Optimal differential protection for phase shifter transformers and special transformers

Due to the energy transition, a demand for renewable energy sources' integration into power grids has arisen. This, in turn, has caused changes in energy generation at different voltage levels. Additionally, this change has overturned the classic working principle of power flow from high to low voltages. Therefore, distribution systems can now assume power transport functions by feeding on transmission grids on a more critical note, the primary system must control the excess stress from renewable energy sources in a reliable manner. The excess stress is a result of energy trading, since the energy must be transported to areas where it is demanded. Phase shifter transformers are implemented to counteract this stress, as well as "complex" automation systems. Both serve to control power flow at the supply limits.

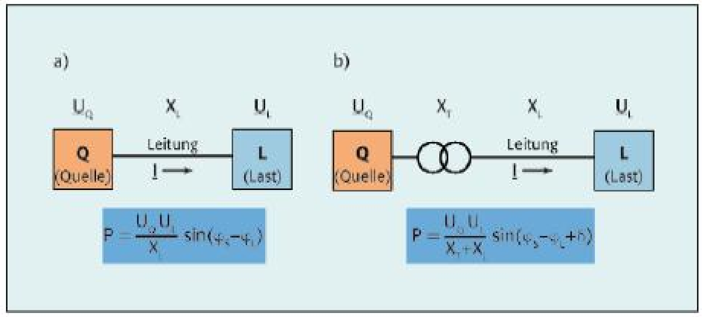

Figure 1: Application of the phase shifter transformer

a) Classic

b) With phase shifter transformer

Another alteration confronting the electrical energy system is the introduction of high-voltage direct current transmission (HVDC), FACTS (flexible AC transmission systems) and variable-speed electrical drives. All of these power electronics components are gaining popularity. The transformer links the power electronics components to the electrical energy system. However, classical transformer designs do not suffice. In order to minimize harmonic system perturbations, so-called "special transformers" are needed. Differential protection is the most important protective component of a special transformer. Adjustability is vital to differential protection, since it must adapt to different applications reliably and safely. Further, adjustability is important in satisfying selectivity requirements (stability for external faults) and sensitivity for internal faults.

Phase shifter transformer basics

Figure 1 depicts the main idea behind controlling active power transmission using a phase shifter transformer. The active power transmitted over an overhead line is determined mainly by the phase angle difference between infeed (source) and load.

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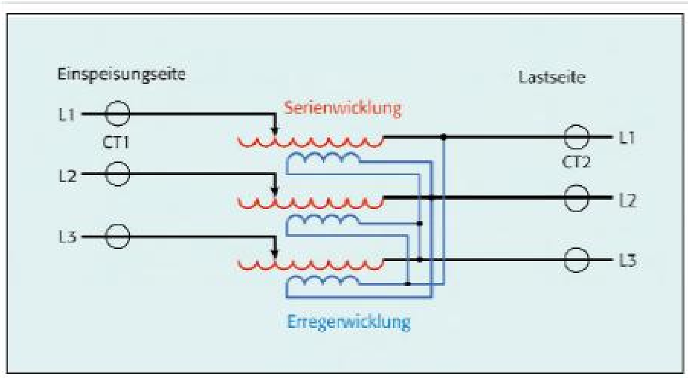

Figure 2: Asymmetrical single-core transformer concept

Voltages and line reactance also play a role (Figure 1a). The load current effects the phase angle difference. Control over the phase angle difference is made possible by connecting a phase shifter transformer in series. Changing the phase angle δ immediately affects active power transmission (Figure 1b).
In practice, there are two basic phase shifter transformer designs (PST). In single-core PSTs all required windings are distributed over a three phase transformer's cores. It consists of a three-phase series winding and a three-phase excitation winding.
The excitation winding is connected in delta and induces a voltage ΔU into the series winding. A tap changer (in the series and excitation winding) adjusts the phase angle rotation δ and the output voltage.
Phase angle rotation is implemented through 90° quadrature regulation or 60° phase angle regulation. The tap changer controls faulty currents and switches only under load. The short-circuit impedance varies with the tap changer position. The basic layout is shown in Figure 2.
The more extensive, detailed design varies slightly between manufacturers. For example, the excitation winding I has an additional tap changer as well as an advanced-retard switch to reverse the direction of the phase angle (see also Figure 6).
In the two-core transformer design, the PST consists of a three-phase series transformer and a separate excitation transformer. The voltage generated by the excitation transformer is injected into the delta winding of the series transformer as the adjustable series voltage ΔU. The voltage phasor addition allows for a phase angle rotation between ± 10° and ± 35°.
Series and excitation transformers can be installed in one tank or in separate tanks.

