Protection of a Transformer with Tap Changer

■ 1. Introduction

Transformers are among the most important and cost-intensive equipment in electrical power systems, meaning that faults which occur in these components not only entail an interruption in the electrical power supply over wide areas but also cause considerable losses in financial terms. A continuous fault-free power supply must therefore be ensured, over the course of years if possible. Faults and signs of potential failures of the transformers must therefore be detected in time in order to take suitable measures for troubleshooting.

For this reason transformers are equipped with various monitoring and protection relays depending on their type and size. The electrical protection should be highlighted particularly in addition to the mechanical protection.

Fuses and definite-time overcurrent-time relays are sufficient in smaller distribution transformers for both technical and economic reasons. Fuses and definite-time overcurrent-time relays represent time-delayed protection measures. Time-delayed protection tripping relays are unacceptable for larger transformers in distribution, transmission and power generation applications and must be disconnected immediately to avoid system instability and cost-intensive shutdowns.

Transformer faults can generally be divided into five categories:

- Interturn and terminal fault
- Winding fault
- Fault on the transformer tank and auxiliary devices
- Fault on the transformer tap changer
- Abnormal operating conditions (temperature, humidity, dirt)
- External fault

This application example gives an insight into the protection of regulated power transformers with tap changer function.

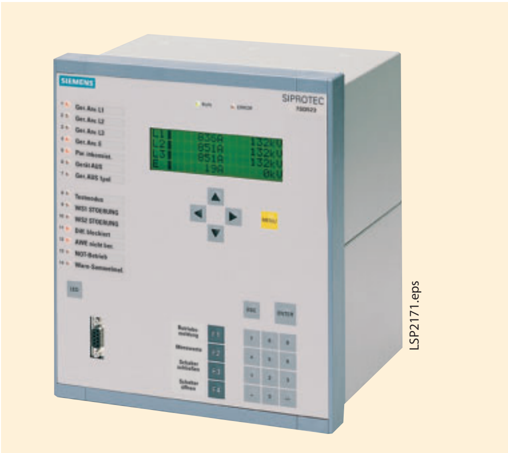

Fig. 1 SIPROTEC 7UT6 transformer protection

■ 2. Protection concept

Depending on the type and size of the transformers, Buchholz protection, overload protection and overcurrent time protection are used as fast, selective short-circuit protection in addition to the classic differential protection (as from approximately 1 MVA and higher). These are only mentioned briefly here because they are described in detail in other application examples.

2.1 Differential protection as main protection

Differential protection represents the main protection function for the transformer and is featured in the SIPROTEC relays 7UT6* (addr. 1201) and 7UM62* (addr. 2001). It also comprises a number of additional functions (matching to transformation ratio and vector group, restraint against inrush currents). Therefore false differential currents caused by transformation errors of the current transformers are to be expected in practice. In regulated transformers an additional error current is to be expected caused by adjustment of the tap changer.

The additional functions integrated in the relays are influenced by the use of a transformer with tap changer and the resulting correction values. This is explained in chapter 4 by a calculation example.

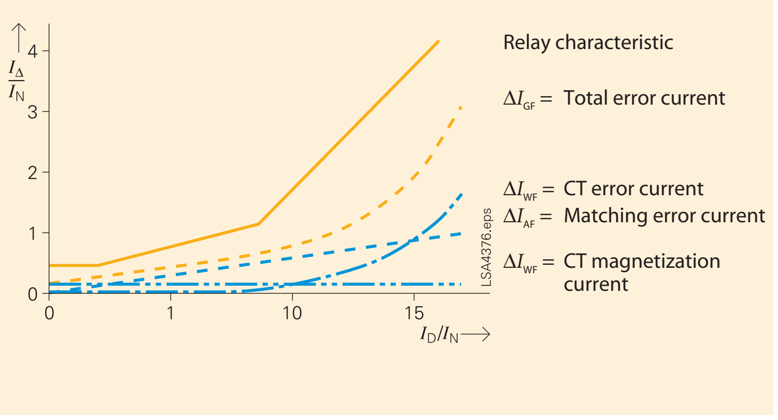

Fig. 2 False differential current in the event of load and continuity faults and matched relay characteristic

Backup protection such as overcurrent time protection are provided in separate relays (e.g. 7SJ602, 7SJ45/46). The overcurrent-time protection and/or overload protection contained in the differential protection relays serve merely as backup protection against external faults in the connected power system.

