Protection of an Autotransformer

■ 1. Introduction

Transformers are valuable equipment which make a major contribution to the supply security of the power system. Optimum design of the transformer protection ensures that any faults that may occur are found quickly, so that consequential damage is minimized. A special variant is the so-called autotransformer in which, unlike in the full transformer, the voltage and current transformation is not performed by two independent windings but uses part of the winding from both sides, allowing a much more compact design. The spectrum of autotransformers ranges from small distribution system transformers (from 1000 kVA) to large transformers of several hundred MVA. Their use becomes more interesting, the less the ratio between the high-voltage (HV) side and low-voltage (LV) side deviates from 1, i.e. the less energy is transmitted via the magnetic coupling which leads to a saving in iron material. In addition to the design notes, a complete setting example with SIPROTEC protection relays for a triple-wound autotransformer in the transmission system is described.

■ 2. Protection concept

Differential protection offers fast, selective short-circuit protection, alone or as a supplement to the Buchholz protection. In larger units from about 5 MVA it is part of the standard equipment. In addition to the main protection function which reliably clears a short-circuit within the protected object, a fully-fledged protection concept contains a number of additional functions which take care of other problems such as overload, overexcitation, etc. All the necessary functions are already contained in the SIPROTEC 4 relays. Backup protection functions are a useful addition.

Fig. 2 shows an example of a full protection concept for an autotransformer.
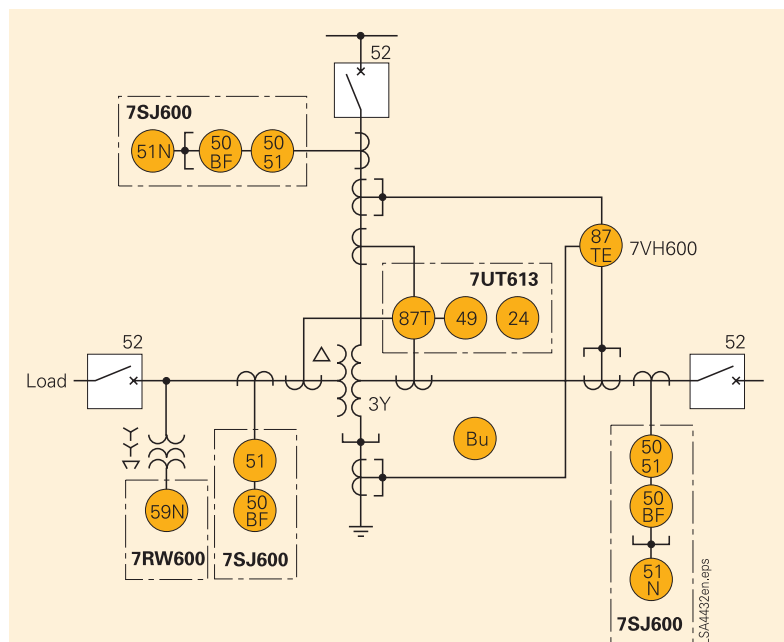

Fig. 1 SIPROTEC 7UT6 transformer protection

Fig. 2 Protection of an autotransformer

For this example a differential protection ANSI 87T (3-windings version) must be selected (7UT613), so that the delta stabilizing winding can be included in the protected zone (different alternatives for connection are explained in detail in chapter 3). If this is missing, an autotransformer can also be fully protected with the 7UT612. The integrated overload protection ANSI 49 is adapted to the load and protects the transformer from overheating and premature aging. The over-excitation protection ANSI 24 prevents impermissible heating of the iron.

To increase the earth-fault sensitivity, an additional high-impedance earth-fault differential protection ANSI 87TE is often used in English-influenced regions. The single-phase relay 7VH600 is on the parallel circuit of the outgoing side transformers and of the star-point transformer. The seven transformers (3 side 1, 3 side 2, 1 star point) must be provided additionally, however, and be designed according to class TPS (IEC 60 044-6). A pickup value of 10 % I_n is usually achieved. Additionally or alternatively, an overcurrent relay $I_e > t$ ANSI 50N can be provided in the star-point link. However, this must be in time coordination with the subordinate overcurrent relay.

The delta winding which, in addition to its stabilizing (restraint) function, is also often used for autonomous supply, gets its own overcurrent-time protection ANSI 50, 50N for external phase faults. The voltage relay 7RW600 (ANSI 59N) on the open delta winding of the voltage transformer measures the displacement voltage $3U_0$ with which an earth fault in the tertiary winding or in the connected distribution system is indicated.

An overcurrent-time protection ANSI 50, 50N is arranged on the HV and LV sides, each with a instantaneous tripping stage $I\gg$ and delayed stage $I>$ (against phase and earth-faults). Integrated overcurrent-time protection can also configured optionally in 7UT613 on one of the two sides. For every outgoing circuit the breaker failure protection ANSI 50 BF must be activated in the relevant protection relay.

The individual elements shown in an overview are described step by step as follows.
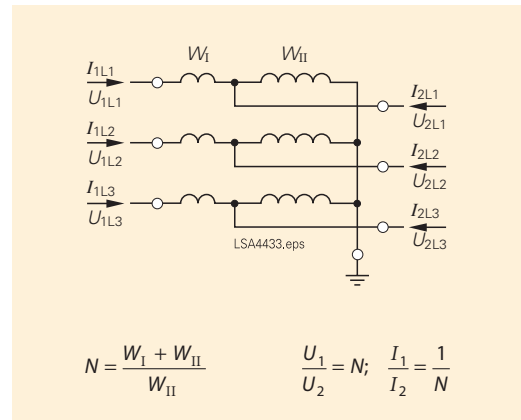
■ 3. Structure of an autotransformer

$$N = \frac{W_{\mathrm{I}} + W_{\mathrm{II}}}{W_{\mathrm{II}}} \qquad \frac{U_1}{U_2} = N; \quad \frac{I_1}{I_2} = \frac{1}{N}$$

Fig. 3 Structure and transmission ratios of a two-winding autotransformer

Autotransformers only have the vector group YNyn0; i.e. there is no phase shift of the currents and voltages between the primary and secondary sides. The common star point is always earthed. Therefore both sides are always electrically connected. The distribution of the star-point current on both sides depends on several factors, e.g. winding distribution and presence of a tertiary winding.

