer it is possible to control active power flow by altering the phase angle of the currents. Although a phase-shifting transformer is a major investment for an utility, it will pay off due to the dynamics of the electricity market within a couple of years.

To explain the principle of a phase-shifting transformer we want to revise the basics of active power transfer on transmission lines. For a simplified line model, where resistive losses are ignore, active power flow P over a power line is affected by the line reactance X and the phase angle difference φ_1-φ_2 between the two ends of the line, according to the following equation (1):

$$P = \frac{V_1 V_2}{X} \sin(\varphi_1 - \varphi_2) \qquad (1)$$

By introducing an additional phase shift δ the value can be altered as follows (2):

$$P = \frac{V_1 V_2}{X} \sin(\varphi_1 - \varphi_2 + \delta) \qquad (2)$$

The most important protection principle for power transformers is differential protection. Differential protection evaluates the difference of the currents on both sides of the transformer. By introducing a variable phase shift for the current, this will affect the difference value and has to be considered by the protection, so that the requirements regarding selectivity and stability are met. The most challenging situation for the protection relay occurs for a two-phase outside fault, where the differential protection should be stable. The phase-shift of the transformer will cause a differential current in the non-faulty phase too. But the stabilizing current for this phase is rather low, so that this can cause an erroneous trip of the relay.

The different relay manufacturers use different approaches to cope with this problem and ensure stability for the protection. The differential protection element has to adapt according to the variable phase shift of the transformer. Usually the current phase-shift is signalled to the protection relay using binary contacts from the tap changer.

2 Principle of phase-shifting transformers

The principle of phase-shifting transformers is based on the introduction of a variable phase-shift for the purpose of controlling the real power flow over a specific network path. In the US phase-shifting transformers are mostly called phase angle regulating (PAR) transformers, whereas in UK they are known as quadrature boosters. Within this paper we stick with the term phase-shifting.

The variable phase-shift is usually achieved by introducing voltage components shifted by 90° (hence the name quadrature) from a delta connected winding, whereas the magnitude is varied using different moveable taps. The principle of a simple phase-shifter is shown in a 3-phase circuit in Figure 1.

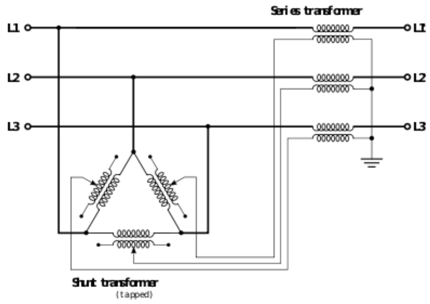

Figure 1: Principle of a phase-shifting transformer

Using the shunt transformer in delta connection voltage components shifted by 90° with respect to each phase are achieved. The output of the shunt transformer is then added to the phase voltages using a series transformer, which creates the vectorial sum of the phase voltage and the smaller 90° components. The tap connections on the shunt transformer allow to control the magnitudes of the 90° components and therefore the magnitude of the phase shift. Phase shifts both in positive and negative directions are possible. The two transformer units are usually built as separate units in their separate tanks. But there are other constructions, where all the windings are on the same core (single-core), so that a single tank is more economical.

Another common technical solution is an integration of a phase-shifting transformer into a power transformer for transforming from one voltage level to another. Power transformers between different voltage levels usually have multiple taps with slightly different turns-ratios for voltage regulation already. Then additional taps for the phase-shifting are built into the same transformer too. Since taps for voltage regulation can be available either on the high voltage or low voltage side the phase-shifting taps are then mostly realized on the opposite side of the voltage regulating taps.

An example is shown in Figure 2 with a 410kV:230kV YNy0 transformer with 450MVA. The transformer has a conventional voltage regulation tap changer on the high voltage side with 17 taps. On the low voltage side there are 35 taps with phase shifts from -17.22° to +17.22°. The polarity of the phase shift is switched with a separate switch, usually called advance/retard switch, before the taps are wired to the online tap changer (OLTC).

This transformer is built into two separate tanks, as it is indicated by the dashed lines surrounding the separate units. The regulating transformer is just connected on the lower end of the low voltage wye winding and there is the delta winding from the main transformer tank to create the 90° phase-shifted voltages. This allows for a more economical construction of the regulating unit.