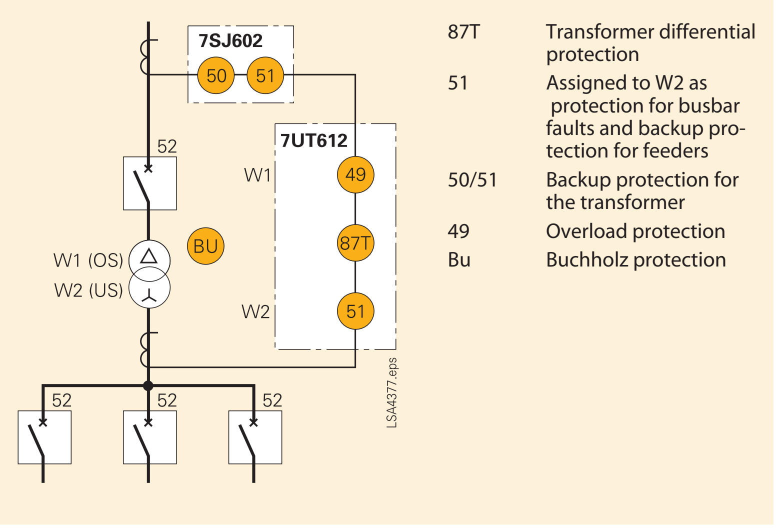

Fig. 3 Protection of a two-winding transformer

2.2 Earth-fault differential protection

In transformer windings with star-point earthing via an impedance (earth-current limiting), the earth-current differential protection (7UT6* addr. 1301) is an ideal supplement to the phase protection to enhance the response sensitivity in the earth fault.

In this method the measured star-point current I_0* in the transformer star-point is compared with the calculated summation current I_0** of the phase currents.

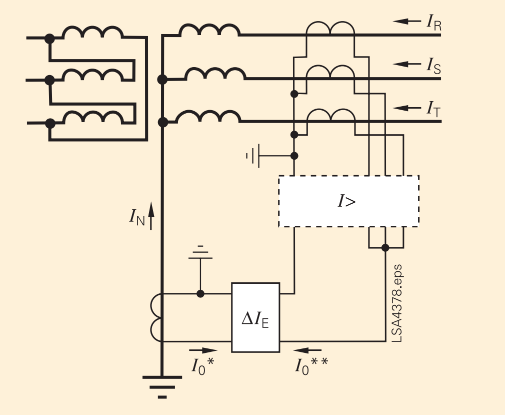

Fig. 4 Earth-fault differential protection

2.3 Buchholz protection

The Buchholz protection is coupled into the relay (alarm, tank and trip message) as an external protection (7UT6*, 7UM62* addr. 8601, 8701) and is used for liquid-cooled transformers and reactors with expansion tank. The Buchholz relay responds to faults which cause the forming of gas in the tank (winding fault, interturn fault, loss of insulating fluid, accumulation of air).

3. Integration of the transformer tap changer in differential protection

3.1 Purpose of a transformer tap changer

Voltage regulation on transformers with load tap changers is an important topic for power supply companies. In accordance with DIN/IEC standards it is necessary to keep the 230 V/400 V voltage in the public low-voltage system constant, at least in the range ± 10 %. To keep the voltage constant in this bandwidth, a transformer tap changer is controlled by a transformer voltage regulator (e.g. Maschinenfabrik Rheinhausen TAPCON® 230/240). The voltage regulator constantly compares the actual value U_{act} (output voltage at the transformer) and a fixed or load-dependent setpoint U_{setp}.