■ 4. Implementation with SIPROTEC

4.1 Differential protection

Transformer differential protection contains a number of additional functions (matching to transformation ratio and vector group, stabilization (restraint) against inrush currents and over-excitation) and therefore requires some fundamental consideration for configuration and selection of the setting values. The additional functions integrated per relay can be used to advantage. However, it must be considered that backup protection functions must be arranged in separate hardware (further relay) for reasons of hardware redundancy. This means that the overcurrent-time protection in the differential protection 7UT612/ 613 can only be used as backup protection against external faults in the connected power system. The backup protection for the transformer itself must be provided as a separate overcurrent relay (e.g. 7SJ602). The Buchholz protection as fast short-circuit protection is supplied with the transformer.

Designations according to ANSI (American National Standard) are used for the individual functions. The differential protection therefore has ANSI No. 87, for example. The differential protection is provided as a definite-time fast short-circuit protection in addition to the Buchholz protection.

The differential protection for an autotransformer can be implemented in 2 different ways depending on the available current transformers.

1. Differential protection over the whole transformer bank (protection to be used 7UT612 (2 windings) / 7UT613 (3 windings):
In this case, as shown in Fig. 4, three phase current transformers are used for each side. The star-point transformer is insignificant for the differential protection but can be used for backup overcurrent-time protection. It can be set on both sides depending on further use by other protection functions.

2. Current comparison per autotransformer winding
Use of phase current transformers upstream of the star-point junction (earth-current winding). Fig. 5 shows, that the supply lines to the star (neutral) point all have a phase current transformer. In this case, the autotransformer can be treated as a node object with three terminals.

Both connection types are basically different and are treated separately in chapter 5.

4.2 Earth-fault differential protection
The earth-fault differential protection cannot be used in the autotransformer.

4.3 Backup protection functions
The integrated overcurrent-time protection (ANSI 51) in the 7UT613 serves as backup protection for faults in the supplied system. Separate overcurrent protection on the LV side is therefore unnecessary. The 7JS600 relay on the HV side can be used as backup protection against short-circuits in the transformer and as additional backup protection against LV side faults. The high-set, fast tripping stage $I>>$ (ANSI 50) must be set above the short-circuit current flowing through it, so that it does not pick up in the event of faults on the LV side. The delayed tripping (ANSI 51) must be graded with the overcurrent protection in the 7UT613.

The windings S1 and S2 can be protected with the integrated overload protection.

Sides:
S1 HV side of the autotransformer winding on the main protected object
S2 LV side of the autotransformer winding (tapping) on the main protected object
S3 Side of the tertiary winding (stabilizing winding) on the main protected object
3-phase measuring locations, assigned:
M1 Measuring location for side 1 assigned to the main protected object
M2 Measuring location for side 2 assigned to the main protected object
M3 Measuring location for side 3 assigned to the main protected object
Additional measuring locations 1-phase, assigned (summation current of the transformer set):
Z3 Measuring location for side 1 and side 2 assigned to the main protected object

Fig. 4 Topology of a transformer bank consisting of 3 single-phase autotransformers with a stabilizing winding designed as a tertiary winding

Sides:
S1 HV side of the autotransformer winding on the main protected object
S2 LV side of the autotransformer winding (tapping) on the main protected object
S3 Star-point side of the autotransformer on the main protected object
3-phase measuring locations, assigned:
M1 Measuring location for side 1 assigned to the main protected object
M2 Measuring location for side 2 assigned to the main protected object
M3 Measuring location for side 3 assigned to the main protected object
Additional measuring locations 1-phase, assigned (summation current of the transformer set)
Z3 Measuring location for side 1 and side 2 assigned to the main protected object

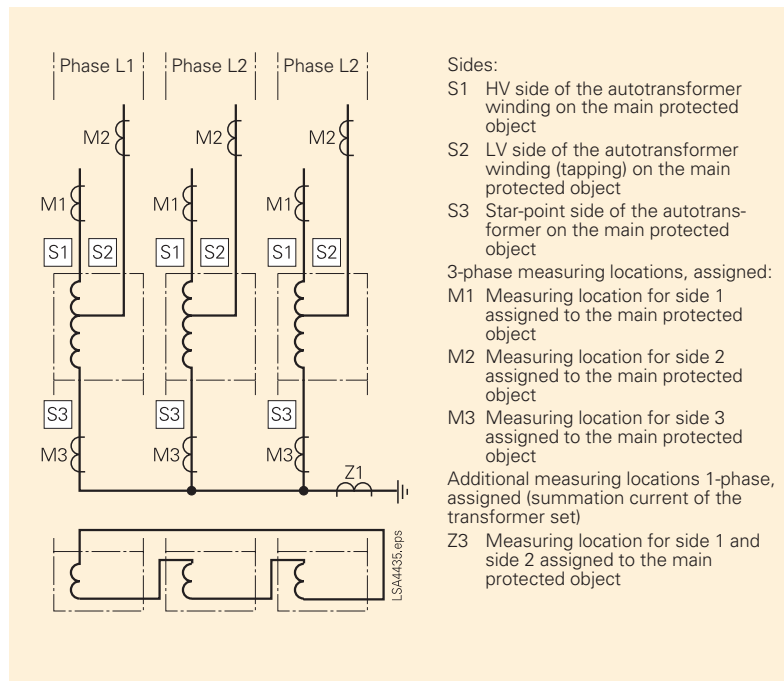**Fig. 5** Topology of a transformer bank consisting of 3 single-phase autotransformers; topology definitions for one current comparison protection per phase, i.e. there is phase-selective current measurement at M3 before the star-point junction

The delta winding – which is often only used for own, internal supply – has its own overcurrent-time protection (ANSI 51) against phase faults and because of its reduced rated power it requires a separate overload protection. Both can be realized with a 7SJ600 as shown in Fig. 2, for example.

