Protection of a Three-Winding Transformer

Three-winding transformer

110 kV/25 kV/10 kV
Yyn0d5
25 kV-side: Solidly earthed

Protection functions

ANSI 87 T - *Differential protection*
ANSI 87 N - *Earth-fault differential protection*
ANSI 50/51 - *Definite-time overcurrent-time*
                   protection as backup
ANSI 49   - *Thermal overload protection*
ANSI 46   - *Load unbalance protection*
                   (negative-sequence protection)
ANSI 24   - *Overexcitation protection*

■ 1. Introduction

Transformers are valuable equipment which make a major contribution to the supply security of a power system. Optimum design of the transformer protection ensures that any faults that may occur are cleared quickly and possible consequential damage is minimized.

In addition to design notes, a complete setting example with SIPROTEC protection relays for a three-winding transformer in the transmission system is described.

■ 2. Protection concept

The range of high-voltage transformers comprises small distribution system transformers (from 100 kVA) up to large transformers of several hundred MVA. Differential protection offers fast, selective short-circuit protection, alone or as a supplement to Buchholz protection. It is part of the standard equipment in larger units from about 5 MVA.

2.1 Differential protection

Transformer differential protection contains a number of additional functions (matching to transformation ratio and vector group, restraint against inrush currents and overexcitation). Therefore it requires some fundamental consideration for configuration and selection of the setting values.

The additional functions integrated per relay are advantageous. However, backup protection functions have to be arranged in separate hardware (other relay) for redundancy reasons. Therefore the overcurrent-time protection contained in the

Fig. 1 SIPROTEC Transformer protection relay

differential protection relay 7UT613 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 delivered with the transformer.

Designations in accordance with ANSI (American National Standard) are used for the individual functions. The differential protection therefore has the ANSI No. 87 for example.

The 7UT613 differential protection relay is provided as independent, fast-acting short-circuit protection in addition to the Buchholz protection.
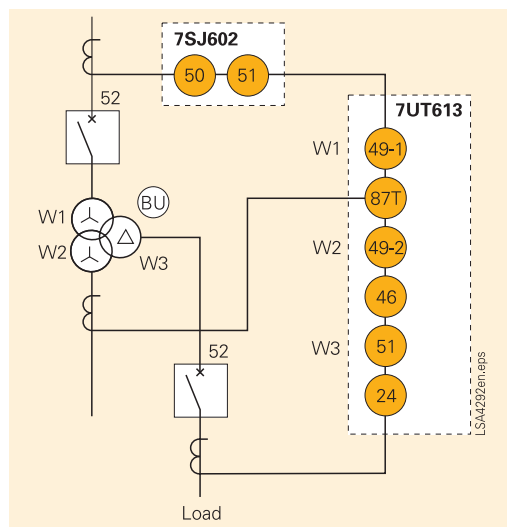

Fig. 2 Protection of a three-winding transformer

2.2 Earth-fault differential protection

Earth-fault differential protection detects earth-faults in transformers in which the star (neutral) point has low resistance or is solidly earthed. It enables fast, selective disconnection in the event of an earth fault in the winding. The protection is based on a comparison of the star-point current I_{SP} with the phase currents of the main winding.
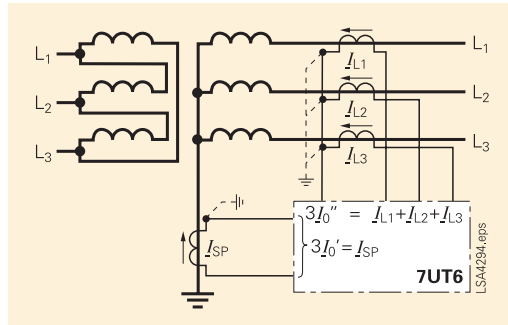

Fig. 3 Connection of an earth-fault differential protection relay

The pickup sensitivity should be ≤ 10 % of the current in the event of terminal earth fault (90 % protected zone). The single-phase auxiliary measuring input with connection I_{Z1} of 7UT613 should be used for this and assigned to the corresponding main winding by setting. The earth current of this input is then compared with the phase currents of the main winding.

