New algorithms to improve the sensitivity of differential protection of regulating transformers

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***Abstract*--Early detection of incipient failures is an important issue on the way to improve the reliability of energy supply and reduces the cost of maintenance activities. In this paper an advanced method of digital protection will be demonstrated. The new approach based on adaptive adjustment of percentage differential characteristic takes into account the current tapping position of regulating transformers and so provides the timely recognition of low-current faults being undetected before due to insufficient sensitivity to small current magnitude.**

The presented adjustment algorithm has been tested for two different transformer models set up using ATP-EMTP. Both of them are proved to be suitable for sensitivity improvement, which leads to enhanced information quality regarding the risk assessment of supply breakdown.

***Index Terms*— ATP-EMTP, Differential protection, Modeling, Regulating transformer, Sensitivity, Tap changer.**

I. INTRODUCTION

The rapid development in the field of information and communication technology in a first step has enabled the integration of the protective devices into a digital control system. Further development of hardware and sensor technology permits now the integration of additional monitoring tasks into protective devices. This has been implemented already successfully by manufacturers for the calculation of the hot spot temperature of power transformers. The growing integration of information and better hardware capabilities allow new features. For example an increasing sensitivity of protective devices allows to give a warning message if low-current faults occur. Of course all high current faults have to be detected within milliseconds by the new algorithms, too.

The percentage-differential relays are generally available with different percent slopes. The purpose of the percent-slope characteristic is to prevent any undesired relay operation because of unbalanced current signals.

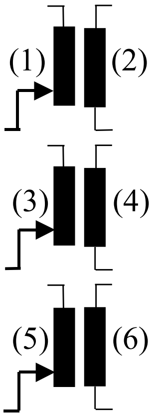
The most important reason for unbalance is the tap changing. Commonly the minimum sensitivity level is set to more than 30% of rated current.

So it is worth to tune the algorithms of differential protection systems taking into account the position of the tap changer. In this paper new adaptive algorithms to improve the sensitivity of differential protection devices for different regulating transformers are discussed. To confirm the new algorithms it was necessary to establish a model for regulating transformers since there were no practicable models available in this field.

II. MODEL OUTLINE

The model is based on the physical concept of representing windings as coupled coils. An analysis similar to the analysis presented in [1] is used and the model established on this basis. The algorithm can be divided into two parts as indicated below:

Part 1: In this step the excitation and short circuit tests in positive and zero sequences are used to compute two matrices [R] and [L] modelling a regulating transformer with nominal position of the tap changer (0 position). In the case of a three-phase transformer, with two windings for each phase and the tap changer on the primary side, these matrices are of order 6 as shown in Fig. 1.



$$[R]=\begin{bmatrix} R_{1(i)} & 0 & 0 & 0 & 0 & 0 \\ 0 & R_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{3(i)} & 0 & 0 & 0 \\ 0 & 0 & 0 & R_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{5(i)} & 0 \\ 0 & 0 & 0 & 0 & 0 & R_6 \end{bmatrix}$$

$$[L]=\begin{bmatrix} L_{1(i)} & L_{12(i)} & L_{13(i)} & L_{14(i)} & L_{15(i)} & L_{16(i)} \\ \ldots\ldots & L_2 & L_{23(i)} & L_{24} & L_{25(i)} & L_{26} \\ \ldots\ldots & \ldots\ldots & L_{3(i)} & L_{34(i)} & L_{35(i)} & L_{36(i)} \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & L_4 & L_{45(i)} & L_{46} \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & L_{5(i)} & L_{56(i)} \\ \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & \ldots\ldots & L_6 \end{bmatrix}$$

Fig. 1. [R] and [L] matrices of a three-phase transformer

R_k and L_k are the resistance and the self-inductance of coil k, and M_{kl} is the mutual inductance between coils k and l. In this manner the transformer will be handled as mutually coupled branches.

An auxiliary routine of ATP-EMTP, BCTRAN, allows the calculation of matrices [R] and [L], [2].