The voltage regulator supplies the setting variable for the transformer's load tap changer dependent on the deviation of the actual value from the setpoint. The load tap changer switches when the given bandwidth (U_{setp} +/- B%) is dropped below or exceeded. The voltage at the transformer is thus kept constant. Fluctuations within the permissible bandwidth have no influence on the control behavior or the switching process.

The parameters of the voltage regulator can be adapted optimally to the behavior of the system voltage so that a balanced control behavior is achieved at a low number of cycles of the load tap changer.

system data. Former relay generations required separate matching transformers for (e.g.) vector group adaptation.

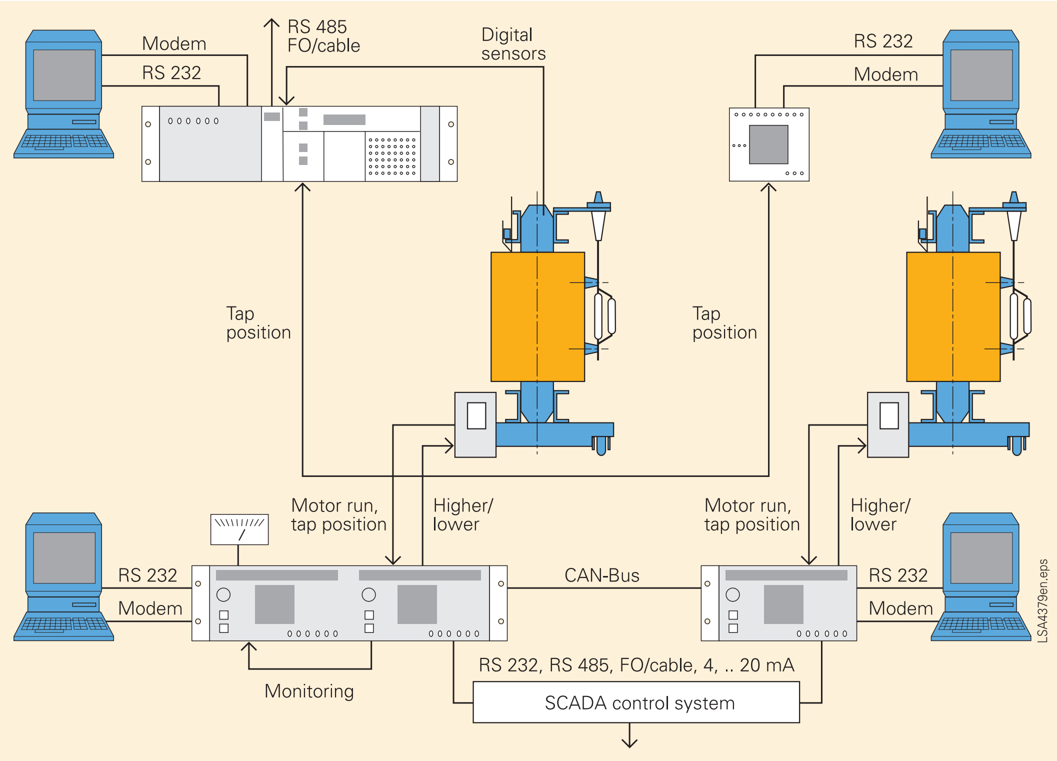

Fig. 5 Voltage regulation of a regulated transformer using a TAPCON® system

3.2 Correcting "false" differential currents

Most calculations of differential and restraint currents are made without taking the tap changer position into account. In practice, however, most power transformers are equipped with a tap changer. Two types are distinguished:

- Off-load tap changer
- On-load tap changer

Whilst most transformers are equipped for off-load tap changing, on-load tap changing is used for voltage regulation in power systems. The protection parameterization must take the different tap changer positions into consideration to avoid the possibility of false tripping (especially with extreme positions).