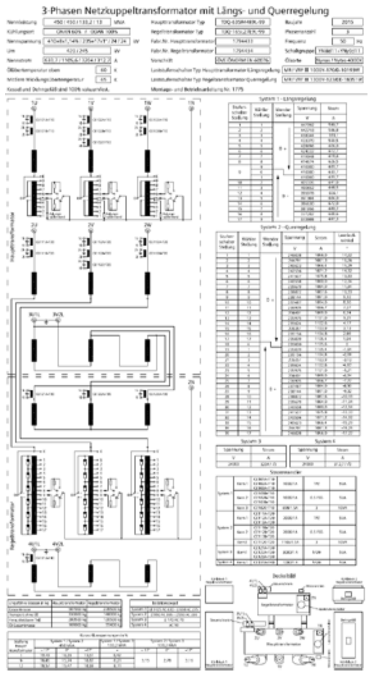

Figure 2: 3-Phase power transformer 410kV:230kV with voltage control taps on the HV-side and phase-shifting taps LV

The principle how the phase-shift is generated for this transformer is depicted in Figure 3. For each phase a small voltage part from both of the two other phases in equal magnitude is added to the main phase voltage, so that a component with 90° is added finally.

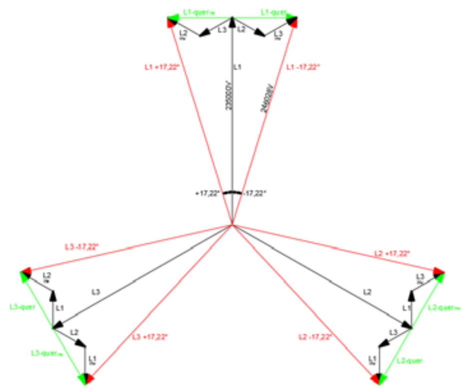

Figure 3: Principle for creating phase-shifts with voltage components from the two other phases

As a second example of a phase-shifting transformer 220kV:110kV with 300MVA in a single-core/single-tank construction is shown in Figure 4. This transformer has again voltage regulating taps on the high voltage side (29 taps including an OLTC). On the low voltage side 17 phase-shifting taps are realized with a possible phase shift from -15.2° to +15.2°.

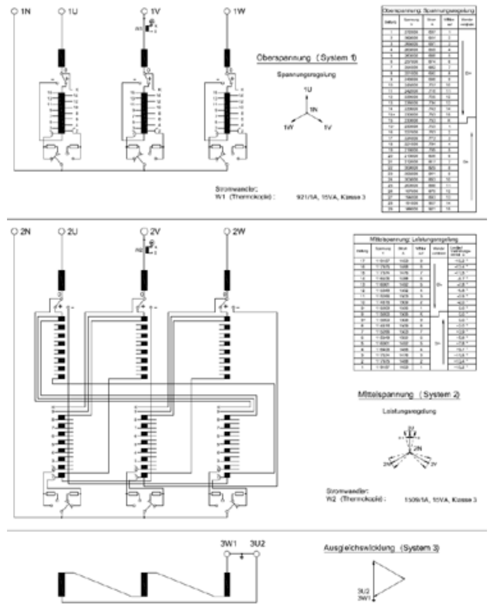

Figure 4: 3-Phase phase-shifting power transformer 220kV:110kV

With this winding configuration the reactive voltage is realized as the sum of two components, one from the own phase and one with double the magnitude from one of the other phases, as it can be seen in Figure 5 within the phasor diagram (right triangle with 60°).

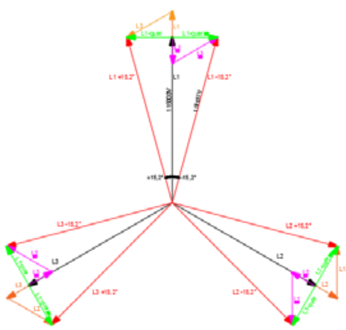

Figure 5: Principle for creating phase-shifts with a voltage component just from one of the other phases

3 Challenges for differential protection

The main protection principle for power transformers is differential protection (ANSI 87T). Differential protection elements supervise the differential current between high voltage and low voltage side and trip as soon as the differential value exceeds a certain threshold. To stabilize the protection usually a percentage restraint characteristic is used, where a restraint quantity (bias current) is used, which usually reflects the magnitude of the currents through the transformer. Using a percentage restraint characteristic the differential current threshold can be controlled depending on the bias current. For higher bias current a higher threshold is necessary.