4.4 Integration of Buchholz protection

The Buchholz protection of the transformer evaluates the gas pressure of the transformer tank and therefore detects internal faults in the transformer quickly and sensitively. The following should be considered for the integration:

- The trip command of the Buchholz protection should act on the circuit-breaker directly and independently of the differential protection
- The trip command of the Buchholz protection should be recorded in the fault event log / fault record of the differential protection

Coupling the trip command via the binary input of the differential protection provides informative data for evaluation in the event of a fault.
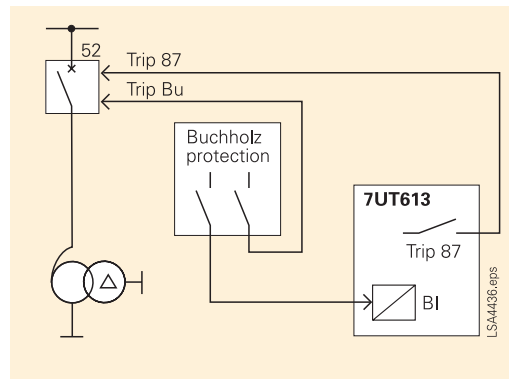
Fig. 6 Integration in the Buchholz protection

5. Settings

5.1 Setting instructions for differential protection over the whole transformer bank

The differential protection as a main protection function of the 7UT612/613 is parameterized and set in a few steps:

- Parameterize protected object "autotransformer"
- Assign the measuring locations on the main protected object

Sides:
S1 HV side of the main protected object (autotransformer)
S2 LV side of the main protected object (autotransformer)
S3 Side of the tertiary winding (stabilizing winding) of the main protected object (autotransformer)
3-phase measuring locations, assigned:
M1 Measuring location for side 1 assigned to the main protected object
M2 Measuring location for side 1 assigned to the main protected object
M3 Measuring location for side 2 assigned to the main protected object
M4 Measuring location for side 3 assigned to the main protected object

Fig. 7 Topology of an autotransformer with a stabilizing winding designed as a tertiary winding

The topology in the autotransformer is defined as follows:
Side 1 is the first of the autotransformer windings; the HV side is usually chosen here.
Side 2 is the second of the autotransformer windings; the LV side is usually chosen here.

This may be followed by further tappings. If there is a delta stabilizing winding, this should be assigned last.

The relay requires the following data of the protected object:

- The primary rated voltage U_N in kV (line-to-line)
- The secondary rated voltage U_N in kV (line-to-line)
- The rated apparent power which is the same for both sides in the autotransformer.

The "autotransformer" setting in the configuration automatically defines that no vector group shift is performed (phase angle 0° between HV and LV side) and the zero current elimination is performed on both sides.

In transformers, the currents measured on the secondary side of the current transformer when current flows through are not generally equal, but are determined by the ratio of the transformer to be protected and the rated currents of the current transformers. To make the currents comparable they therefore have to be matched first. This takes place arithmetically in the 7UT613. External matching equipment is therefore normally superfluous (frequent exception: tertiary winding with low rated apparent power). The digitized currents are converted to the respective transformer rated currents. To do this, the transformer rating data, i.e. rated apparent power, rated voltages and the primary rated currents of the current transformers, are entered in the protection relay.

Fig. 8 shows an example for magnitude matching. The primary rated currents of the two sides S1 (288.7 A) and S2 (525 A) are calculated from the rated apparent power of the transformer (200 MVA) and the rated voltages of the windings (400 kV and 220 kV). Since the current transformer rated currents deviate from these transformer rated currents, the secondary currents are multiplied by the factors k1 and k2. The third winding (S3) on the other hand is only dimensioned for 12 MVA (e.g. as an auxiliary supply winding). The rated current of this winding (= side of the protected object) is therefore 346 A. For the differential protection, however, comparable currents according to the ratio of the individual sides of the transformer must be used for the calculation. Therefore the rated power of the protected object of 200 MVA must likewise be taken as basis for the third winding. This gives a theoretical rated current (here = current under rated conditions of the protected object, i.e. at 200 MVA) of 5773.5 A. This is the reference variable for the currents of the third winding. The currents are therefore multiplied by factor k3. The relay performs this magnitude matching based on the set rated values.

The technical data of the 7UT612/613 show a permissible ratio of 0.25 < k < 4 specified for phase currents. This means that in the case of the winding 3, k3 has an impermissibly small ratio. A matching transformer must be provided here to reach the permissible range. It should be dimensioned so that the matching factor reaches just above the minimum figure of 0.25. In this case it could therefore be assumed:

n > 0.25 / (400A / 5773.5A) = 3.6, e.g. n=4.
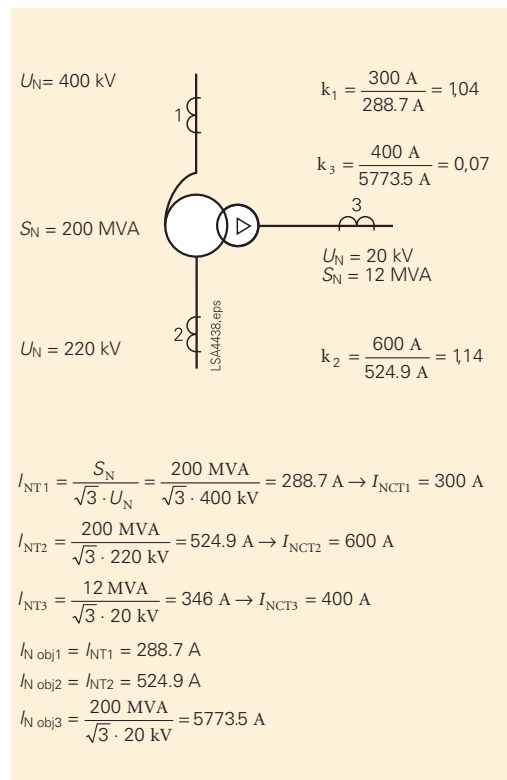
Fig. 8 Example of an autotransformer for magnitude matching

U_N= 400 kV

$k_1 = \dfrac{300\ A}{288.7\ A} = 1{,}04$

$k_3 = \dfrac{400\ A}{5773.5\ A} = 0{,}07$

S_N = 200 MVA

U_N = 20 kV
S_N = 12 MVA

U_N = 220 kV

$k_2 = \dfrac{600\ A}{524.9\ A} = 1{,}14$

$$I_{NT1} = \frac{S_N}{\sqrt{3} \cdot U_N} = \frac{200\ \text{MVA}}{\sqrt{3} \cdot 400\ \text{kV}} = 288.7\ A \rightarrow I_{NCT1} = 300\ A$$

$$I_{NT2} = \frac{200\ \text{MVA}}{\sqrt{3} \cdot 220\ \text{kV}} = 524.9\ A \rightarrow I_{NCT2} = 600\ A$$

$$I_{NT3} = \frac{12\ \text{MVA}}{\sqrt{3} \cdot 20\ \text{kV}} = 346\ A \rightarrow I_{NCT3} = 400\ A$$

$$I_{N\ obj1} = I_{NT1} = 288.7\ A$$

$$I_{N\ obj2} = I_{NT2} = 524.9\ A$$

$$I_{N\ obj3} = \frac{200\ \text{MVA}}{\sqrt{3} \cdot 20\ \text{kV}} = 5773.5\ A$$

Together with the autotransformer information the protection relay is now able to perform a current comparison. The principle is explained in the following example (see Figs. 9 and 10):
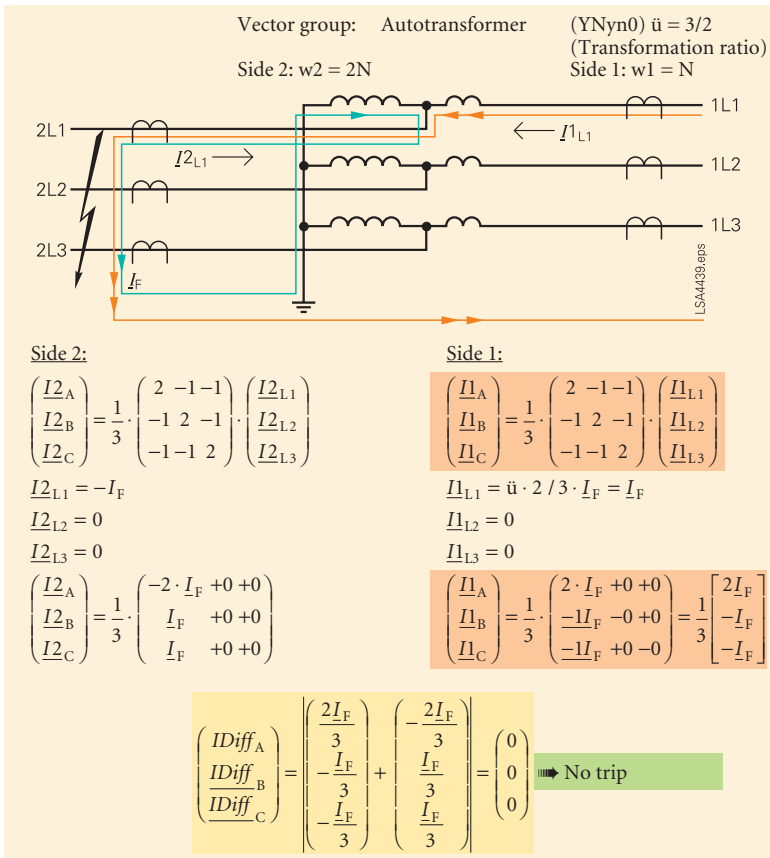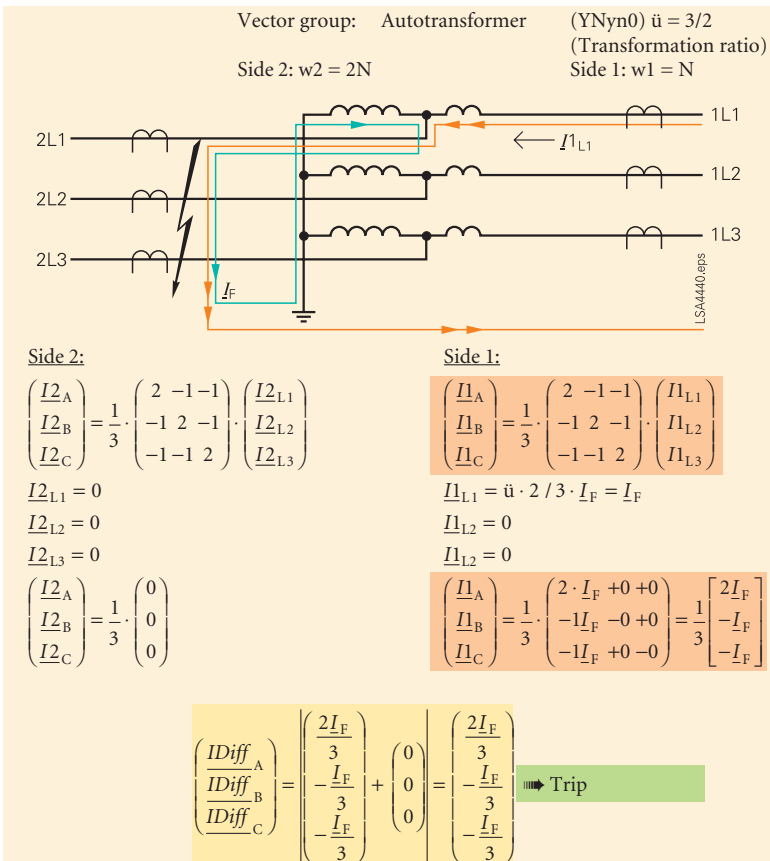
Both sides are converted to a "virtual" side, based on which the current comparison is made. In case of vector group 0 (as is always the case with the autotransformer) this is done by a standard matrix. The matrices used are given by the standard matrix by subtracting the zero current from the measurement (corresponds to 1/3 of the sum of all three phase currents). This is necessary, because it is not possible to divide the star-point current on both sides of the protected object.