Correct operation of the differential protection requires that the differential currents on the primary and secondary side correspond to real conditions under normal load and fault conditions. The primary and secondary side current transformers do not pick up the real transformer ratio. Today's protection relays such as those in the SIPROTEC series compensate these faults with calculated correction factors based on the parameterized power

If the winding is regulated, not the actual rated voltage is used as U_N for the stabilized side, but the voltage corresponding to the mean current of the regulated range.

$$U_N = 2 \cdot \frac{U_{max} \cdot U_{min}}{U_{max} + U_{min}} = \frac{2}{\frac{1}{U_{max}} + \frac{1}{U_{min}}}$$

with U_{max}, U_{min} as limits for the regulated range.

Example:

Transformer Ynd5
35 MVA
110 kV/20 kV
Y side regulated ± 20%

For the regulated winding (110 kV) this results in

Maximum voltage U_{max} = 132 kV
Minimum voltage U_{min} = 88 kV

Voltage to be set

$$U_{N\text{-PRI SIDE 1}} = \frac{2}{\frac{1}{132\ \text{kV}} + \frac{1}{88\ \text{kV}}} = 105.6\ \text{kV}$$

Parameters in relevant SIPROTEC relays

7UT612	addr. 240
7UT613/63*	addr. 311
7UM62	addr. 240

4. Calculation example Influence of tap positions on differential and restraint currents

A two-winding transformer with a tap change range of –15 % to + 5 % is used for the following example. The tap changer is integrated in the primary winding for voltage regulation.

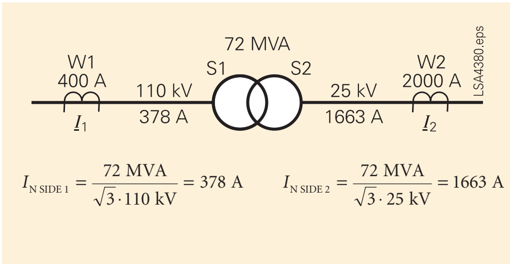

Fig. 6

Transformer	YNd5
	(irrelevant for the calculation)
	72 MVA
	110 kV/25 kV
	Y side regulated -15 %/+5 %
	CT_1 = 400 (1 A)
	CT_2 = 2000 (5 A)

4.1 Calculations of the voltage, object rated currents and correction factors to be set

The voltage to be set is calculated using the formula in chapter 3.2 and parameterized as $U_{N\,WIND.S1}$ in the SIPROTEC relays 7UT6*, 7UM62*.

For the regulated winding (110 kV) this gives a calculated
maximum voltage U_{max} = 115.5 kV
minimum voltage U_{min} = 93.5 kV

Voltage to be set

$$U_{N\,1} = 2\cdot\frac{U_{max}\cdot U_{min}}{U_{max}+U_{min}} = \frac{2}{\frac{1}{U_{max}}+\frac{1}{U_{min}}}$$

$$= 2\cdot\frac{115.5\text{ kV}\cdot 93.5\text{ kV}}{115.5\text{ kV}+93.5\text{ kV}} = 103.3\text{ kV}$$

Object rated current of the regulated side

$$I_{N\,1} = \frac{S_N}{\sqrt{3}\cdot U_{N\,1}} = \frac{72\text{ MVA}}{\sqrt{3}\cdot 103.3\text{ kV}} = 402.3\text{ A}$$

corresponds on the CT_1 secondary side to

$$I_{N\,1} = \frac{I_{N1}}{CT_1} = \frac{402.3\text{ A}}{400} = 1.00575\text{ A} \cong I_{NObj}$$

(referred to S1)

Object rated current of the unregulated side (remains constant)

$$I_{N2} = \frac{S_N}{\sqrt{3}\cdot U_{N2}} = \frac{72\text{ MVA}}{\sqrt{3}\cdot 25\text{ kV}} = 1663\text{ A}$$

corresponds on the CT_2 secondary side to

$$I_{N2} = \frac{I_{N2}}{CT_2} = \frac{1663\text{ A}}{2000} = 0.8315\text{ A} \cong I_{NObj}$$

