Universal Adaptive Differential Protection for Regulating Transformers

Tammam Hayder, Ulrich Schaerli, Kurt Feser, *Fellow, IEEE*, and Ludwig Schiel

***Abstract*—Since regulating transformers have proved to be efficient in controlling the power flow and regulating the voltage, they are more and more widely used in today's environment of energy production, transmission and distribution. This changing environment challenges protection engineers as well to improve the sensitivity of protection, so that low-current faults could be detected (like turn-to-turn short circuits in transformer windings) and a warning message could be given. Moreover, the idea of an adaptive protection that adjusts the operating characteristics of the relay system in response to changing system conditions has became much more promising. It improves the protection sensitivity and simplifies its conception. This paper presents an adaptive adjustment concept in relation to the position change of the on load tap changer for universal differential protection of regulating transformers; such a concept provides a sensitive and cost-efficient protection for regulating transformers. Various simulations are carried out with the Electro-Magnetic Transients Program/Alternative Transients Program. The simulation results indicate the functional efficiency of the proposed concept under different fault conditions; the protection is sensitive to low level intern faults. The paper concludes by describing the software implementation of the algorithm on a test system based on a digital signal processor.**

***Index Terms*—Differential protection, Electromagnetic Transients Program (EMTP), phase shifters, regulating transformer, tap changer.**

I. INTRODUCTION

REGULATING TRANSFORMER (RT) is a generic term for transformers, including a regulating winding. Functionally, they may be used for "inphase" regulation or for "phase-shifting" regulation. The inphase regulation provides means for increasing or decreasing the system voltage magnitude at its location under load without changing the phase angle. By phase-shifting regulation the phase angle of voltage is changed with or without a change of magnitude. Concerning the design, there is a wide variety of regulating transformer types [1]. Generally there are two main designs. First, a single core design, in which a regulating winding is built into a power transformer. For "inphase" regulation, the regulating winding is located on the same leg as the primary winding (PW) and secondary winding (SW) pertaining to a phase and is called "inphase regulating winding" (IRW), (Fig. 1). For phase shifting,

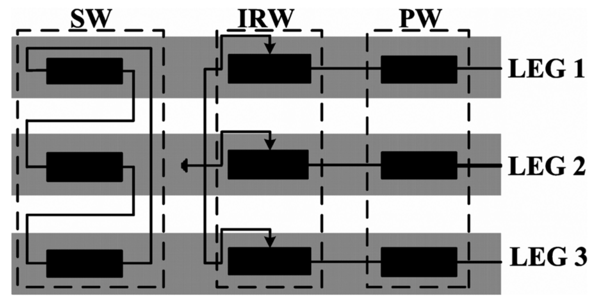

Fig. 1. Transformer with an inphase regulating winding.

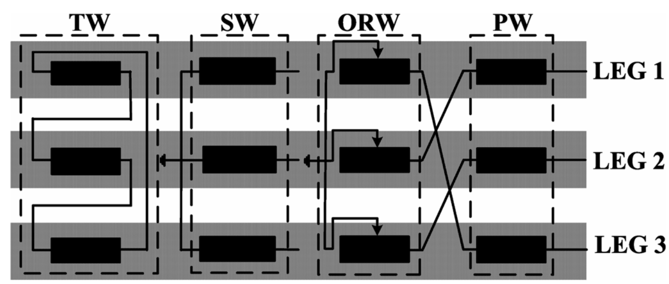

Fig. 2. Transformer with an out of phase regulating winding.

it is located on a different leg than the PW and SW pertaining to a phase and is called "out-of-phase regulating winding" (ORW). The tertiary delta-connected winding (TW) presented in Fig. 2 provides a low impedance path for zero-sequence current to flow during external ground faults.

Second a dual core design: It consists of a main transformer (MT) and an auxiliary transformer (AT). An important kind of a dual core design is a symmetrical phase shifting transformer (Fig. 3): The main transformer is equipped with a ORW which is connected in Y as is the PW itself. The AT consists of a center-tapped SW per phase connected into the transmission path. The load current flows through this winding. The center-tapping is connected with the PW of the MT. In Fig. 4, another dual core design is presented, which consists of an autotransformer with TW as MT, the PW of the AT pertaining phase could be connected arbitrary to any phase of TW, thereby a phase shifting between the source and load side voltage (φ_S) of 0°, -60° or $+60^{\circ}$ can be achieved. With the IRW of the AT, it is possible to increase or decrease the amplitude of the load side voltage. In Fig. 5 a new dual core design of a regulating transformer consisting of a main transformer including an IRW and an auxiliary autotransformer including an ORW, which is connected parallel to the load side is presented. In [2]–[4], further new designs of regulating transformers are described.