5.2 Setting instructions for differential protection in current comparison per autotransformer winding

If current transformers are available for each phase on the supply lines to the star point (earth winding), one node protection per phase can be implemented. Current transformation ratios and their tap changes have no effect, because the three entry points of the current are measured here and form the end points of the Kirchoff node. Such a current comparison is more sensitive for earth-faults than normal differential protection (see Fig. 11). This is of interest, because these faults have the highest probability in transformer banks. Any stabilizing winding or tertiary winding must not be integrated in the protection in this application, even if it is connected externally and equipped with current transformers, because this does not belong to the protected (phase-selective) node.

Vector group: Autotransformer (YNyn0) ü = 3/2 (Transformation ratio)
Side 2: w2 = 2N · Side 1: w1 = N

Side 2:

$$\begin{pmatrix} \underline{I2}_A \\ \underline{I2}_B \\ \underline{I2}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \begin{pmatrix} \underline{I2}_{L1} \\ \underline{I2}_{L2} \\ \underline{I2}_{L3} \end{pmatrix}$$

$\underline{I2}_{L1} = -I_F$
$\underline{I2}_{L2} = 0$
$\underline{I2}_{L3} = 0$

$$\begin{pmatrix} \underline{I2}_A \\ \underline{I2}_B \\ \underline{I2}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} -2 \cdot I_F & +0 & +0 \\ I_F & +0 & +0 \\ I_F & +0 & +0 \end{pmatrix}$$

Side 1:

$$\begin{pmatrix} \underline{I1}_A \\ \underline{I1}_B \\ \underline{I1}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \cdot \begin{pmatrix} \underline{I1}_{L1} \\ \underline{I1}_{L2} \\ \underline{I1}_{L3} \end{pmatrix}$$

$\underline{I1}_{L1} = ü \cdot 2/3 \cdot \underline{I}_F = \underline{I}_F$
$\underline{I1}_{L2} = 0$
$\underline{I1}_{L3} = 0$

$$\begin{pmatrix} \underline{I1}_A \\ \underline{I1}_B \\ \underline{I1}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 2 \cdot \underline{I}_F & +0 & +0 \\ -1\underline{I}_F & -0 & +0 \\ -1\underline{I}_F & +0 & -0 \end{pmatrix} = \frac{1}{3} \begin{bmatrix} 2\underline{I}_F \\ -\underline{I}_F \\ -\underline{I}_F \end{bmatrix}$$

$$\begin{pmatrix} IDiff_A \\ IDiff_B \\ IDiff_C \end{pmatrix} = \begin{vmatrix} \frac{2\underline{I}_F}{3} \\ -\frac{\underline{I}_F}{3} \\ -\frac{\underline{I}_F}{3} \end{vmatrix} + \begin{pmatrix} -\frac{2\underline{I}_F}{3} \\ \frac{\underline{I}_F}{3} \\ \frac{\underline{I}_F}{3} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} \quad \text{⟼ No trip}$$

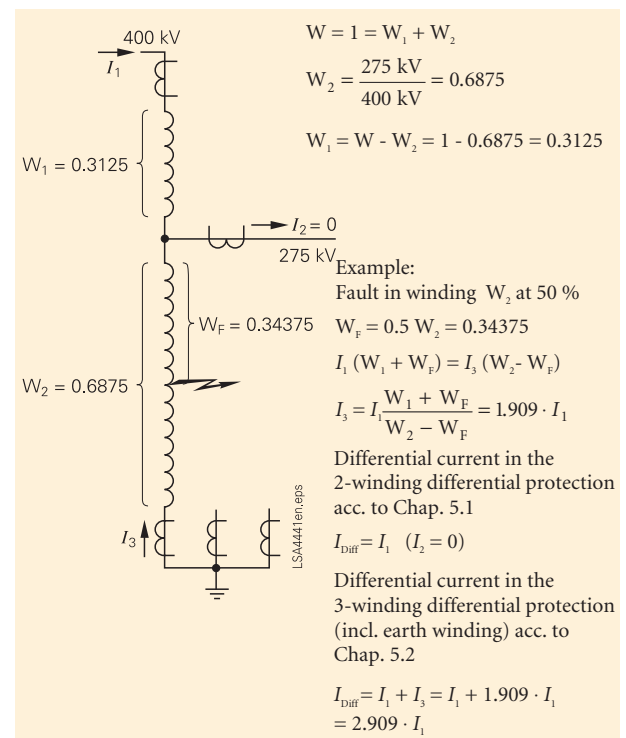**Fig. 9** Calculation of the differential current in the autotransformer for an external fault