2.3 Backup protection functions

The integrated overcurrent-time protection (ANSI 51) in 7UT613 serves as backup protection for faults in the system to which power is supplied. Separate overcurrent protection on the low-voltage (LV) side is therefore unnecessary. The 7SJ602 relay can be used as backup protection against short-circuits in the transformer and as additional backup protection against faults on the LV side. The high-set, fast tripping stage $I{>}{>}$ (ANSI 50) must be set above the through-fault current, so that it does not pick up in case of faults on the low-voltage (LV) side.

The delayed trip (ANSI 51) must be of higher priority than the overcurrent protection in 7UT613.

Owing to the different ratings, windings S2 and S3 are assigned a separate overload protection (integrated in 7UT613). The delta winding (often only used for own internal supply) has its own overcurrent-time protection (ANSI 51, integrated in 7UT613) against phase faults.
At low ratings of the tertiary winding and accordingly adapted transformer ratio, it should be checked whether an external matching transformer may be required.

2.4 Integration of Buchholz protection

The Buchholz protection of the transformer evaluates the gas pressure of the transformer tank and therefore detects internal transformer faults quickly and sensitively. The following considerations are necessary for 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 log/fault record of the differential protection

Coupling the trip command via a binary input of the differential protection provides informative data for evaluation in the case of a fault.
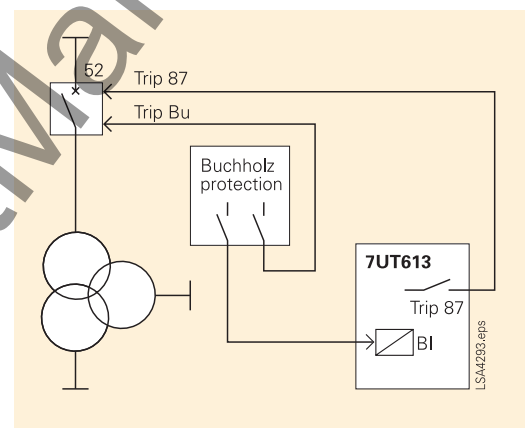

Fig. 4 Scheme for Buchholz protection

■ 3. Settings

3.1 Setting instructions for differential protection

The differential protection as a main function of the 7UT613 is parameterized and set in a few steps:

- Parameterize "three-phase transformer" protected object
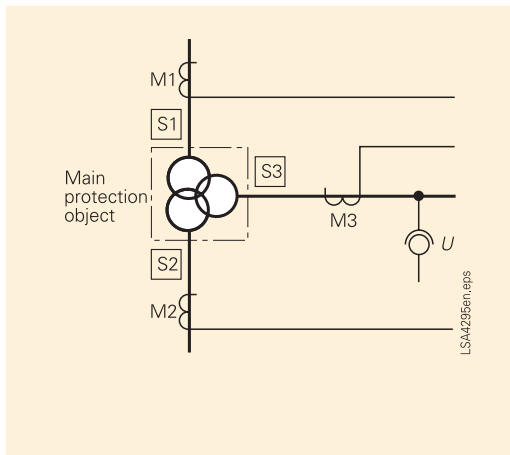- Assign the measuring locations on the main protected object

Example:

Fig. 5 Assigning of measurement locations

Sides:

Sides:
S1 HV side of the main protected object (transformer)
S2 LV side of the main protected object (transformer)
S3 Side of the tertiary winding of the main protected object (transformer)

Measuring locations assigned 3-phase:
M1 Measuring location assigned to the main protected object for side 1
M2 Measuring location assigned to the main protected object for side 2
M3 Measuring location assigned to the main protected object for side 3

When defining the sides, the assignments made regarding the measuring locations (Fig. 5) at the main protected object must be observed. Side 1 is always the reference winding and therefore has current phase position 0° and no vector group code. This is usually the HV winding of the transformer. The object data refer to specifications for every side of the protected object as fixed in the assignment definition.