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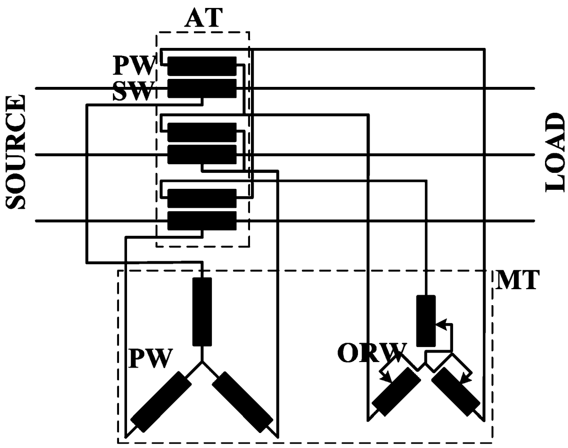

Fig. 3. Dual core symmetrical phase shifting transformer.

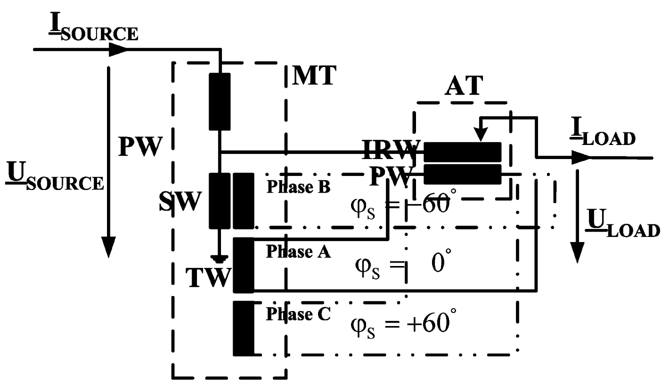

Fig. 4. Dual core regulating transformer for inphase and out of phase.

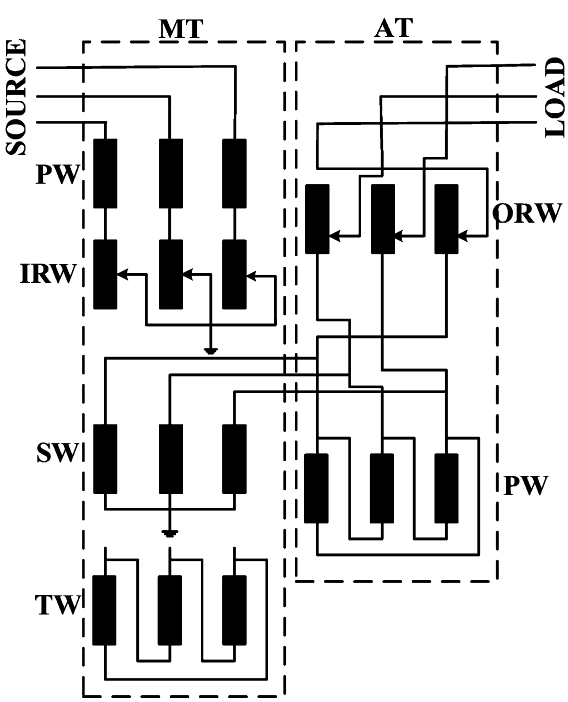

Fig. 5. New design of dual core regulating transformer. An AT transformer is an autotransformer with in delta connected PW and ORW.

The current approach for differential protection of regulating transformers is as follows: For power transformers with regulating winding (mostly inphase type), the percentage slope of the differential relay should be high enough to accommodate the full range of voltage change, as already used for tap-changing power transformers. A general set to operate for a current imbalance of 15% greater than the imbalance due to maximum regulation is recommended [5]. Thereby the protection sensibility is significantly impaired.