(referred to S2)

4.2 Calculations of the differential/restraint currents in the tap changer extreme positions

4.2.1 Tap position +5 %

Object current in maximum tap position

$$I_{N\,1(+5\%)} = \frac{S_N}{\sqrt{3}\cdot U_{max}} = \frac{72\text{ MVA}}{\sqrt{3}\cdot 115.5\text{ kV}} = 359.9\text{ A}$$

corresponds on the CT_1 secondary side to

$$I_{N\,1(+5\%)} = \frac{I_{N1(+5\%)}}{CT_1} = \frac{359.9\text{ A}}{400} = 0.8997\text{ A} \cong 0.8946\cdot I_{NObj}$$

Differential current in maximum tap position

$$I_{Diff} = \left|I_{N\,1(+5\%)} - I_{NObj}\right| = \left|0.8946\cdot I_{NObj} - I_{NObj}\right| = 0.1054\cdot I_{NObj}$$

Restraint current in maximum tap position

$$I_{Restraint} = \left|I_{N1(+5\%)}\right| + \left|I_{NObj}\right| = \left|0.8946\cdot I_{NObj}\right| + \left|I_{NObj}\right| = 1.8946\cdot I_{NObj}$$

4.2.2 Tap position -15 %

Object current in minimum tap position

$$I_{N\,1(-15\%)} = \frac{S_N}{\sqrt{3}\cdot U_{min}} = \frac{72\text{ MVA}}{\sqrt{3}\cdot 93.5\text{ kV}} = 444.6\text{ A}$$

corresponds on the CT_1 secondary side to

$$I_{N\,1(-15\%)} = \frac{I_{N1(-15\%)}}{CT_1} = \frac{444.6\text{ A}}{400} = 1.1115\text{ A} \cong 1.1051\cdot \mathrm{I}_{NObj}$$

Differential current in maximum tap position

$$I_{Diff} = \left|I_{N\,1(-15\%)} - I_{N2}\right| = \left|1.1051\cdot I_{NObj} - I_{NObj}\right| = 0.1051\cdot I_{NObj}$$

Restraint current in maximum tap position

$$I_{Restraint} = \left|I_{N\,1(+5\%)}\right| + \left|I_{N2}\right| = \left|1.051\cdot I_{NObj}\right| + \left|I_{NObj}\right| = 2.1051\cdot I_{NObj}$$

At the voltage to be set according to chapter 3.2 the same differential current portion of the object rated current is measured respectively in the extreme positions ⇨ The calculated voltage U_{N1} to be set corresponds to the middle position of the transformer tap changer.

4.3 Difference between operating current and restraint current

$I_{op} = m \cdot I_{Restraint}$

Presetting m = 0.25

$I_{op} = 0.25 \cdot I_{Restraint}$

At maximum tap position + 5 % it follows that

$$I_{op} = 0.25 \cdot 1.8496 \cdot I_{NObj} = 0.4624 \cdot I_{NObj}$$

At minimum tap position - 15 % it follows that

$$I_{op} = 0.25 \cdot 2.1051 \cdot I_{NObj} = 0.5263 \cdot I_{NObj}$$

From the calculations it can also be derived that, under rated conditions and at the tap changer extreme positions, the operating currents are not in the tripping area (due to the characteristic). Therefore the slope (gradient) of the trip characteristic (7UT6* addr. 1241, 7UM62* addr. 2041) need not be adapted to conditions (presetting m = 0.25).

5. Parameterization notes

Direct coupling of the transformer tap changer into the protection algorithm is available as from V4.6 for 7UT63* relays (approx. available as of mid-2005). By reading in the tap positions (with the codings BCD, binary, 1 from n table), the transformation ratio can be adapted depending on the position, and the faulty differential currents compensated as a result. This improves both the sensitivity and the stability of the differential protection.