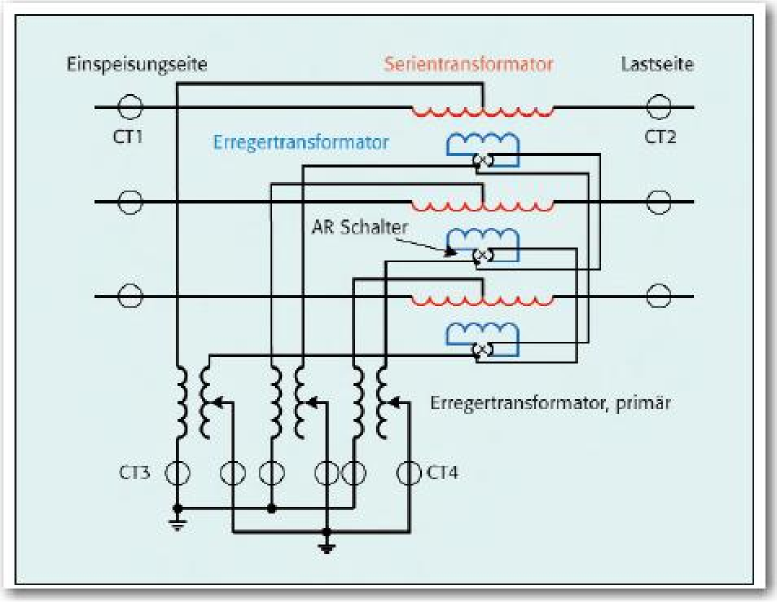

Figure 3: Symmetrical two-core transformer concept

The two-core design is advantageous because it allows the easy selection of the tap voltage and of the current in the excitation winding. No load current flows through the tap changer. Moreover, the output voltage is unaffected by the phase angle change. Figure 3 shows the basic design of the two-core transformer.
Following the protection concept according to IEC 62032, it is unnecessary to evaluate the tap changer position. However, the position of the advanced retard switch (AR switch) has to be considered if it is positioned within the delta winding (according to Figure 3). This implies that the phase angle has to be rotated by 0° (vector group 0) or 180° (vector group 6). To capture all fault events, a primary differential protection (measuring points CT1, CT2, CT3) and a secondary differential protection (measuring points CT1, CT2, CT4) are used.
The current transformer CT4 is located on the regulated side of the primary excitation transformer.

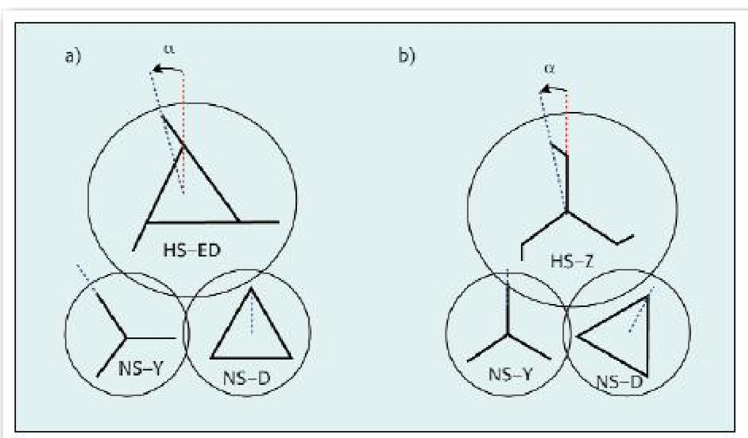

Figure 4: Basic layout of a special transformer
a) Delta design (D(+7.5°)y11d0
b) Zigzag design (Y(+7.5°)y0d1

Schaltgruppe/Phasenwinkeldrheung		
	Schaltgruppe	Phasenwinkeldrehung (von NS zur HS)
HS-Seite	D	0°
NS-Seite1	y11	+ 330°
NS-Seite 2	d 0	0°
NS-Seite 3	y11 1/2	+ 345°
NS-Seite 4	d0 1/2	+ 15°

Table 1: Vector group and phase angle rotation

Special transformer basics

Special transformers have a fixed number of windings. However, the phase angle rotation is not a multiple of 30°. For example, phase angle rotation values of ± 7.5° or 15° are possible. Special transformers are mostly used as converter transformers. The number of windings (sides) is determined by the converter arrangement (12- or 24-pulse converters or higher). These devices feed e.g. medium-voltage motors or FACTS. The design is tailored to the harmonic interference reduction. Typically, these transformers have three windings. For higher-pulse converter systems, a significantly higher number of windings is used (up to seven and more).