In the case of a dual core design, a concept of protection for every arrangement is developed. For the most commonly used design in Fig. 3. dual, redundant protection systems including a percentage-differential relay with harmonic restraint and an individual current transformer for each system are used. So far, several tests had to be carried out to determine the current transformer connection and ratio requirements and to adjust the relays [6], [7].

II. Adaptive Differential Protection for Regulating Transformers

A protection concept on the basis of an adaptive current balance of primary and secondary currents (source and load by a dual core design) on the regulating transformer in relation to the tap changer position (TCP) enables the attainment of two goals: 1) the improvement of the protection sensitivity and 2) the simplification of the protection concept. For an implementation of the concept, the protection must be able to detect the tap changer position and to adapt the adjustment of the secondary currents as a function of the tap changer position.

Prerequisite for the adaptive system is the recording of the tap position. There are several possibilities for receiving the tap position. One possible way is via a direct connection to the tap changer. In this case the protection unit must be equipped with a processing unit for the conversion and transmission of the signal into an adequate code (like the BCD code). Another possibility for recording the position is via the communication system in the substation. The IEC 61850 is the international standard for substation automation systems. It defines the communication between devices in the substation and the related system requirements. It supports all substation automation functions and their engineering. For the tap changer position a "logical node" of the type ATCC (i.e., an automatic tap change controller) is defined [8].

The main idea of the concept is the description of transformers by an analytical complex function consisting of the number of turns of the windings and including the regulating winding(s) as variables, which are determined and adjusted online depending on the tap changer position as well as other controlled variables in the function (e.g., angle) (Section III).

The concept uses the well-known protection method: biased differential protection. A typical percentage differential characteristic which is used for power transformer protection is shown in Fig. 6.

The differential and the through current are calculated by the following equations (for the fundamental component):

$$I_{\text{diff}} = \left|\sum(\underline{I}_{\text{P}} + \underline{I}_{\text{S}})\right| \tag{1}$$

$$I_{\text{bias}} = \sum\left(|\underline{I}_{\text{P}}| + |\underline{I}_{\text{S}}|\right). \tag{2}$$

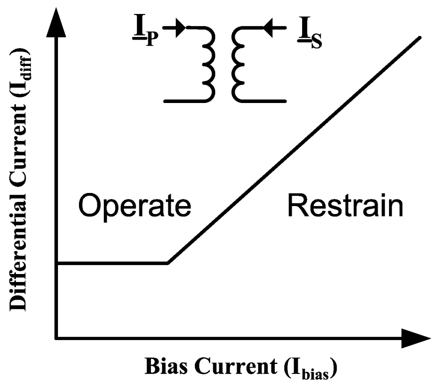

Fig. 6. Bias-differential current characteristic.

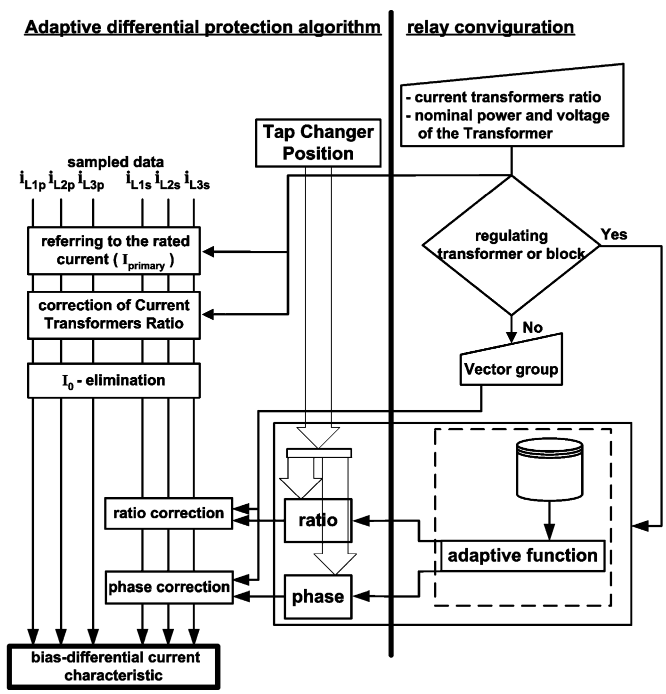

Fig. 7. Flowchart of the proposed algorithm.

In addition, the relay should be equipped with a second-harmonic restraint for inrush currents and a fifth-harmonic restraint for an overexcitation condition.