Vector group: Autotransformer (YNyn0) ü = 3/2 (Transformation ratio)
Side 2: w2 = 2N · Side 1: w1 = N

Side 2:

$$\begin{pmatrix} \underline{I2}_A \\ \underline{I2}_B \\ \underline{I2}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \cdot \begin{pmatrix} \underline{I2}_{L1} \\ \underline{I2}_{L2} \\ \underline{I2}_{L3} \end{pmatrix}$$

$\underline{I2}_{L1} = 0$
$\underline{I2}_{L2} = 0$
$\underline{I2}_{L3} = 0$

$$\begin{pmatrix} \underline{I2}_A \\ \underline{I2}_B \\ \underline{I2}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

Side 1:

$$\begin{pmatrix} \underline{I1}_A \\ \underline{I1}_B \\ \underline{I1}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \cdot \begin{pmatrix} I1_{L1} \\ I1_{L2} \\ I1_{L3} \end{pmatrix}$$

$\underline{I1}_{L1} = ü \cdot 2/3 \cdot \underline{I}_F = \underline{I}_F$
$\underline{I1}_{L2} = 0$
$\underline{I1}_{L2} = 0$

$$\begin{pmatrix} \underline{I1}_A \\ \underline{I1}_B \\ \underline{I1}_C \end{pmatrix} = \frac{1}{3} \cdot \begin{pmatrix} 2 \cdot \underline{I}_F & +0 & +0 \\ -1\underline{I}_F & -0 & +0 \\ -1\underline{I}_F & +0 & -0 \end{pmatrix} = \frac{1}{3} \begin{bmatrix} 2\underline{I}_F \\ -\underline{I}_F \\ -\underline{I}_F \end{bmatrix}$$

$$\begin{pmatrix} \underline{IDiff}_A \\ \underline{IDiff}_B \\ \underline{IDiff}_C \end{pmatrix} = \begin{vmatrix} \frac{2\underline{I}_F}{3} \\ -\frac{\underline{I}_F}{3} \\ -\frac{\underline{I}_F}{3} \end{vmatrix} + \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix} = \begin{vmatrix} \frac{2\underline{I}_F}{3} \\ -\frac{\underline{I}_F}{3} \\ -\frac{\underline{I}_F}{3} \end{vmatrix} \quad \text{⟼ Trip}$$

Fig. 10 Calculation of the differential current in the event of an internal fault

W = 1 = W₁ + W₂
$W_2 = \dfrac{275 \text{ kV}}{400 \text{ kV}} = 0.6875$
$W_1 = W - W_2 = 1 - 0.6875 = 0.3125$

400 kV
I_1
$W_1 = 0.3125$
$I_2 = 0$
275 kV
$W_F = 0.34375$
$W_2 = 0.6875$
I_3

Example:
Fault in winding W₂ at 50 %
$W_F = 0.5 \, W_2 = 0.34375$
$I_1 (W_1 + W_F) = I_3 (W_2 - W_F)$
$I_3 = I_1 \dfrac{W_1 + W_F}{W_2 - W_F} = 1.909 \cdot I_1$

Differential current in the 2-winding differential protection acc. to Chap. 5.1
$I_{Diff} = I_1 \quad (I_2 = 0)$

Differential current in the 3-winding differential protection (incl. earth winding) acc. to Chap. 5.2
$I_{Diff} = I_1 + I_3 = I_1 + 1.909 \cdot I_1 = 2.909 \cdot I_1$

Fig. 11 Increasing the sensitivity by using phase-selective earth windings

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The topology is determined as follows:
The two autotransformer windings become S1 and S2 (tapping).
The earth winding must in this case be set as side 3. If there is a further tapping, the earth winding is specified as side 4. As soon as one of the sides is defined as earth winding, the protection automatically places node differential protection across all autotransformer windings involved.

The differential protection function must be activated by parameterization. The differential protection relay 7UT613 is delivered in inactive-circuit state. This is because the protection may not be operated without at least having set the vector groups and matching values correctly first. The relay may react unpredictably without these settings.

Setting of the characteristic of the differential protection is based on the following considerations:

- The presetting for $I_{Diff} >$ of 0.2 x I_N referred to the rated current of the transformer can be taken as a pickup value for the differential current as a rule.
- The slope 1 together with base point 1 take into account current-proportional false currents which may be caused by transformation errors of the CTs. The slope of this section of the characteristic is set to 25 %.
- The add-on restraint increases the stability of the differential protection in the very high short-circuit current range in the event of external faults; it is based on the setting value EXF-$_{Restraint}$ (address 1261) and has the slope 1 (address 1241).
- The slope 2 together with base point 2 lead to higher stabilization in the higher current range at which current transformer saturation can occur. The slope of this characteristic section is set to 50 %.
- The $I_{Diff} >>$ stage works without restraint (stabilization) and is designed for high internal fault currents on the primary side of the transformer with a high degree of saturation. It should be set to at least 20 % above the max. through flowing fault current or the max. inrush currents, respectively.