Phase shifting can be accomplished by a special interconnection of the high-voltage winding. This winding is designed as an extended delta winding or zigzag winding.
Figure 4 shows the conventional design and illustrates the phase angle rotation. The transformer in Figure 4a is a modification of design Dy11d0 and Figure 4b of type Yy0d. Other arrangements can be implemented, such as the phase angle rotation of the low-voltage side. For example, a five-winding transformer is designed as Dy11, d0, y111/2, d01/2. The special phase angle rotation is represented with different designations (e.g.: 111/2, 11.30, 11(+15°)). Table 1 shows the ratio of phase angle 1.

New design of the differential protection function

The differential protection for power transformers accounts for a phase angle rotation through the vector group, which can be either 0° or a multiple of 30°. The phase angle rotation is implemented in matrices found in the firmware of digital protection devices. The corresponding matrix is selected according to the vector group number. A universal transformer matrix is required, so that any phase rotation can be accommodated for. So far, interconnecting measuring points (geometric addition of currents) has served as a makeshift solution. This allowed for maximum angle rotations of 15°. The protection setting accounted for the remaining fault, and was less sensitive as result. Equation 1 describes the idea and the basic structure of the new universal matrix. Depending on the respective application, the angle or vector group has to be adjusted. With help of the protection device, the matrix elements are then calculated [f(α), f(α-120°),f(α+120°)].
In the case of classic power transformers and special transformers, the calculation of the matrix elements is fixed and results when setting the parameters of the protection device.

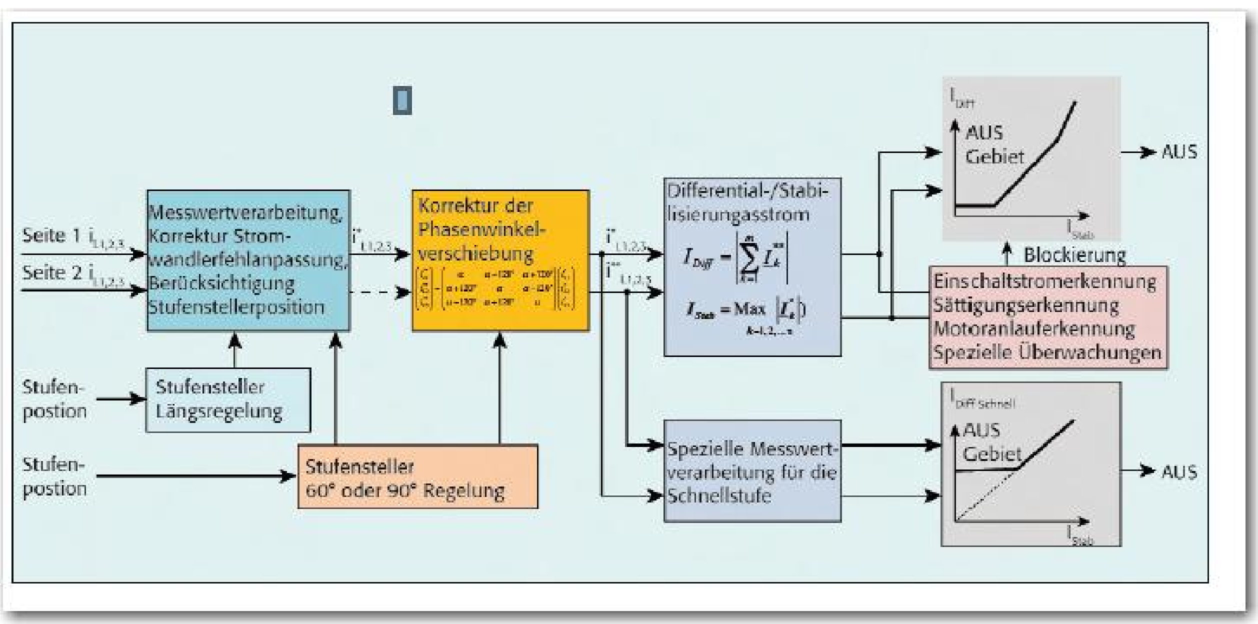

Figure 5: Overview of the function blocks of the differential protection

$$
\begin{pmatrix} i^{**}_{L1} \\ i^{**}_{L2} \\ i^{**}_{L3} \end{pmatrix} = \begin{pmatrix} f(\alpha) & f(\alpha - 120°) & f(\alpha + 120°) \\ f(\alpha + 120°) & f(\alpha) & f(\alpha - 120°) \\ f(\alpha - 120°) & f(\alpha + 120°) & f(\alpha) \end{pmatrix} \begin{pmatrix} i^{*}_{L1} \\ i^{*}_{L2} \\ i^{*}_{L3} \end{pmatrix}
$$