For the calculation of the fundamental and harmonic components, there are many digital algorithms available [9], [10]. In practice, the algorithm based on the Fourier sine and cosine components (described in [11]) becomes widely accepted. The sine and cosine components for rth harmonics of a current signal are given as follows:

$$I_{\mathrm{s}}^{(\mathrm{r})} = \frac{2}{N}\sum_{n=1}^{N} i_{\mathrm{n}} \cdot \sin\left(n \cdot \frac{2\pi \mathrm{r}}{N}\right) \tag{3}$$

$$I_{\mathrm{c}}^{(\mathrm{r})} = \frac{2}{N}\sum_{n=1}^{N} i_{\mathrm{n}} \cdot \cos\left(n \cdot \frac{2\pi \mathrm{r}}{N}\right) \tag{4}$$

where N is the number of samples per cycle.

The magnitude of the rth harmonic component at any time instant is given by

$$\left|I^{(\mathrm{r})}\right| = \sqrt{\left(I_{\mathrm{c}}^{(\mathrm{r})}\right)^2 + \left(I_{\mathrm{s}}^{(\mathrm{r})}\right)^2}. \tag{5}$$

The flowchart of the algorithm is shown in Fig. 7. In applying the differential protection, a variety of considerations has to be taken into account. After the referring to the rated current the correction of current transformers ratio and the elimination of zero sequence currents, the ratio and the phase of signals on either side of the windings must be corrected. Instead of constant correction factors for normal transformers the concept arranges software blocks for the correction of ratio and phase in relation to the tap changer position. In the case of regulating transformer the tap changer position should be received through a special interface.

The adaptive function of a regulating transformer has the following form:

$$\underline{\ddot{u}} = A.\mathrm{e}^{\mathrm{j}\theta}. \tag{6}$$

For the correction of ratio the secondary currents have to be divided by A, for the correction of phase they have to be multiplied by the following phase-adaptation-matrix (PAM):

$$PAM = \frac{2}{3} \cdot \begin{bmatrix} \cos(\theta) & \cos(\theta+120^\circ) & \cos(\theta-120^\circ) \\ \cos(\theta-120^\circ) & \cos(\theta) & \cos(\theta+120^\circ) \\ \cos(\theta+120^\circ) & \cos(\theta-120^\circ) & \cos(\theta) \end{bmatrix}.$$

The adaptive function is configured in the "placing in service" phase depending on the type of the regulating transformer. An open input interface allows easy implementation of the functions.

III. Derivation of Analytical Adaptive Functions

The well-known equivalent circuit (positive-sequence) of a transformer is used. The circuit consists of a serial impedance and a complex ratio of turns. Only the ratio of turns is relevant for the concept.

The way of the derivation of the function depends on the design type of the regulating transformer. In case of a single-core regulating transformer, the internal connection of windings should be analyzed. In case of a double-core regulating arrangement, one has to distinguish between two types according to the connection of the auxiliary unit: If the auxiliary transformer is connected in parallel with the load side (Fig. 5), the complex ratio of turns can be calculated by multiplying the ratio of turns of both units with each other

$$\underline{\ddot{u}} = \underline{\ddot{u}}_{\mathrm{MT}} \cdot \underline{\ddot{u}}_{\mathrm{AT}}. \tag{7}$$

In the other type, a winding of the auxiliary unit is connected into the transmission path and to the main unit (Figs. 3 and 4). In this case, the auxiliary unit can be replaced by a controlled voltage source with an impedance. The further mathematical handling of the equivalent circuit diagram leads to a simple three-phase two-winding transformer. As an example, the phase shifting transformer in Fig. 3 is considered. Since the