Part 2: In this step the ratios between the elements of two successive positions i and $i\pm 1$ of the tap changer are derived. The elements with index i of the above mentioned matrices are modified.

The inductance of the primary coil, where the tap changer is located, is considered as main inductance L_m and leakage inductance L_σ:

$$L_p = L_m + L_\sigma \tag{1}$$

The main inductance is given by the following equation:

$$L_m = \frac{N^2}{R_m} \tag{2}$$

where N is the number of turns and R_m is the magnetic resistance. Thus the subsequently given relation can be derived:

$$L_{m(i\pm1)} = L_{m(i)} \cdot \left(\frac{N_{i\pm1}}{N_i} \right)^2 \tag{3}$$

The leakage inductance between two coils can be calculated from the electromagnetic energy stored in the coil:

$$W = \frac{\mu_0}{2} \iiint_V H^2 dV \tag{4}$$

This is simplified by following hypotheses:

- no saturation phenomena occur,
- current density is constant in the windings,
- magnetic-field is parallel to the axis of the core,
- magnetic-field is symmetric in relation to the core axis,

all these hypotheses are fulfilled in event of position change of tap changer.

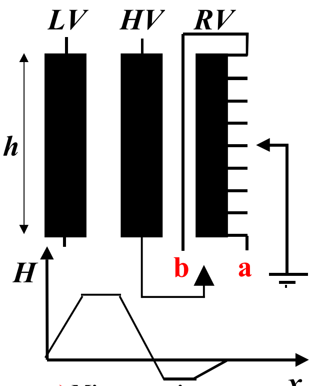
Because of the first hypothesis, the magnitude of field $\vec{H}$ is close to zero everywhere in the core itself. Moreover, because of the last two hypothesis, the magnitude H at any point in the air depends only on the distance x between the axis of the core and this point. So it is then possible to calculate the energy W stored in the windings. The equation (4) can be written as the following:

$$W = \frac{\mu_0}{2} \left[\begin{array}{l} \iiint_{V_1} H^2 dV + \iiint_{V_{12}} H^2 dV + \\ \iiint_{V_2} H^2 dV + \iiint_{V_{23}} H^2 dV + \iiint_{V_3} H^2 dV \end{array} \right] \tag{5}$$

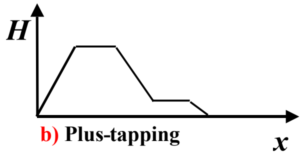
where v_1, v_{12}, v_2, v_{23} and v_3 are the volumes of the low voltage winding, the space between low and high voltage windings, the high voltage winding, the space between high and regulating voltage windings and the regulating voltage winding, Fig. 2.

Finally the total leakage inductance of the winding is calculated using the equation:

$$W = \frac{1}{2} L_\sigma i^2 \tag{6}$$



a) Minus-tapping



b) Plus-tapping

Fig. 2. Distribution of magnetic-field-intensity in the windings

A complete analysis for calculating the leakage inductance between two concentric coils in a power transformer is presented in [1] including the necessary assumptions and the correction factors.

From these relations we can calculate a “new” self inductance for another tap changer position:

$$L_{1,3,5(i\pm1)} = L_{p(i\pm1)} = L_{m(i\pm1)} + L_{\sigma(i\pm1)} \tag{7}$$

In order to describe the mutual inductance by the new position $i\pm1$ of the tap changer, we have to define the factor ε as the ratio of the leakage factor σ_{ps} of tap changer position $i\pm1$, and the leakage factor of the tap changer position i,

$$\varepsilon = \frac{\sigma_{ps(i\pm1)}}{\sigma_{ps(i)}} = \frac{L_{p(i)}L_s - M^2_{ps(i)}}{L_{p(i\pm1)}L_s - M^2_{ps(i\pm1)}} \cdot \frac{L_1}{L_{p(i\pm1)}} \tag{8}$$