The relay requires the following data for the primary winding (side S1):

- The primary rated voltage U_N in kV (line-to-line)
- The rated apparent power
- The conditioning of the star point
- The transformer vector group

Generally, the currents measured on the secondary side of the current transformers with a current flowing through them are not equal. They are determined by the transformation ratio and the vector group of the transformer to be protected, and by the rated currents of the current transformers. The currents therefore have to be matched first to make them comparable.

This matching takes place arithmetically in the 7UT613. External matching equipment is therefore normally not necessary. The digitized currents are converted to the respective transformer rated currents. To do this, the transformer's rating data, i.e. rated apparent power, rated voltage and the primary rated currents of the current transformers, are entered in the protection relay.
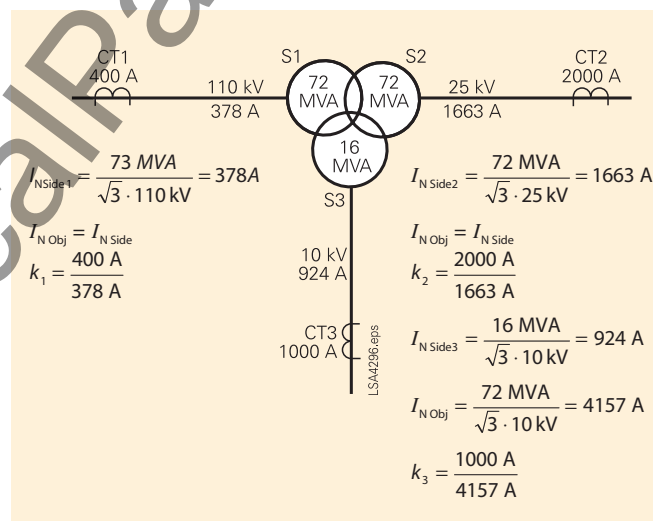
Fig. 6 Magnitude matching

Fig. 6 shows an example of magnitude matching. The primary rated currents of the two sides (windings) S1 (378 A) and S2 (1663 A) are calculated from the rated apparent power of the transformer (72 MVA) and the rated voltages of the windings (110 kV and 25 kV). Since the current transformer's rated currents deviate from rated currents of these sides, the secondary currents are multiplied by the factors k1 and k2.

The third winding (S3) on the other hand is only dimensioned for 16 MVA (e.g. as auxiliary supply winding). The rated current of this winding (= side of the protected object) is therefore 924 A. For the differential protection, however, comparable currents must be used for the calculation. Therefore, the protected object rated power of 72 MVA must also be used as a basis for the third winding. This results in a rated current (here: current under rated conditions of the protected object, i.e. at 72 MVA) of 4157 A. This is the reference variable for the currents of the third winding.

The currents are therefore multiplied by factor k3. The relay does perform this matching on the basis of the set rated values. Together with the vector group which also has to be entered, it is able to perform the current comparison according to fixed arithmetic rules. This is explained by the following example for the vector group Y(N)d5 (with earthed star-point):
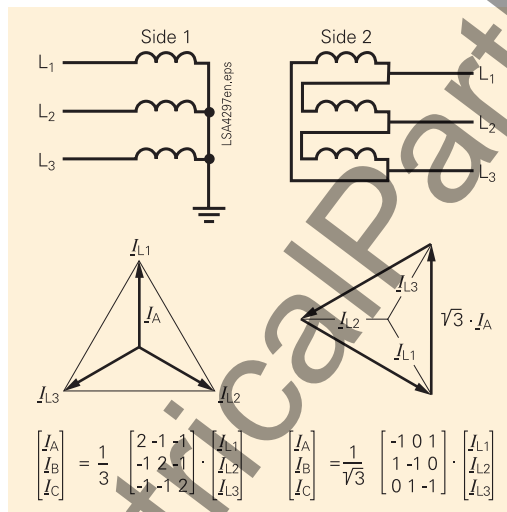

$$\begin{bmatrix} \underline{I}_{A} \\ \underline{I}_{B} \\ \underline{I}_{C} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_{L1} \\ \underline{I}_{L2} \\ \underline{I}_{L3} \end{bmatrix} \qquad \begin{bmatrix} \underline{I}_{A} \\ \underline{I}_{B} \\ \underline{I}_{C} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} -1 & 0 & 1 \\ 1 & -1 & 0 \\ 0 & 1 & -1 \end{bmatrix} \cdot \begin{bmatrix} \underline{I}_{L1} \\ \underline{I}_{L2} \\ \underline{I}_{L3} \end{bmatrix}$$