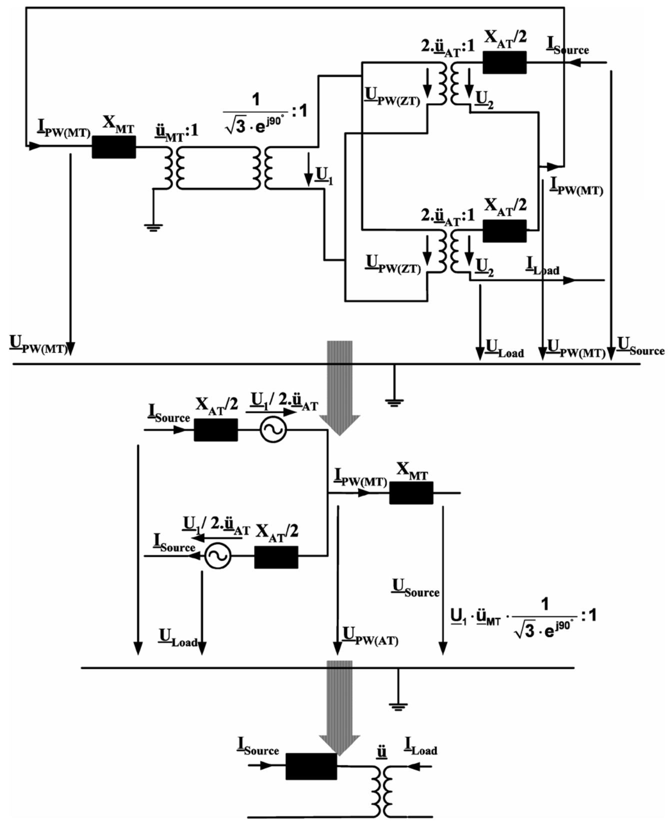

Fig. 8. Developing the equivalent circuit of the dual core regulating transformer in Fig. 3.

SW of the AT is tapped in the middle, the AT can be replaced by two identical transformers connected back to back, each of them is replaced by a controlled voltage source with an impedance (Fig. 8).

From the equivalent circuit in Fig. 8, the following relations result:

$$-\frac{\underline{I}_{\mathrm{PW(MT)}}}{2}\cdot\underline{\ddot{u}}^{*}_{\mathrm{MT}}\cdot\frac{1}{\sqrt{3}\cdot e^{\mathrm{j}90^\circ}}\cdot 2\underline{\ddot{u}}^{*}_{\mathrm{AT}}=\underline{I}_{\mathrm{Source}} \quad (8)$$

$$\underline{I}_{\mathrm{Load}}=\underline{I}_{\mathrm{Source}}-\underline{I}_{\mathrm{PW(MT)}} \quad (9)$$

$$\underline{U}_{\mathrm{Source}}-\underline{U}_{\mathrm{Load}}-\frac{\underline{U}_1}{\underline{\ddot{u}}_{\mathrm{AT}}}-\underline{I}_{\mathrm{Load}}\frac{X_{\mathrm{AT}}}{2}-\underline{I}_{\mathrm{Source}}\frac{X_{\mathrm{AT}}}{2}=0 \quad (10)$$

$$\underline{U}_1\left[\underline{\ddot{u}}_{\mathrm{MT}}\cdot\frac{1}{\sqrt{3}.e^{\mathrm{j}.90^\circ}}-\frac{1}{2.\underline{\ddot{u}}_{\mathrm{AT}}}\right]- \underline{U}_{\mathrm{Load}}-\underline{I}_{\mathrm{Load}}\frac{X_{\mathrm{AT}}}{2}+\underline{I}_{\mathrm{PW(MT)}}.X_{\mathrm{MT}}=0. \quad (11)$$

The further mathematical handling of this relations leads to a simple three-phase two winding transformer with a complex ratio of turns referring to (6) with

$$A=1$$
$$\theta=2\cdot\arctan\left(\frac{\sqrt{3}}{2}\cdot\frac{N_{\mathrm{ORW(MT)}}}{N_{\mathrm{PW(MT)}}}\cdot\frac{N_{\mathrm{SW(AT)}}}{N_{\mathrm{PW(AT)}}}\right)$$

where N is the number of turns.

In Table I, a catalog containing adjustment functions for several common designs of regulating transformers (introduced in I) is compiled.

IV. EMTP Simulation Results

A. Simulation Models

Two models have been used.

1) A geometrical model whose elements are derived from the geometrical arrangement of the transformer [12]–[14]. Different fault conditions can be simulated by changing the appropriate impedances. A change of the tap changer position can be accounted for by changing the turns ratio of the ideal transformer on the regulating winding.
2) A matrices model. It is based on the physical concept of representing windings as coupled coils, so a system can be described in the time domain using two matrices [R] and [L] and the Laplace operator p

$$[u]=[R][i]+[L][pi]. \quad (12)$$

This model is successfully implemented in the simulation program EMTP–ATP as a routine named BCTRAN [15]. In order to model internal faults, new elements can be added which are computed using mathematical equations modelling the faulted transformer [16]. A model for a regulating transformer can be created by calculating the ratios between the [R], [L] matrices elements of two successive positions of the tap changer. The mathematical derivation is presented in [17].