Thus the following relations for the calculation of the mutual inductances result:

$$M_{ps(i\pm1)} = M_{ps(i)} \sqrt{\varepsilon} \sqrt{\frac{L_{p(i\pm1)}}{L_{p(i)}}} \sqrt{1 + \frac{1-\varepsilon}{\varepsilon} \cdot \frac{L_{p(i)}L_s}{M^2_{ps(i)}}} \tag{9}$$

$$M_{ps(i\pm1)} = \frac{N_{i\pm1}}{N_i} \cdot M_{ps(i)} \tag{10}$$

$$M_{pp(i\pm1)} = \left(\frac{N_{i\pm1}}{N_i} \right)^2 \cdot M_{pp(i)} \tag{11}$$

Equation (9) represents the mutual inductance for the case when the windings are on the same leg, for the case when the windings are situated on different legs the mutual inductance is calculated by (10). Equation (11) delivers the set of mutual inductances for the primary windings.

The resistance will be determined as follows:

$$R_{i\pm1} = \frac{N_{i\pm1}}{N_i} \cdot R_i \tag{12}$$

III. ADAPTIVE MONITORING METHOD

The suggested method is based on the tap changer position monitoring which gives a signal to the digital relay. The position of the tap changer can be detected and communicated to the protection by different ways:

- detection with binary input signals to the protection relay. The stepping can be differently coded (e.g. binary or decimal).
- controlling and detection of the stepping in the substation control unit. The current position is communicated to the protection by a communication link .
- measurement of the voltage on the primary and secondary windings of the transformer. This measurement can be used also for control of the stepping.

With the application of the first two methods a malfunctioning of the position detection has to be signalled and then leads to the activation of an appropriate pre-setting.

The relay may change the value of its settings according to the new position of the tap changer. During a tap changer position change the relay should not issue any trip signal. In the meantime the relay has to adapt its sensitivity to the new tap changer position. A transformer with in-phase regulation (off-nominal ratio), where only a change in the amplitude of the voltage occurs, may be used standalone (direct voltage adjustment) or in conjunction with a auxiliary transformer (indirect voltage adjustment).

A. Direct voltage adjustment

In this type of regulating transformers the change of the ratio takes place directly at the windings of the transformer. In series to either the primary or the secondary windings tapped windings are connected. For this type of transformers the sensitivity of the digital relay is adapted to different tap changer positions by the usage of the following equation:

$$\frac{I_2}{I_1} = K \cdot \frac{N_1 \pm N}{N_2} \tag{13}$$

N_1 and N_2 are the number of turns in the primary and secondary winding of the transformer at rated tap changer position. The factor *k* depends on the vector group of the transformer. *N* is the increase of N_1.

The effect of the magnetising current occurs if the tap changer is located on the primary side. The value of the magnetising current is small (about 5 % of the rated current at 115 % nominal voltage [3]).

B. Indirect voltage adjustment

These types of transformers basically consist of a main unit and an auxiliary unit, located on separate cores. These units can be enclosed in one tank, but usually they are constructed in two separate tanks.

In most cases the main transformer is an auto transformer with tertiary winding, see Fig. 3.

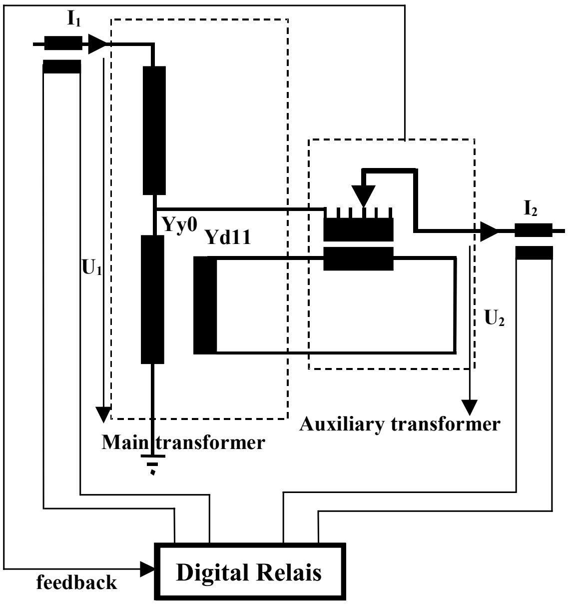


Fig. 3. Single phase equivalent circuit diagram of a regulating transformer with indirect voltage adjustment