Restraining the differential element with a bias current is used to achieve stability for a lot of different circumstances during transformer operation, such as CT errors or CT saturation. Additionally the percentage restraint characteristic can compensate for small differences in the calculated differential currents due to voltage regulating taps of the transformer. Although there are some protection relays, which take the current tap position into account and adjust the turns ratio accordingly.

For the calculation of the restraint quantity (bias current) the different relay manufacturers use quite different approaches and formulas. There are protection relays, which determine the bias current individually for every single phase, whereas other relays choose a maximum value among all the phases to get good stability for all different vector groups.

For a transformer with taps for phase-shifting the influence of the phase-shift in both angle and magnitude cannot be compensated for with a higher percentage restraint characteristic anymore. Phase shifts up to 20° and more result in a current transformation behaviour, which is almost similar to a different vector group. So for protection of phase-shifting transformers the differential relays have to adapt its behaviour according to the current tap position to achieve consistent stability for all different operating states of the transformer.

A special challenge for the differential protection arises for 2-phase faults outside of the protected transformer. The phase-shift achieved within the transformer is effective for the positive sequence components as specified. But for the negative sequence currents the phase angle is applied into the opposite direction. This will cause an unsymmetrical distribution of the currents through the transformer for 2-phase faults, where negative sequence currents are present, and will introduce a considerable differential current in the non-faulty phase too.

The current distribution on a phase-shifting transformer for a 2-phase outside fault is shown in Figure 6 for a single-core phase-shifter.

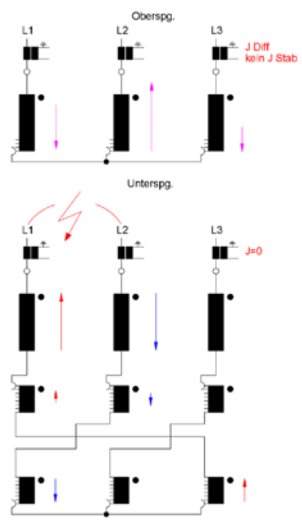

Figure 6: Current distribution for a phase-shifting transformer for an outside 2-phase fault

There is an outside fault L1-L2 on the low voltage side, which will force fault current with a phase angle of 180° through the L1 and L2 phase. But due to the winding parts from the other phases, which are used to introduce the 90° component for phase shifting, a current is introduced in the non-fault phase on the high voltage side too. The currents for the faulty phases L1 and L2 on the HV-side are not symmetrical anymore.

The same effect can be observed for other winding configurations too (see [2]). For the differential protection this additional current in the non-faulty phase can cause a differential trip, since there is no additional bias current in the non-faulty phase. Differential protection for phase-shifting transformer has to cope with this situation and the protection has to guarantee stability for outside faults in all operating situations and for all tap positions of the phase-shifting taps. The different relay manufacturers do apply different solutions, which should be discussed in the next chapter.

4 Differential Protection for Phase-Shifting Transformers

Differential protection for phase-shifting transformers has to take into account the phase-shift of the currents for accurate calculation of differential currents. Older standard transformer differential relays were not designed to cope with this specific requirements. Nevertheless for the protection of phase-shifting transformers protection devices designed for conventional transformer protection can be used if an artificial third winding is used to mimic the phase-shifted currents. This is a quite often used approach and has been documented by the various manufacturers in application notes for their relays. Newest generation of transformer differential relays are already designed to support phase-shifting transformers and can model the specific behaviour of the transformer within the relay algorithm in firmware.

As an example for the approach with a third winding we discuss a solution for the protection of a phase-shifting transformer at a utility in Austria. There a transformer differential relay for a 3-winding transformer from Schneider Electric has been used. Current inputs for the high voltage side are wired as usual into inputs A. For the low voltage side the secondary currents from the CT are first wired to the inputs B and then in series through the inputs C for the third winding of the 3-winding relay.