B. Simulated Objects

A lot of regulating transformers of different types have been simulated. The rated data of most of these transformers have been provided by transformer manufacturers. In this section, representative simulation results of the regulating transformers have been chosen. Their rated data are listed in Table II.

C. Results

First, the accuracy of the derived adjustment functions has been checked. In a further step, different short circuits in windings to ground and turn-to-turn short circuits have been simulated. The following conclusions can be drawn: When checking out the adjustment functions, the correctness of the derived analytical functions has been improved. They satisfactorily describe the complex ratio between the primary and secondary currents of a regulating transformer in relation to TCP. Without using these functions, the differential currents are rather high: For type-2 (see Table II) about 0.15 p.u. (Fig. 9), for type-5 about 0.3 p.u. (Fig. 10) and for other types even higher values. Using the adjustment functions, the differential current can be reduced significantly. The amount of the remaining differential current depends on the side the tap changer is installed. With the tap changer installed on the primary winding, the residual differential current will be bigger (about 0.02 p.u. for transformer type-2 (Fig. 9) and about 0.07 p.u. for transformer type-5 (Fig. 10), because of a magnetizing current; otherwise, the residual current will be less than 0.005 p.u. (Figs. 11 and 12).

TABLE I
ADAPTIVE FUNCTIONS OF REGULATING TRANSFORMERS (PRESENTED IN CHAPTER I)

Type	Amplitude	Phase	Control variables
1 **Fig. 1.**	$\sqrt{3}\cdot\left(\frac{N_{PW}\pm N_{IRW}}{N_{SW}}\right)$	330°	N_{IRW}
2 **Fig. 2.**	$\frac{\sqrt{\left(2\cdot N_{PW}-(\pm N_{ORW})\right)^2+\left(\sqrt{3}\cdot(\pm N_{ORW})\right)^2}}{2\cdot N_{SW}}$	$\arctan\left(\frac{\sqrt{3}\cdot(\pm N_{ORW})}{2\cdot N_{PW}-(\pm N_{ORW})}\right)$	N_{ORW}
3 **Fig. 3.**	———	$\arctan\left(\sqrt{3}\cdot\frac{\pm N_{ORW(MT)}\cdot N_{SW(AT)}}{N_{PW(MT)}\cdot 2\cdot N_{PW(AT)}}\right)$	$N_{ORW(MT)}$
4 **Fig. 4.**	$\frac{N_{PW(MT)}}{N_{SW(MT)}\cdot\sqrt{1-2\cdot\frac{N_{TW(MT)}}{N_{SW(MT)}}\cdot\frac{\pm N_{LRW(AT)}}{N_{PW(AT)}}\cdot\cos(2\cdot\varphi_S)+\left(\frac{N_{TW(MT)}}{N_{SW(MT)}}\cdot\frac{\pm N_{LRW(AT)}}{N_{PW(AT)}}\right)^2}}$	$-\arctan\frac{\left(-\frac{N_{TW(ET)}}{N_{SW(ET)}}\cdot\frac{\pm N_{LRW(ZT)}}{N_{PW(ZT)}}\cdot\sin(2\cdot\varphi_S)\right)}{1-\left(\frac{N_{TW(ET)}}{N_{SW(ET)}}\cdot\frac{\pm N_{LRW(ZT)}}{N_{PW(ZT)}}\cdot\cos(2\cdot\varphi_S)\right)}$	$N_{IRW(AT)}$ $\varphi_S=0,\pm 60$
5 **Fig. 5.**	$\frac{N_{PW(MT)}\pm N_{LRW(MT)}}{N_{SW(MT)}}\cdot\sqrt{\left(1-\left(\frac{\sqrt{3}}{2}\cdot\frac{+N_{ORW(AT)}}{N_{PW(AT)}}\right)\right)^2+\left(\frac{3}{2}\cdot\frac{\pm N_{ORW(AT)}}{N_{PW(AT)}}\right)^2}$	$\arctan\frac{\frac{3}{2}\cdot\frac{\pm N_{ORW(AT)}}{N_{PW(AT)}}}{1-\left(\frac{\sqrt{3}}{2}\cdot\frac{+N_{ORW(AT)}}{N_{PW(AT)}}\right)}$	$N_{IRW(MT)}$ $N_{ORW(AT)}$