Equation 1

$f(\alpha)$ Trigonometric transformation function

$i^{*}_{L1,2,3}$ Amplitude of adjusted current (adjustment of current transformer mismatch and tap changer mismatch)

$i^{**}_{L1,2,3}$ Phase angle adjusted current

For single-core phase shifter transformers, the matrix elements need to be calculated online during operation, depending on the tap changer position. The angle and voltage are provided in a table for each tap changer position. The calculation selects elements based on the tap. This novel design allows differential protection to be adjusted optimally to various applications. This generates a high sensitivity for phase shifter and special transformer applications. Figure 5 outlines the basic structure of the new differential protection function.

The input quantities are phase currents, updated according to the sampling frequency. This allows a high sensitivity over a wide range of working frequency. In the first function block, currents are adjusted by means of their amplitudes. The lateral current derived from the maximum winding rating serves as the scaling quantity. The tap changer also requires an amplitude correction, which is realized simultaneously with the aforementioned adjustments.

$$
I_{\mathrm{Diff}} = \left| \sum_{k=1}^{m} I^{**}_{k} \right|
$$

Equation 2

$$
I_{\mathrm{Stab}} = \underset{k=1,2,\dots n}{\mathrm{Max}} \left| \left(I^{*}_{k} \right) \right|
$$

Equation 3

Where:

n: number of transformer measuring points (n ≥ m)

m: number of transformer sides (windings)