Notes on add-on restraint

In systems with very high traversing currents, a dynamic add-on restraint becomes effective for external faults. Presetting 4.0 can, as a rule, be taken over without change. The value is referred to the rated current of the protected object.
Note that the restraint current is the arithmetic sum of the currents flowing into the protected object, i.e. is double the traversing current. The
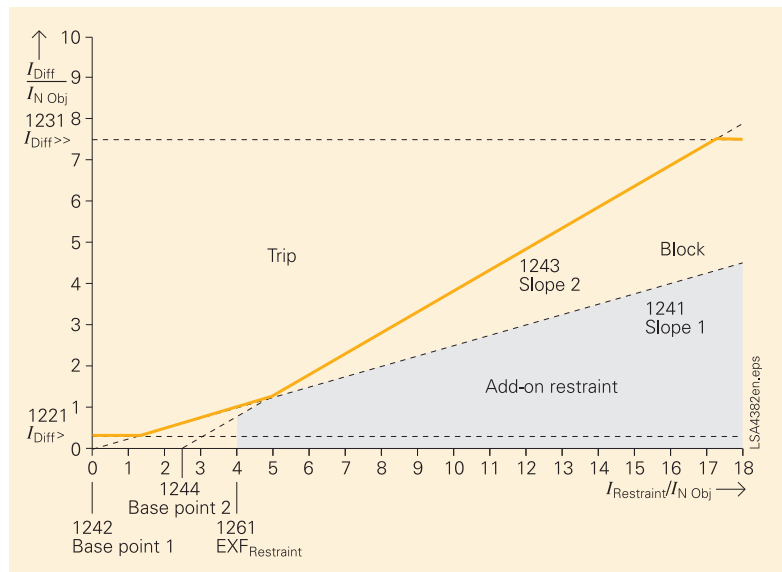

Fig. 12 Differential protection tripping characteristics

add-on restraint does not affect the $I >>$ stage. The maximum duration of add-on restraint after detecting an external fault is set in multiples of a period (AC cycle). The recommended setting value is 15 periods (preset). The add-on restraint is automatically disabled before the set time period expires as soon as the relay has detected that the operation point $I_{Diff}/I_{Restraint}$ is located steadily (i.e. for at least one period) within the tripping zone near to the fault characteristic. The add-on restraint operates separately for each phase but can be extended to blocking all phases depending on the used vector group (crossblock function). The recommended setting value for the crossblock function is 15 periods (preset).

Notes on setting the inrush blocking

An inrush current with a high proportion of 2nd harmonics is generated when switching the transformer on, which can lead to false tripping of the differential protection. The preset value for the inrush restraint with 2nd harmonics of 15 % can be accepted unchanged. A lower value can be set for greater restraint in exceptional cases under unfavorable energizing conditions resulting from the design of the transformer.

The inrush restraint can be extended by the crossblock function. This means, that all three phases of the $I_{Diff} >$ stage are blocked when the harmonic component is exceeded in only one phase. A setting value of 3 periods, effective for the time of mutual blocking after exceeding the differential current threshold, is recommended (preset).

Notes on setting the overexcitation blocking

Stationary overexcitation in transformers is characterized by odd harmonics. The third or fifth harmonic is suitable for restraint. Since the third harmonic is often eliminated in transformers (e.g. in a delta winding), the 5th harmonic is mostly used. The proportion of 5th harmonics which leads to blocking of the differential protection is set at 30 % (preset). It is not usually necessary to set the crossblock function in this case.

5.3 Backup protection functions

5.3.1 Overcurrent time protection

The definite-time overcurrent-time protection of the 7UT612/613 serves as backup for the short-circuit protection of the downstream power system sections when faults cannot be cleared in time there, meaning that the protected object is in danger.

The overcurrent-time protection can be assigned to one of the three voltage sides of the transformer. Correct allocation between the measuring inputs of the relay and the measuring locations (current transformer sets) of the power plant must also be observed. The stage $I>>$ together with stage $I>$ or stage I_P produces a two-stage characteristic. If the overcurrent-time protection acts on the feed side of the transformer, stage $I>>$ is set so that it picks up for short-circuits extending into the protected object, but not for a short-circuit current flowing through it.

Calculation example:

Autotransformer YNyn0
50 MVA
66 kV/33 kV
u_{SC} = 12 %
Current transformer 500 A/1 A on the 66 kV side
The overcurrent-time protection acts on the 66 kV side (= feed side).
The maximum possible three-phase short-circuit current on the 33 kV side with rigid voltage on the 66 kV side would be:

$$I_{3\,\text{pole max}} = \frac{1}{u_{SC\,\text{Transfo}}} \cdot I_{N\,\text{Transfo}} = \frac{1}{u_{SC\,\text{Transfo}}} \cdot \frac{S_{N\,\text{Transfo}}}{\sqrt{3}U_N}$$

$$= \frac{1}{0.12} \cdot \frac{35\,\text{MVA}}{\sqrt{3} \cdot 66\,\text{kV}} = 3645\,\text{A}$$

With a safety factor of 20 % this gives the primary setting:

$I>>$ = 1.2 x 3645 A = 4374 A

With parameterization in secondary values the currents in amperes are converted to the secondary side of the current transformers.

Secondary setting value:

$$I>> = \frac{4375\,\text{A}}{500\,\text{A}} \cdot A = 8.75\,\text{A}$$

i.e. at short-circuit currents above 4374 A (primary) or 8.8 A (secondary), there is definitely a fault in the transformer area, which can be eliminated immediately by the overcurrent time protection. Increased inrush currents must be considered as well. The inrush restraint does not affect the stage $I>>$.

Stage $I>$ represents the backup protection for the downstream busbar. It is set higher than the sum of the rated outgoing currents. Pickup by overload must be ruled out because the relay operates with correspondingly short command times as short-circuit protection in this mode and not as overload protection. This value must be converted to the higher-voltage side of the transformer. The delay time depends on the grading time in the outgoing lines. It should be set e.g. 200 ms more than the greatest grading time on the LV side. Moreover, the inrush restraint for the $I>$ stage must be parameterized effectively in this case, so that false pickup of the $I>$ stage (resulting from the inrush of the transformer) is prevented.