Fig. 7 Phasor diagram for vector group matching

Fig. 7 shows the windings and below them the phasor diagrams of symmetrical currents. The matrix equation in a general form is:

$$(\underline{I}_m) = k \cdot (k) \cdot (\underline{I}_n)$$

The phase currents on the left-hand (star-point) side are equal to the winding currents (The magnitude matching of the absolute value is not taken into account in the figure).

Since there is no point earthed within the protected zone, no considerable zero-sequence current (residual current) can be produced within the protected zone in case of an earth fault outside the protected zone. This is also valid if the system star-point is earthed anywhere else in the system. In case of an earth fault within the protected zone, a zero-sequence current may occur at a measuring location if the system star-point is earthed anywhere else or another earth fault is present in the

system (double earth fault in a non-earthed system). Thus, zero-sequence currents are of no concern for the stability of the differential protection as they cannot occur in case of external faults. In the case of internal faults, on the other hand, the zero-sequence currents (because they come from the outside) are absorbed almost totally by the sensitivity. A very high sensitivity in the event of earth faults in the protected zone can be achieved with overcurrent-time protection for zero-sequence current and/or the single-phase overcurrent-time protection, which can also be used as high impedance differential protection. 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 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 error currents which may be caused by transformation errors of the CTs. The slope (gradient) 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 section of the characteristic is set to 50 %.
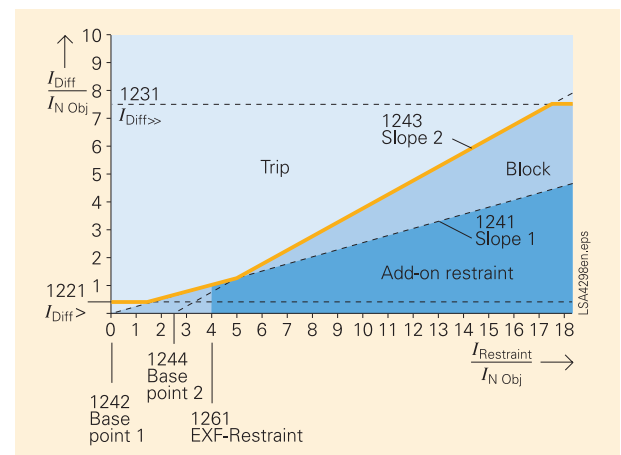

Fig. 8 Tripping characteristics of the differential protection

3.1.1 Notes on add-on restraint

In systems with very high through-flowing currents, a dynamic add-on restraint (stabilization) becomes effective for external faults. Note, that the restraint current is the arithmetic sum of the currents flowing into the protected object, i.e. is twice the through-flowing current. The 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 disabled automatically – even before the set time period expires – as soon as the relay has detected that the operation point $I_{\text{Diff}}/I_{\text{Rest}}$ is located steadily (i.e. for at least one period) within the tripping zone. The add-on restraint operates separately for each phase. Hence, blocking can be extended to all three phases thanks to the available vector-group (so called "crossblock" function). The recommended setting value for the crossblock function is 15 periods (preset).

3.1.2 Notes on setting the inrush blocking

An inrush current with a high proportion of 2nd harmonics is generated when switching on the transformer, which can lead to false tripping of the differential protection. The default for the harmonic restraint with 2nd harmonics of 15 % can be retained without change. A lower value can be set for greater stabilization 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 $I_{\text{Diff}}\!>$ 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 (default).