For this type an equivalent circuit diagram can be determined. This diagram consists of the equivalent circuit diagrams of the main- and auxiliary transformer. The auxiliary transformer can be replaced as a controlled voltage source with an impedance. The further mathematical handling of this equivalent circuit diagram according to [4] leads to a simple three-phase two-winding transformer (Fig. 4) with a ratio of turns of:

$$\underline{\ddot{U}} = \frac{\underline{\ddot{U}}_2}{1+\beta} \tag{14}$$

$\underline{\ddot{U}}_2$ is the x ratio of turns of the main transformer and ß is:

$$\beta = \frac{N_3 N_5}{N_2 N_4} \tag{15}$$

N_2 and N_3 are the number of turns in a secondary and tertiary winding of the main transformer, N_4 and N_5 are the number of turns in a primary and tapped winding of the auxiliary transformer.

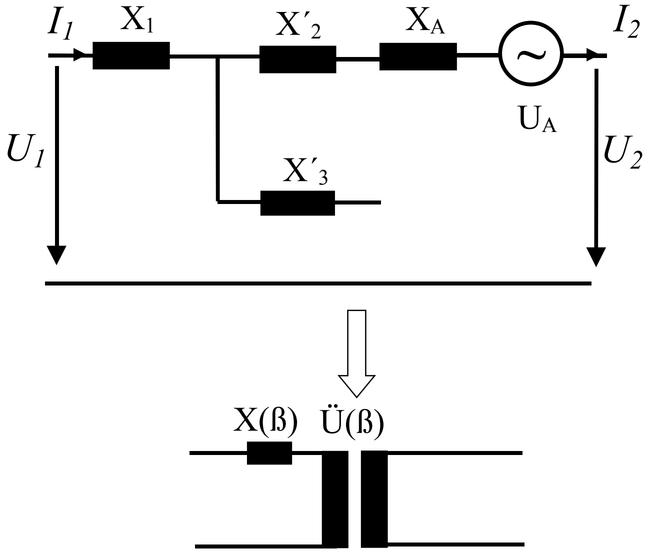


Fig. 4. The transformed equivalent circuit of the regulating block transformer

IV. SIMULATION RESULTS AND CONCLUSION

To show the improvement of sensitivity of the digital relay two types of regulating transformers have been analyzed. The analysis contains the simulation of two regulating transformers based on the algorithms presented in the previous sections. The first type is a standalone regulating transformer 15 MVA, Dy5, 33 kV ± 12 % with 17 taps/16.1 kV. The second type is a block transformer consisting of a power transformer with the following ratings: 220/66/66 MVA, 400/231/30 kV, Yy0d11, and an auxiliary transformer: 40 MVA, 30 kV/24 kV , 15 taps. In the analysis for the first type the adaptive setting of the differential relay is calculated by relation (13) and for the second type the adaptive setting of the differential relay is calculated by relation (14).

The results of simulation for both types of regulating transformers are shown in Fig. 5 and Fig. 6. The Fig. 5 shows the change of amplitude's secondary voltage (decrease and increase subject to tap changer position) in the case of longitudinal regulation (block transformer). As depicted in

Fig. 6 the advantage of the adaptive algorithm is obvious. Especially in the case of the regulating block transformer the remaining differential current mismatch is very small. Even in the case of the stand alone transformer the adaptive adjustment of the protection relay device delivers a significant improvement concerning the sensitivity in the detection of faults.