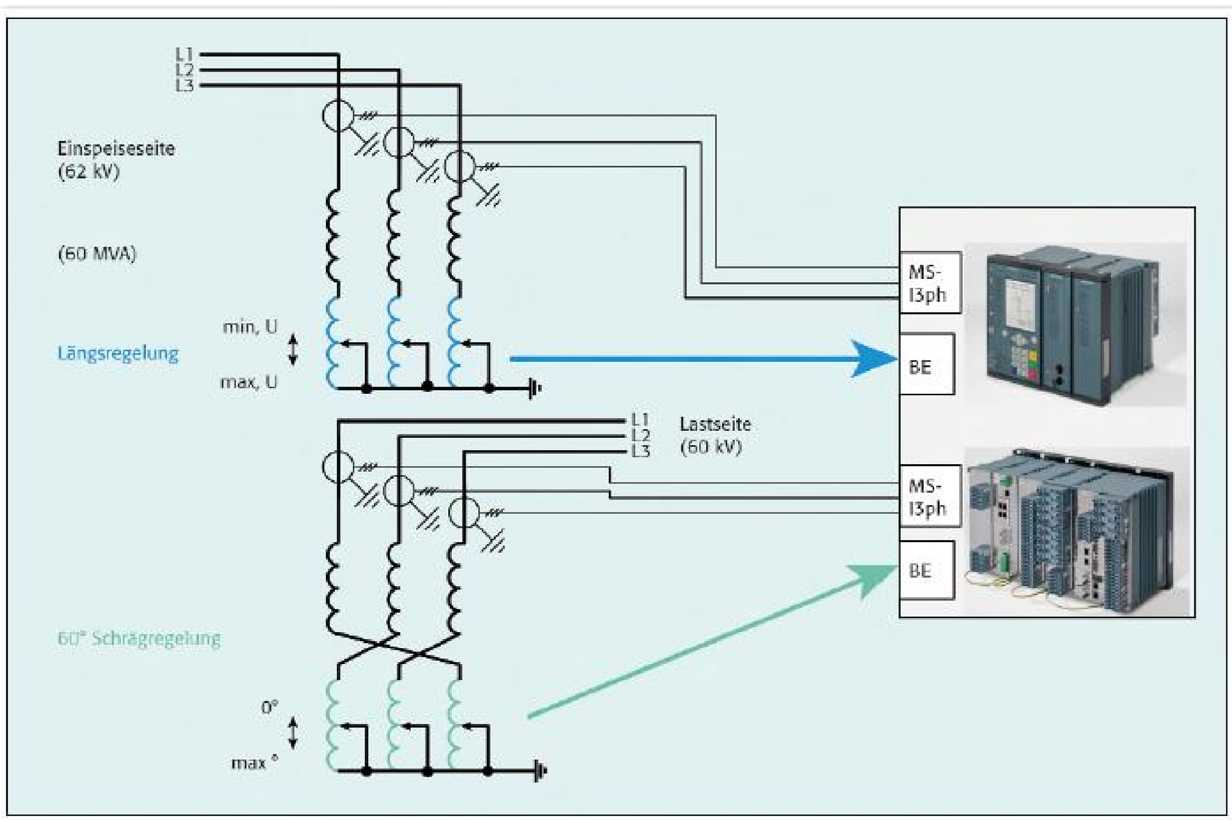

Figure 6: Single-core transformer connected to protection device

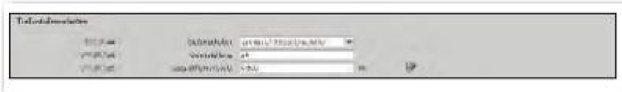

Figure 7:
Setting of the transformer with in-phase regulation

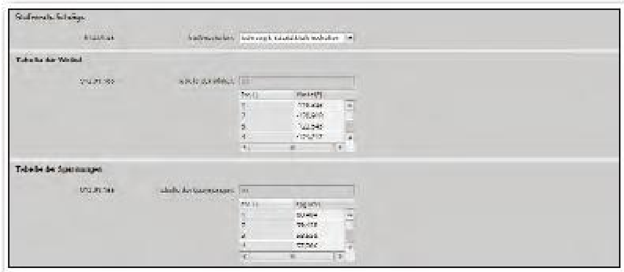

Figure 8:
Setting of the phase angle regulating transformer

This also improves the sensitivity of power transformers with in-phase regulation. Amplitude-adjusted currents are the output quantity.

Afterwards, the universal transformation matrix rotates the angle. Either the angle α is fixed or it is controlled by the tap changer position.

Subsequently, the differential current and the stabilizing current are calculated. In this context, the currents are defined positively toward the protected object. The currents are calculated according to equations 2 and 3. The differential current is the geometric sum of the phase current phasors corrected by magnitude and angle. Due to the phasor creation, only the fundamental component is evaluated and the harmonics are attenuated.

The differential current and the stabilizing current are calculated phase-wise. The maximum lateral current is used as the stabilising current. This yields sufficient stabilization in the event of current transformer saturation, as it will immediately switch to the current of an unsaturated measuring point. This method of calculating the stabilizing quantity has an impact on the characteristics' slopes.