3.1.3 Notes on setting the overexcitation blocking

Stationary overexcitation in transformers is characterized by odd harmonics. The third or fifth harmonic is suitable for stabilization. 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 % (default). It is usually not necessary to set the crossblock function in this case.

3.2 Earth-fault differential protection

The earth-fault differential protection detects – selectively and with high sensitivity – earth faults in transformers with earthed star-point. The prerequisite is that a current transformer is installed in the star-point connection, i.e. between the star point and the earthing electrode. This star-point transformer and the phase current transformer define the limits of the protected zone.

No current I_{St} flows in the star-point connection in normal operation. The sum of the phase currents

$3I_0 = I_{\text{L1}} + I_{\text{L2}} + I_{\text{L3}}$ is almost zero.

In the event of an earth fault in the protected zone (Fig. 9) a star-point current I_{St} will flow; depending on the earthing conditions of the system, an earth current can also feed the fault position via the phase current transformer (dotted arrow), which, however, is more or less in phase with the star-point current. The currents flowing into the protected object are defined positive.
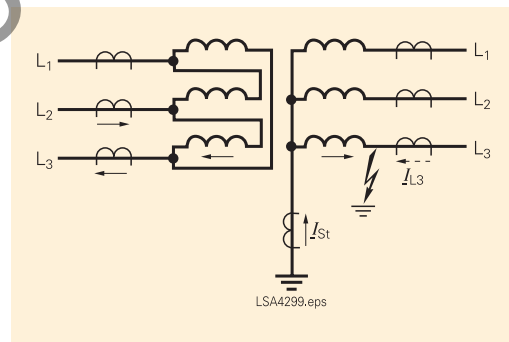

Fig. 9 Currents in case of an earth fault inside the transformer

In the event of an external earth fault a zero-sequence current also flows through the phase current transformers. This current has the same magnitude as the star-point current on the primary side and is phase-opposed to it. Therefore, both the magnitude of the currents and their relative phase positions are evaluated for stabilization. This produces the following tripping characteristic for the earth differential protection:
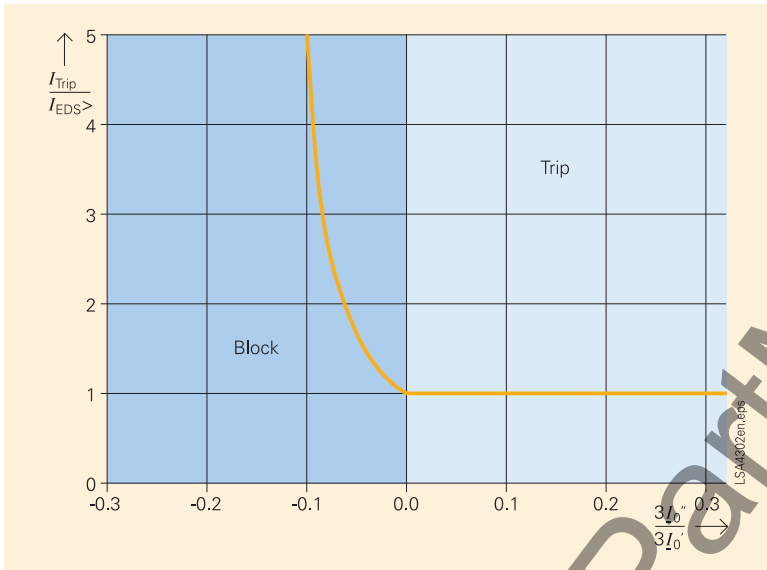

Fig. 10 Tripping characteristic for earth differential protection

In the above examples it was assumed that $3I_0''$ and $3I_0'$ are phase-opposed in the event of an external earth fault, which is correct as far as the primary variables are concerned. However, current transformer saturation can simulate a phase shift between the star-point current and the sum of the phase currents, which weakens the restraint value. The restraint is zero at $\varphi(3I_0''; 3I_0') = 90°$. This corresponds to the conventional method of direction detection by use of the vectorial sum and difference comparison.