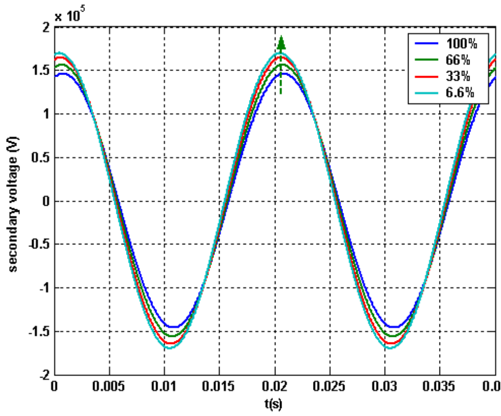
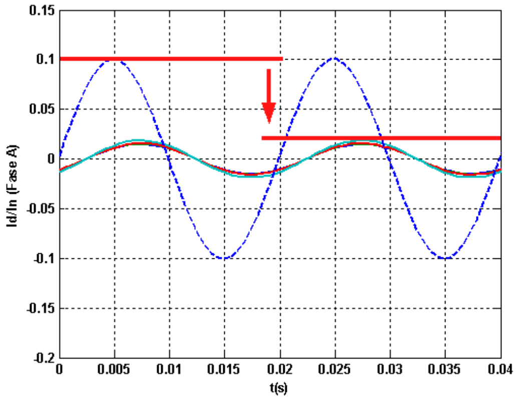
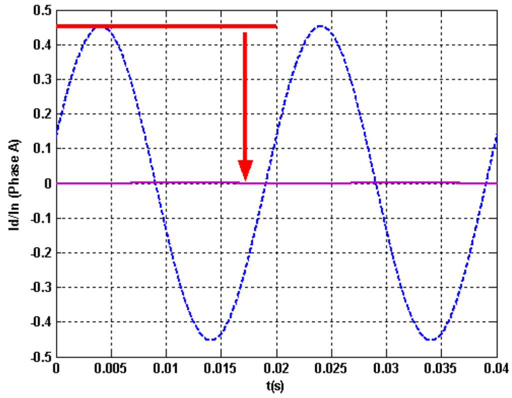


Fig. 5. Simulated secondary voltage of a block transformer as a subject to tap changer position (as percentage of the regulating winding)



a. Stand alone regulating transformer at tap changer position –8
(relay adjustment to nominal tap-changer position 0)



b. Regulating block transformer
(relay adjustment to nominal voltage ratio of main transformer)

Fig. 6. Reduction of differential currents by adjustment of the protective device´s settings (dashed lines: differential currents without adaptive adjustment, solid lines: with adapt. adj.)

V. REFERENCES

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VI. BIOGRAPHIES

Tammam Hayder was born in Lattakia, Syria, in 1968. He studied Electrical Engineering at the university of Tishreen Lattakia, finishing with the Dipl.-Ing. degree in 1992. At the moment, he is PhD-student at University of Stuttgart, Germany, Institute of Power Transmission and High Voltage Technology , D-70569 Stuttgart, Germany (email: thayder@ieh.uni-stuttgart.de). His area of research interest is power system protection.

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Kurt Feser was born in Garmisch-Partenkirchen, Germany, in 1938. He studied Electrical Engineering at the Technical University of Munich and received his Dip.-Ing. and Dr.-Ing. degree from the University of Munich in 1963 and 1970 respectively. In 1971 he joined Haefely & Cie AG, Basel, Switzerland as a chief development engineer. From 1980 he was as director and member of the executive board of Haefely responsible for capacitors and high voltage test equipment. In April 1982 he joined the University of Stuttgart as head of the Power Transmission and High Voltage Institute.

Prof. Feser is a fellow of IEEE, member of VDE and CIGRE, chairman of IEC TC 42 "High voltage test technique" and author of more than 200 papers.

Ludwig Schiel was born in Weimar, Germany, in 1957. He studied Electrical Engineering at the Institute of Technology Zittau, finishing with the Dipl.-Ing. degree in 1984. In 1991 he receivd the Dr.-Ing. degree from the University of Zittau. In the same year he joined the Siemens AG, Germany, Department of Power Transmission and Distribution, Power Automation.