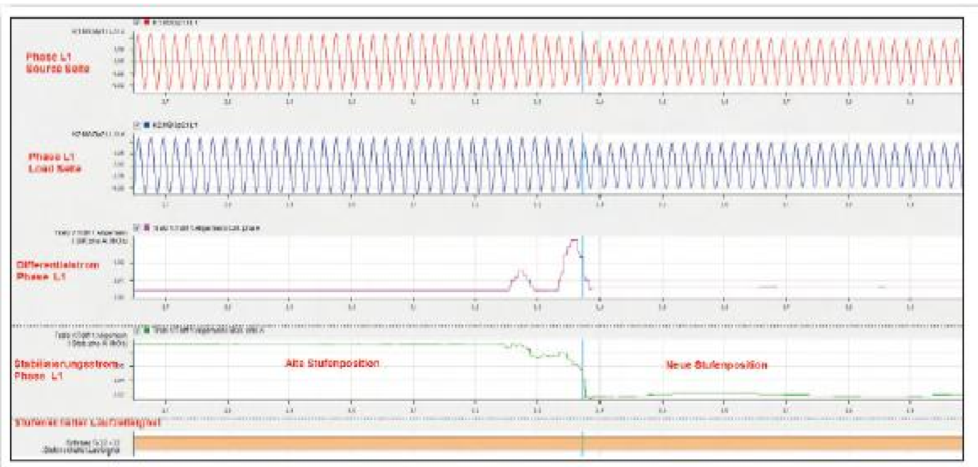

Figure 9:
Fault record of the protection device with active tap changer

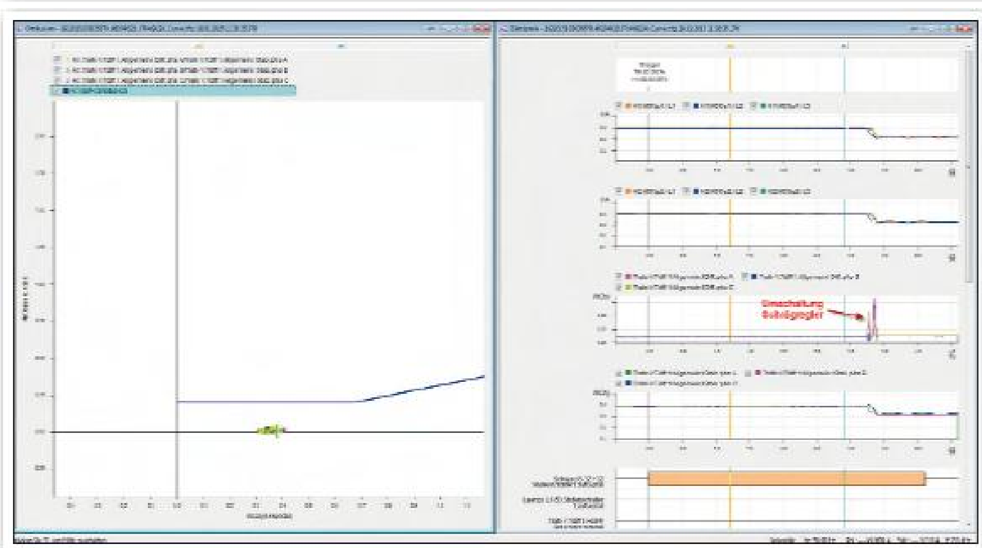

Figure 10:
Fault record
of the protection
device with
active tap changer

They differ slightly from previous designs. Usually, the default setting can be retained.
The subsequent function block is the evaluation of the stabilising characteristic ($I_{Diff} = f(I_{Stab})$). The inrush current detection (2nd harmonic and the waveform analysis [CWA procedures]) and the overexcitation stabilization through the 5th harmonic are active in parallel. Additional stabilising measures include saturation detection of the current transformers. This is to avoid inadvertent tripping on external short-circuits. In order to respond quickly to high-current internal faults, there is an additional differential current stage ($I_{Diff\text{-}fast}$). Upon fault inception, it works exclusively with sampled values and uses filtered values if the fault persists. The pickup value of this stage must be higher than the maximal inrush current (Figure 5).

Protection of a phase shifter transformer in single-core design – a practical example

The new solution was installed on several single-core PST and tested successfully. The transformer in the example has a rated output of 60 MVA. The rated voltage is 62 kV on the feeding side and 60 kV on the load side. Figure 6 shows the circuit layout and the general connection of the protection device. The transformer with in-phase regulation is located on the feeding side and the 60° phase angle regulating transformer on the load side. The large control range of ± 76.95° was interesting. The change of direction of the angle sign is implemented through advanced-retard switches. It is not shown in Figure 6.
Figure 7 and 8 show the setting tabs for tap changers. The setting for the transformer with in-phase regulation is simple, because only the basic position and the voltage change per tap change have to be set. The protection device automatically performs the current adjustment (Figure 7).
The 60° phase angle regulating transformer requires more effort to adjust the voltage and the angle for each tap position (Figure 8). In order to suppress transitory states for the binary injection of the tap changer position, a software filter time can be set at the binary input. This time has to be coordinated with the runtime of the tap changer.
The system was taken into service and its operation is stable. The high sensitivity was confirmed by primary tests. The measured differential current was almost zero under load conditions and at various tap positions. Figure 9 and 10 show a fault record for switching the phase angle regulating transformer under load. The currents at the feeding side and at the load side were depicted for phase L1. This is followed by the differential current (track 3) and the stabilising current (track 4). The differential current is very small (around 0.005 $I/I_{n,Transf.}$). The transitory state upon operating the tap changer can be recognized in the slightly changing differential current. Subsequently, there was a reduced current on the load side (track 2) which also led to a reduced stabilising current (track). The differential current remains constant at the very low value of 4.

Summary

The development and introduction of a universal transformation matrix has expanded the application scope of the differential protection considerably. In addition to the classic power transformers, phase shifter transformers and special transformers can now easily be protected, too. The selected approach enables a high sensitivity of the differential protection function and a high stability for external faults. As the protection was tailored specifically to these applications, engineering and commissioning, too, are facilitated considerably.

Literature

[1] IEC 62032 - IEC 62032 (2012-06 Ed.2) Guide for the Application, Specification and Testing of Phase-Shifting Transformers (IEEE Std. C57.135-2011)

[2] SIPROTEC 5 Transformatordifferentialschutz 7UT82, 7UT85, 7UT86, 7UT87, Handbuch C53000-G5000-C016-6, Siemens AG

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