The following phasor diagram shows the restraint value in the event of an external fault:

Fig. 11 Phasor diagram of restraint (stabilization) value
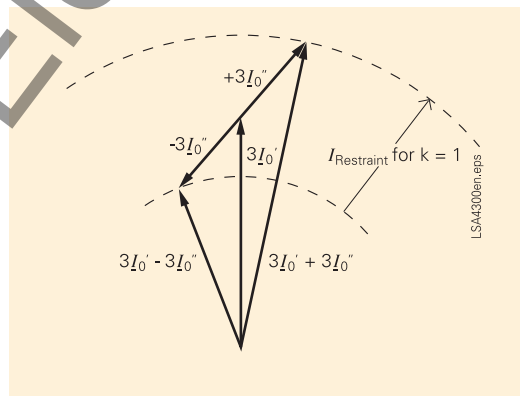
The earth-fault differential protection function must be activated by parameterization. The 7UT613 earth-fault differential protection relay is delivered in inactive-circuit state. This is because the protection relay may not be operated without at least having set the allocation and polarity of the current transformers correctly first. The relay may react unpredictably without these settings.

The setting of the I-EDS> value is decisive for the sensitivity of the protection. This value is the earth-fault current which flows through the star-point connection of the transformer. Another earth current flowing in from the system is not absorbed by the pickup sensitivity. The current value refers to the rated operating current of the side of the transformer to be protected. The preset pickup value of 0.15 I/I_{nS} is normally appropriate.

3.3 Backup protection functions
3.3.1 Overcurrent-time protection

The definite-time overcurrent-time protection of the 7UT613 serves as backup for the short-circuit protection of the downstream 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:

Transformer Y(N)d5

72 MVA

25 kV/10 kV

$u_{SC} = 12\,\%$

Current transformer 2000 A/1 A on the 25-kV-side
The overcurrent-time protection acts on the 25 kV side (= feed side).

The maximum possible three-phase short-circuit current on the 10 kV side with rigid voltage on the 25 kV side would be:

$$I_{3polemax} = \frac{1}{U_{SC\,Transf.}} \cdot I_{N\,Transf.} = \frac{1}{U_{SC\,Transf.}} \cdot \frac{S_{N\,Transf.}}{\sqrt{3} \cdot U_N} =$$

$$\frac{1}{0.12} \cdot \frac{72\,MVA}{\sqrt{3} \cdot 25\,kV} = 13856.4\,A$$

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

$I>> = 1.2 \times 13856.4\,A = 16628\,A$

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

Secondary setting value:

$$I>> = \frac{16628\,A}{2000\,A} \cdot 1\,A = 8{,}314\,A$$

i.e. at short-circuit currents above 16628 A (primary) or 8,314 A (secondary), there is definitely a short-circuit in the transformer area. This can be cleared immediately by the overcurrent-time protection. Increased inrush currents are disarmed by the delay times of the $I>>$ stage if their fundamental exceeds the setting value. The inrush restraint does not affect the stages $I>>$.

Stage $I>$ represents the backup protection for the subordinate 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 HV side of the transformer. The delay time depends on the grading time in the outgoing lines. It should be set 300 ms more than the highest 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.

3.3.2 Load unbalance protection (negative-sequence protection)

The load unbalance protection (phase-balance current protection or negative-sequence protection) can be used in the transformer as sensitive protection function on the feed side for weak-current single and two-pole faults. LV side, single-pole faults can also be detected which cause no zero-sequence current on the HV side (e.g. in vector group DYN).

The load unbalance protection of the HV winding (110 kV in the example) can detect the following fault currents on the LV side (25 kV in the example):