Within the relay different setting groups are used, which parameterize the third winding in such a way, that the phase-shifted components are considered by the differential element according to the current phase-shift of the protected transformer. For positive phase-shifts a vector group of Yy0y8 is used, for negative phase-shifts Yy0y4. Additionally the CT turns ratio setting in the relay for the 3rd winding are set in such a way, that the resulting magnitude is about the same as the 90° component introduced by the phase-shifting transformer.

Using binary input contacts from the tap changer, which controls the phase-shift taps on the LV-side, the relay is switched between the different setting groups instantaneously. It is important that the relay supports a setting group change during normal operation of the protection and does not require a reboot of the firmware or introduce another delay for the protection functions during setting group changing. For this specific application it was sufficient to use 3 setting groups, For the tap in neutral position +/- on tap position setting group 1 was used, which did not use the virtual 3rd winding at all. For all tap position from number 1 to 7 with phase-shifts in positive direction setting group 2 was used and for all taps from 11 to 17 with negative phase-shifts setting group 3. This was sufficient to fulfil the stability requirements under all different tap positions both for the voltage regulating taps on the HV-side combined with any tap position of the phase-shifting side on the LV-side. The setting groups were changed using binary inputs from the tap positions.

The behaviour of the protection on an outside two-phase fault can be visualized by the current distribution including the virtual 3rd winding as shown in Figure 7.

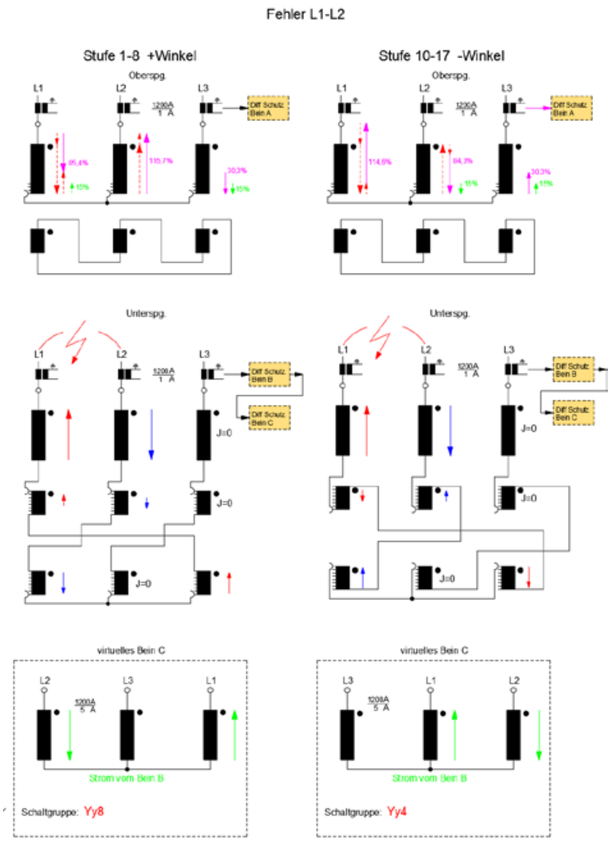

Figure 7: Current distribution for outside 2-phase faults incl. 3rd virtual winding

On the left hand side a two-phase outside fault on the LV-side forces fault current with 180° phase angle into phases L1 and L2. The phase-shifting transformer is supposed to be on a tap position with a negative phase angle. This will introduce a fault current in phase L3 on the HV-side. Using the virtual 3rd winding in y8 vector group will compensate this current in phase L3 with a component in the opposite direction. The current distribution on the right hand side in Figure 7 shows the situation for tap positions with positive phase shift, where the virtual 3rd winding is connected in y4 vector group.

The behaviour of the protection relay could be verified with the percentage restraint characteristic. Now all the differential current values are below the restraint characteristic and do not cause a trip even for the phase L3.

Another example for a differential protection on a phase-shifting transformer 400kV:110kV with 350MVA realized using a transformer differential relay from ABB will be discussed now. This transformer has 27 taps on the HV-side with about 1.25% voltage step. On the LV-side there are 21 taps with phase shift from 0° to 27.34°. The 90° component for this transformer is created using windings from each of the other two phases. The transformer differential relay is connected to the CTs as shown in Figure 8.