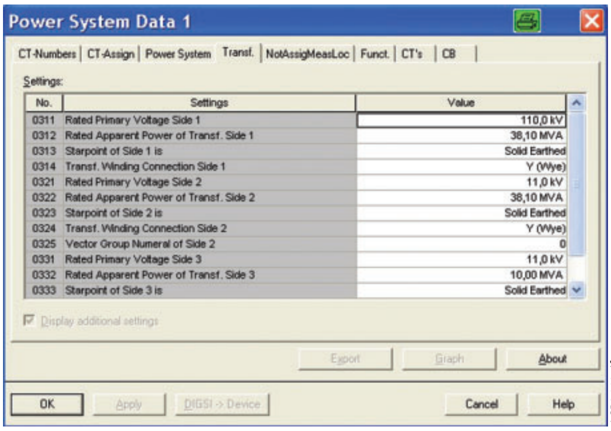

Fig. 7 7UT613/63* parameterization in transformer system data

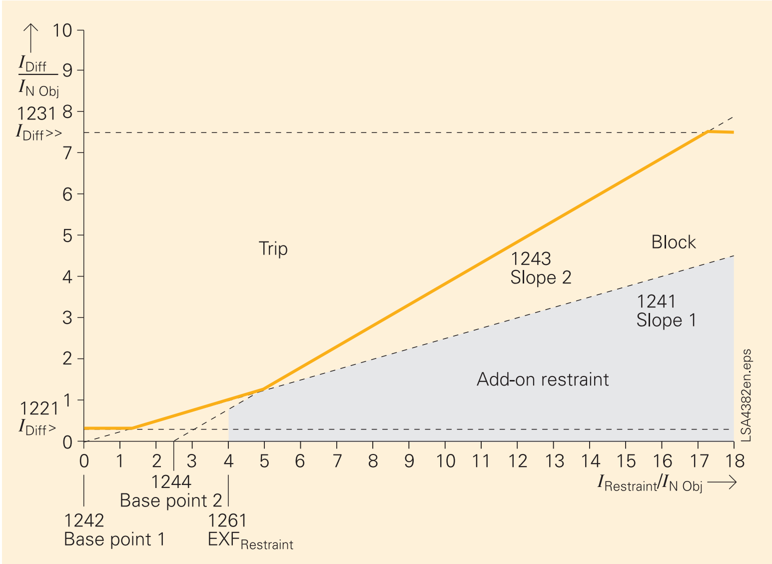

Fig. 8 Tripping characteristic of the differential protection in 7UT6* and 7UM62*

The matching is currently performed by correction of the primary voltage according to the formula in chapter 3.2 and parameterization by means of the appropriate addresses or DIGSI.

6. Integration of tap positions in DIGSI

Transformer taps can be indicated either by the DIGSI PC or the graphic display of the SIPROTEC relay. The transformer taps are signaled via binary inputs on the relay. The binary inputs are assigned according to the coding type and number of transformer taps (see Fig. 9).

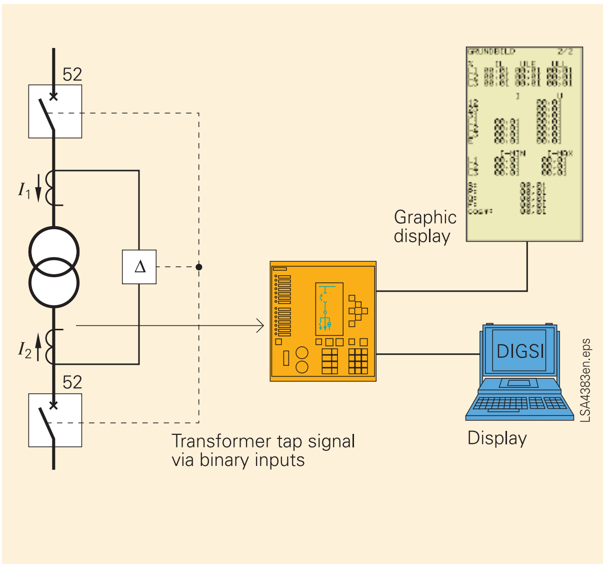

Fig. 9 Schematic diagram – Reading in of tap position by DIGSI or graphic display

In order to display the transformer taps, the transformer tap message type must first be entered in the configuration matrix.