If $I_2 > = 0.1\,A$ is set for the HV side, a fault current of

$$I_{F1} = 3 \cdot \frac{110\,kV}{25\,kV} \cdot \frac{400\,A}{1\,A} \cdot 0.1\,A = 528\,A$$

can be detected for a single-phase fault and of

$$I_{F2} = \sqrt{3} \cdot \frac{100\,kV}{25\,kV} \cdot \frac{400\,A}{1\,A} \cdot 0.1\,A = 305\,A$$

for a two-phase fault on the LV side. This corresponds to 26 % or respectively 15 % of the transformer's rated current. Since this is a LV side short-circuit, the delay time must be coordinated with the times of the subordinate protection relays. The definite-time characteristic is two-stage.
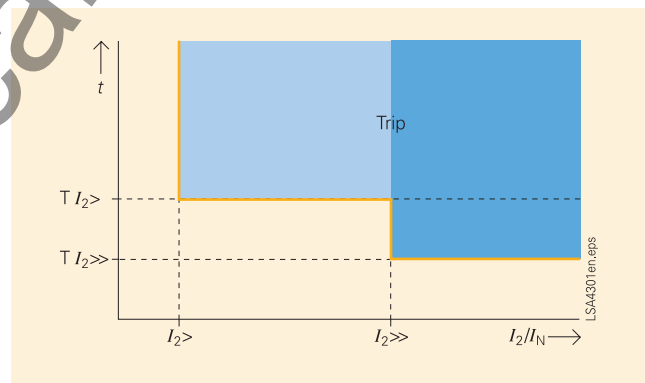

Fig. 12 Tripping characteristic of load unbalance protection

Stage $I_2>$ can be used for warning. A trip command can be given at the end of the delay time of stage $I_2>>$.

3.3.3 Overload protection

The thermal overload protection prevents over-load of the transformer to be protected. Two methods of overload detection are available 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 example. Since the cause of the overload is normally outside the protected object, the overload current is a through-flowing current. The relay calculates the temperature rise according to a thermal single-body model by means of the thermal differential equation

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

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 pre-setting 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.

$$\frac{\tau_{th}}{min} = 0.6 \cdot t6$$

If the transformer winding has a τ_6 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.

3.3.4 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_{NObj}/f_N, a direct measure is obtained of the induction related to the induction under rated conditions B/B_{NObj}. 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).
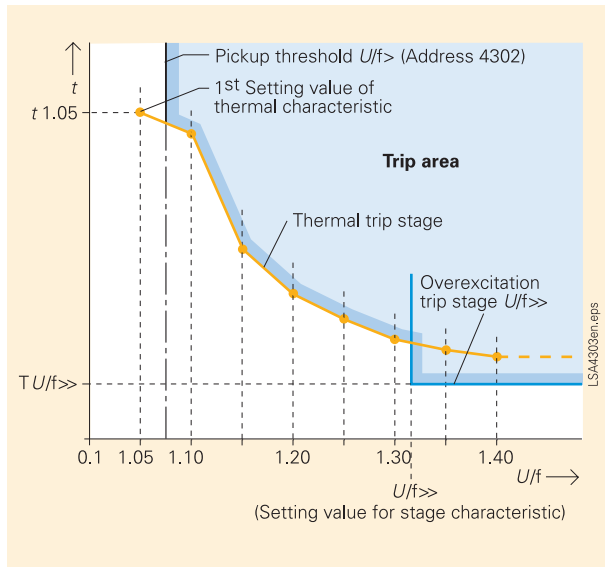

Fig. 13 Tripping characteristic of the overexcitation protection

An alarm is output after 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 highset 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.

■ *4. Further functions*

4.1 Integration into substation control system

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.
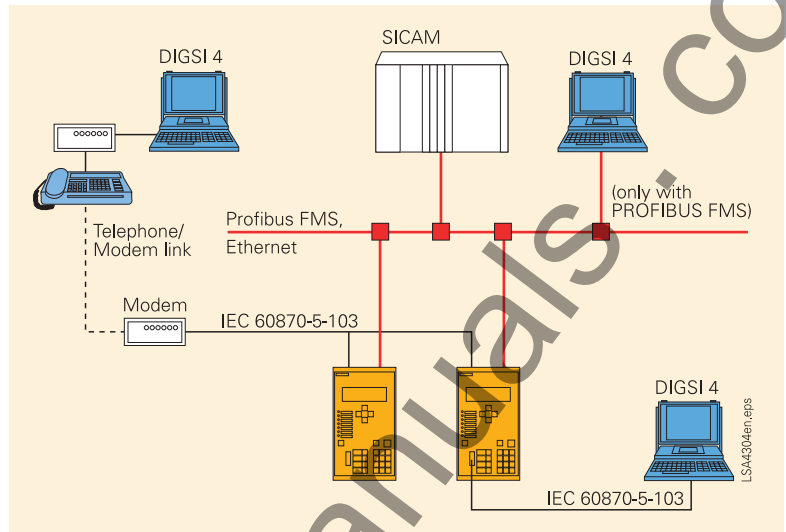