TABLE II
NOMINAL DATA OF THE SIMULATED OBJECTS

		Nominal Power (MVA)	Nominal Voltage (kV)	Vector group
Type 2		300/300/100	400/(±12 X 4.976) /115/30	Ynynd11
Type 3	Main Transformer	240	230/66(±16 tappings)	Y0y0
	Auxiliary Transformer	320	91.41/66.96	Dy11
Type 4	Main Transformer	220/220/66	400/231/30	aynd11
	Auxiliary Transformer	40	30/24(±15 tappings)	Dy5
Type 5	Main Transformer	300/300/100	400 (±12 X 5)/115/30	Y0y0d11
	Auxiliary Transformer	300	115/115(±12 tappings)	Dy0

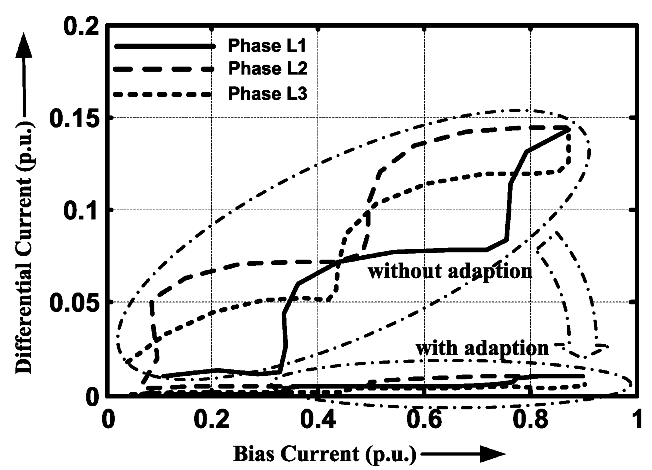

Fig. 9. Reduction of residual differential current by using adaptive adjustment, type-2-transformer, TCP = +12.

The protection has responded to different short circuits to ground and turn-to-turn short circuits. The increase of the fault characteristics in the relay diagram depends on several parameters: winding, place of fault, position of tap changer, and fault resistance. The fault resistance is particularly a variable of transformer aging and should be included especially for turn–turn short circuits [18]. The following simulation results of short circuits to ground and turn-to-turn short circuits by type-3 and type-5 transformers are presented. Fig. 13 shows the ability of the protection to detect short circuits to ground on different windings of transformer type-3 with relatively poor conditions (TCP = 1 and small fault current).

In Fig. 14, the dependence to TCP in case of turn-turn short circuit on SW(AT) of transformer type-3 is presented. At a low position of the tap changer, the detection of faults is difficult, only at higher positions, the protection is able to detect such faults.

Simulations on type-5 regulating transformers have shown that with an adaptive adjustment of the amplitude and the phase of the currents the protection is able to detect low-current turn-

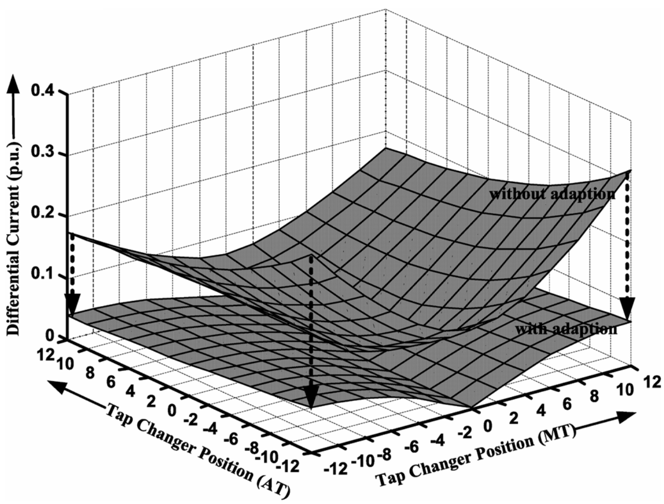

Fig. 10. Reduction of residual differential current by using adaptive adjustment in relation to TCPs, type-5 transformer.