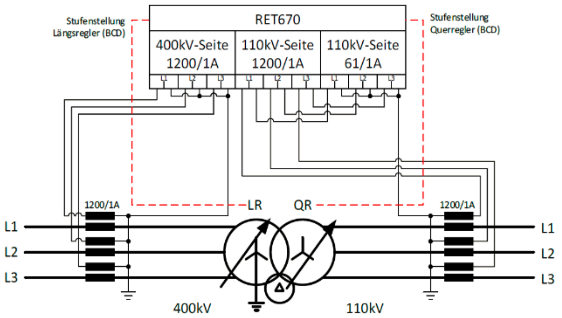

Figure 8: Connection scheme for transformer differential protection using virtual 3rd winding

Again on the 110kV-side the currents from the 1200A:1A CTs are connected in series to winding B and winding C inputs of the relay. The ABB relay does support modelling of the voltage regulating taps on the HV-side and does adapt its current differential elements according to the changed turns-ratio of the transformer.

For the virtual 3rd winding the CT ratio setting within the relay is set to 61A:1A. Within the logic of the protection relay these input quantities are used to calculate 90° current components using logic elements for 3-phase sums (3PH SUM), from the current inputs of the virtual 3rd winding, which are the sum of two elements with permuted phase connections, as shown in Figure 9.

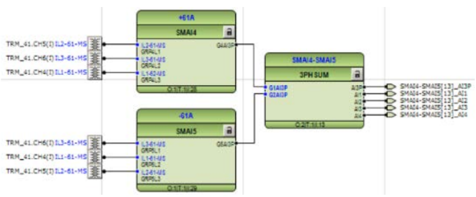

Figure 9: Calculation of the 90° components for 5° phase-shifts using logic elements in the relay

For a single sum element a quantity of $\sqrt{3}\,61A\,e^{j90°} = 105A\,e^{j90°}$ is calculated, which corresponds to the 90° component for a phase shift of 5°. These 90° components are then added to the current components from the LV-winding inputs, whereas depending on the tap position of the phase-shifting taps one or more 5° steps are used, as shown in Figure 10.

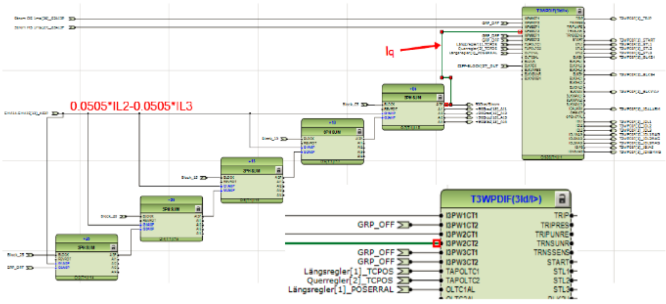

Figure 10: Logic to enable the 3PH SUM logic elements depending on the tap positions of the phase-shifter

The positions of the taps both on the HV-side and the phase-shifting taps on the LV-side are communicated to the relay using binary inputs from the tap changer controller. Within the relay additional logic to verify the correct tap positions is implemented using binary logic elements. This logic verifies that the tap positions are reasonable after a tap change and supervise the timing of additional binary contacts during a tap change procedure. In case of any suspicious behaviour the relay issues alarms to the control centre and forces the differential protection elements into nominal tap positions.

Within the transformer differential protection from ABB the restraint current is taken as the maximum current from all windings and all phases so that the stability for outside two-phase faults is not that critical as with protection relays from other manufacturers. On the other hand for this phase-shifting transformer, which has taps with phase shifts up to 27°, even under stable symmetrical operation a false trip can occur, simply because the introduced reactive current component can cause a differential current above the percentage restraint threshold. Therefore a correction of the tap positions for the differential elements is necessary.

As a last example of a newest generation relay for transformer differential protection the implementation within a Siemens 7UT86 relay should be discussed. The algorithm in the relay allow to model the phase-shifting taps exactly as for the real transformer. Both taps for voltage regulation and taps with additional phase-shifts can be parameterized within the relay. A tap changer can be modelled both for the HV and/or the LV-side. Therefore the detailed tap settings have to be entered within the relay settings software including rated voltage values and phase shifts in degree.