Fig. 14 Integration into substation control system

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 allocated to the LEDs or alarm contacts in the protection relay. This 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 clearing is insufficient, the fault data provide hints for an efficient service mission.
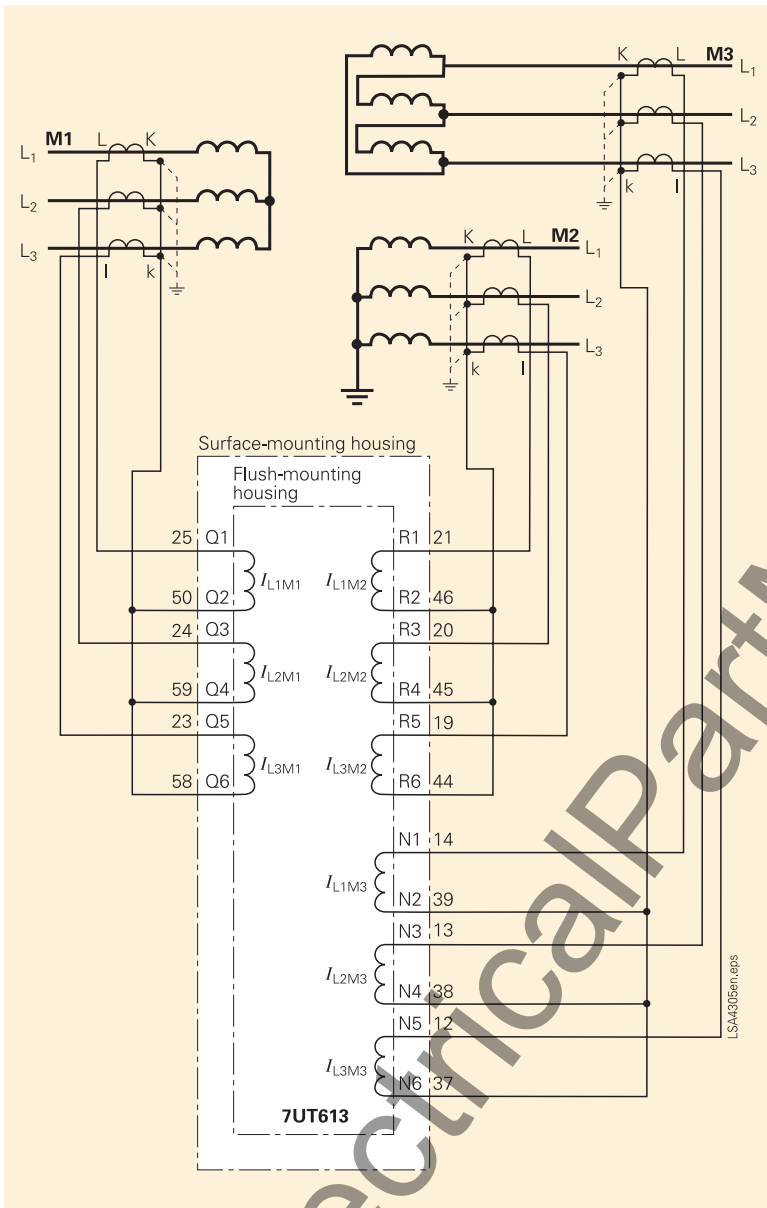
■ 5. Connection diagram

Fig. 15 Connection diagram of 7UT613

■ 6. 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 SIPROTEC 7UT613 relay offers extensive short-circuit protection for both the main and the backup protection of transformers in one single relay. 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.