5.3.2 Overload protection

The thermal overload protection prevents overloading of the transformer to be protected. Two methods of overload detection are possible in the 7UT6:

- Overload protection with thermal replica according to IEC 60255-8,
- Hot-spot calculation with determining of the relative ageing rate according to IEC 60354

One of these two methods can be selected. The first is notable for easy handling and a low number of setting values; the second requires some knowledge of the protected object, its ambient context and its cooling, and needs the input of the coolant temperature via a connected thermobox. The second method is used when the transformer is operated at the limit of its performance and the relative ageing rate is to be monitored by the hot-spot calculation.

Overload protection with thermal replica (to act on the HV side) is chosen for this application. Since the cause of the overload is normally outside the protected object, the overload current is a traversing current. The relay calculates the temperature rise according to a thermal single-body model by means of the thermal differential equation

$$\frac{d\Theta}{dt} + \frac{1}{\tau_{th}} \cdot \Theta = \frac{1}{\tau_{th}} \cdot \left(\frac{I}{k \cdot I_{N \, Obj}} \right)^2$$

The protection function therefore represents a thermal replica of the object to be protected (overload protection with memory function). Both the history of an overload and the heat transmitted to the ambient area are taken into account. Pickup of the overload protection is output as a message.

Notes on the setting

In transformers, the rated current of the winding to be protected, which the relay calculates from the set rated apparent power and the rated voltage, is significant. The rated current of the side of the main protected object assigned to the overload protection is used as the basic current for detecting the overload. The setting factor k is determined by the ratio of the thermally permissible continuous current to this rated current:

$$k = \frac{I_{max}}{I_{N \, Obj}}$$

The permissible continuous current is at the same time the current at which the e-function of the overtemperature has its asymptote. The presetting of 1.15 can be accepted for the HV winding.

Time constant τ in thermal replica:

The heating time constant τ_{th} for the thermal replica must be specified by the transformer manufacturer. It must be ensured that the time constant is set in minutes. There are often other specifications from which the time constant can be determined:

Example:
t_6 time: This is the time in seconds for which 6 times the rated current of the transformer winding may flow.

$$\frac{\tau_{th}}{min} = 0.6 \cdot t_6$$

If the transformer winding has a t6 time of 12 s

$$\frac{\tau_{th}}{min} = 0.6 \cdot 12 \, s = 7.2$$

the time constant τ must be set to 7.2 min.

5.3.3 Overexcitation protection

The overexcitation protection serves to detect increased induction in generators and transformers, especially in power station unit transformers. An increase in the induction above the rated value quickly leads to saturation of the iron core and high eddy current losses which in turn lead to impermissible heating up of the iron.

Use of the overexcitation protection assumes that measuring voltages are connected to the relay. The overexcitation protection measures the voltage/frequency quotient U/f, which is proportional to the induction B at given dimensions of the iron core. If the quotient U/f is set in relation to voltage and frequency under rated conditions of the protected object $U_{N \, Obj}/f_N$, a direct measure is obtained of the induction related to the induction under rated conditions $B/B_{N \, OBj}$. All constant variables cancel each other:

$$\frac{B}{B_{N \, Obj}} = \frac{\dfrac{U}{U_{N \, Obj}}}{\dfrac{f}{f_N}} = \frac{U / f}{U_{N \, Obj} / f_N}$$

The relative relation makes all conversions unnecessary. All values can be specified directly related to the permissible induction. The rated variables of the protected object have already been entered in the 7UT613 relay with the object and transformer data when setting the differential protection.

Setting instructions

The limit value of permanently permissible induction in relation to the rated induction (B/B_N) specified by the protected object manufacturer forms the basis for setting the limit value. This value is at the same time a warning stage and the minimum value for the thermal characteristic (see Fig. 13)

Fig. 13
Tripping characteristic of the overexcitation protection

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An alarm is output after of the relevant set delay time (about 10 s) of the overexcitation stage *U/f* has expired. Major overexcitation endangers the protected object already after a short time. The high-set, fast tripping stage *U/f>>* is therefore set to a maximum of 1 s.

The thermal characteristic should simulate the heating, i.e. temperature rise, of the iron core resulting from overexcitation. The heating characteristic is approximated by entering 8 delay times for 8 given induction values B/B_{NObj} (referred to in simplified form as *U/f*). Intermediate values are obtained by linear interpolation. If no data are available from the protected object manufacturer, the preset standard characteristic is used.

■ 6. Further functions

6.1 Integration in substation control and protection

The protection can be connected to a substation control system via the system interface and operated in parallel by PC via the service interface to a star coupler for separate remote communication.

Fig. 14   Integration in substation control and protection

Via the interface,

- Messages
- Alarms
- Measured values

are transmitted from the transformer differential protection to the substation control system. Messages are available for every one of the activated protection functions, which can be either transmitted to the substation control system in the course of plant equipment parameterization, or configured to the LEDs or message contacts in the protection relay. Configuration is made clear and easy by the DIGSI matrix.

Service interface

The 7UT613 has a separate service interface which can be read out by telecommunication via a modem. The user is informed in the office quickly and in detail about the transformer fault. The data are then analyzed in the office by DIGSI. If this remote fault clearance is insufficient, the fault data provide hints for an efficient service mission.

■ 7. Summary

Optimum protection of the transformer with SIPROTEC relays means security of investment for valuable operating equipment and therefore makes a contribution to maximum supply security.

From a technical point of view, the 7UT612 or 7UT613 relay offers extensive short-circuit protection for both the main and the backup protection of transformers in one single relay. Further SIPROTEC relays supplement the main protection and enhance the reliability of the protection scheme by way of hardware redundancy.

Extensive measuring functions allow trouble-free connection of the relay without the need for additional equipment, and enable monitoring of the transformer in operation in terms of its electrical and thermal parameters. The relay's presettings are chosen so that the user need only parameterize the known data of the main and primary transformers. Many of the default settings can simply be accepted as they are, and therefore make parameterization and setting easier.