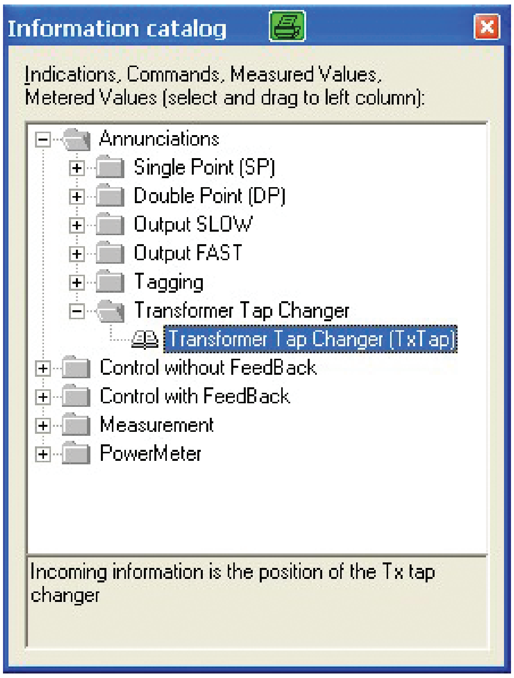

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Fig. 10 Activating the transformer tap message in the information catalog

The transformer tap message is entered in the configuration matrix and activated by configuration of the binary inputs.

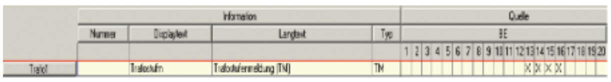

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Fig. 11 Entry of the transformer tap message in the DIGSI configuration matrix

Detailed settings must be made under the object properties of the transformer tap message.

- Number of bits: necessary for coding; number depends on the selected coding
- Display offset: the value by which the size of the displayed value is to be shifted in positive or negative direction in relation to the magnitude of the actual value
- Moving contact: if the moving contact option is activated, the tap position is not recognized as valid and accepted until the moving contact signals that it has reached the taps (always the highest ranking contact)

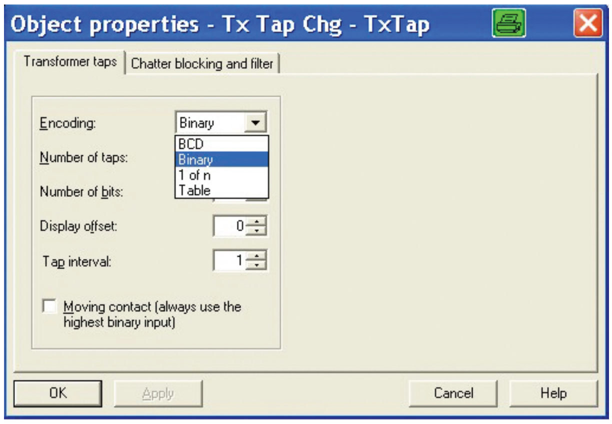

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Fig. 12 Object properties, transformer tap message

7. Summary

In most differential protection relays the influence of the transformer tap changer is mainly taken into account with the corrected input of the primary voltage (determined in the middle position of the tap changer).

Owing to the demand for stabilized voltages and regulation by tap changers, the probabilities of tripping faults in the extreme positions of the tap changer can be limited in future by matching of the transformation ratio. This requirement is met by inclusion of the tap position in the protection relay and consideration of the protection algorithm in the SIPROTEC 7UT63* relays.