The Siemens relay has different possibilities to get the actual tap positions from the tap changer using binary inputs. E.g. it can be configured to encode the actual tap position as a binary coded decimal (BCD) value on multiple binary inputs. Tap positions for voltage regulating taps, e.g. on the HV-side, and phase-shifting taps can be captured independently. See [3] for more details.

5 Commissioning and testing of protection relays for phase-shifting transformers

Since all the solutions for protection of phase-shifting transformer involve either complex customized logic in the relays or elaborate detailed settings a comprehensive commissioning and testing is necessary before the protection is put into operation. It has to be verified, that for all tap positions the relay behaves as designed and that the requirements regarding stability and selectivity are met.

A utility in Austria did commission a phase-shifting transformer with a primary short-circuit test on the transformer. Therefore primary injection was done using a mobile diesel generator set and distribution transformers 20kV:400V. They did inject on the 200kV-side of the transformer and made a short-circuit on the secondary 110kV-side. The short-circuit current was applied with 100A – which did result in a voltage of 3.3kV. Tests were done for 3-pole, 2-pole and single-pole outside faults. The resulting currents were applied to the protection relay and the IDiff and IBias values were retrieved from the protection device connected. Within the percentage restraint characteristic the values were scaled up according to the nominal short-circuit voltage of the transformer, which correspond to realistic infeed conditions during normal operation. For all the tests done it could be shown that the protection was stable for outside fault using the protection principle with the virtual 3rd winding.

For secondary testing a model of the transformer to calculate its current distribution was developed based on a mathematical model of the transformer (see [1]) in an Excel spreadsheet. Using these values protection testing with injection of steady-state values according to the calculated values were possible, which did show the same results as the primary tests done.

The most convenient tests are possible using a new protection testing software, which is capable to simulate the transient behaviour of a phase-shifting transformer. Within this software the transformer with all its taps both on the HV- and LV-side is modelled. Then different scenarios with steady-state and dynamic faults can be simulated easily, whereas the resulting transient current signals can be injected to the protection relay using a conventional protection testing device. The user interface of this software is shown in Figure 11.

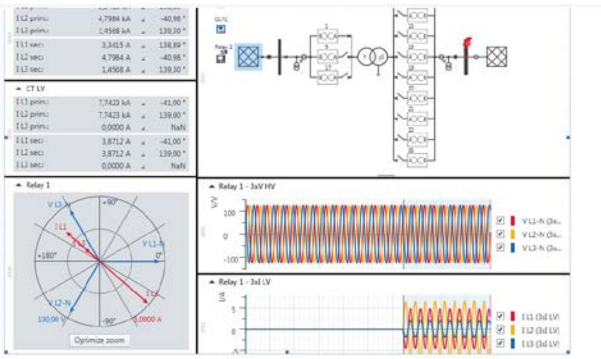

Figure 11: Protection testing software which can simulate a phase-shifting transformer

Again all tests for all the different tap positions did show the correct results and prove that the protection concept does fulfil the requirements for stability and selectivity.

6 Summary

Transformer differential relays for phase-shifting transformers have to consider the tap position of the voltage and phase-shifting tap changer into account to be able to calculate correct IDiff and IBias quantities. A common approach used with conventional transformer differential protection relays is to use a virtual 3rd winding with currents from the CTs in series to the LV-winding. Using this approach it is possible to simulate the 90° current component using logic elements of the relay or a corresponding vector group within the protection device. Using binary inputs from the tap changer the relay logic can adapt or switch between different setting groups in the relay accordingly. In the newest generation of transformer differential relays it is already possible to model the detailed behaviour of voltage and phase-shifting taps within the firmware of the relay.

For commissioning of differential relays on phase-shifting transformer, it is necessary to verify the correct behaviour of the protection for the different tap positions of the phase-shifter. For the critical case with a 2-phase outside fault, which will cause an additional differential current in the non-faulty phase, there should not be any false trips.

Using a new simulation-based protection testing software, which can simulate a phase-shifting transformer with all its voltage and phase-shifting taps, a convenient way to test and commission such protection relays is possible. A manual calculation of the test quantities, which is complicated and error pone, is not necessary anymore.

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