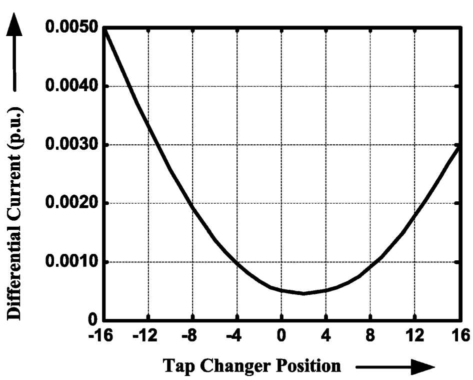

Fig. 11. Residual differential current by using adaptive adjustment in relation to TCPs, type-2 transformer.

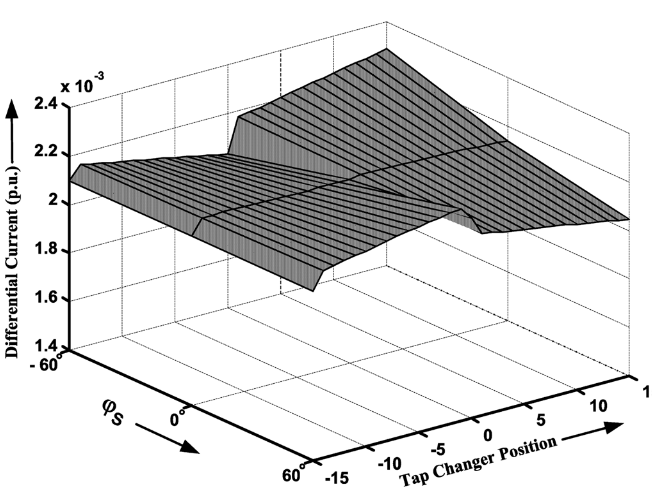

Fig. 12. Residual differential current by using adaptive adjustment in relation to TCP and the phase shifting (φ_S) by transformer type-4.

turn short circuits (Fig. 15), which could not be detected with the normal static protection (compared with Fig. 10).

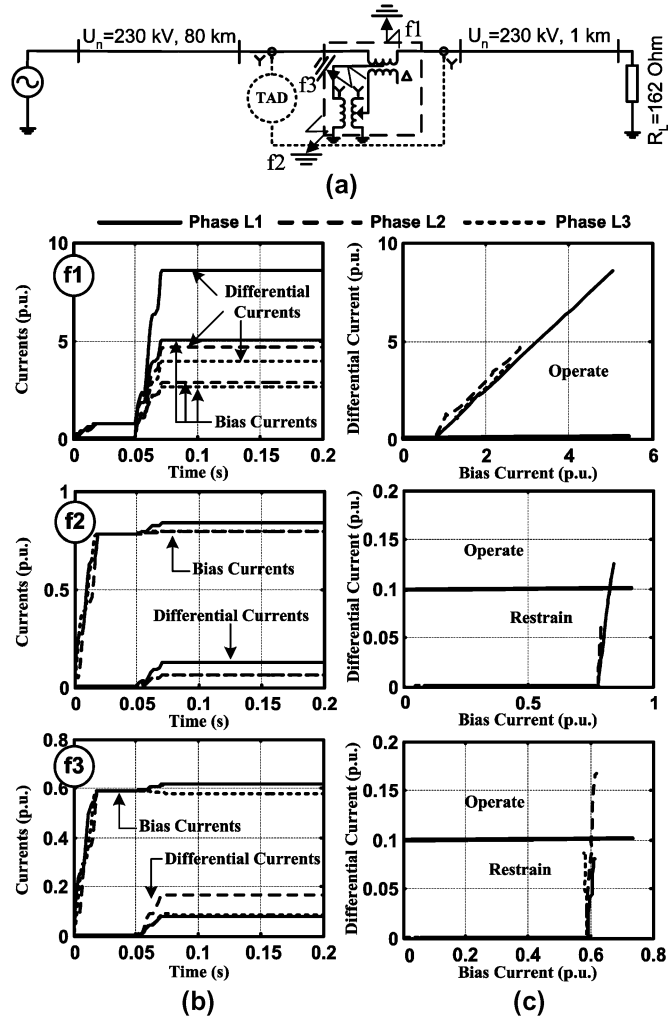

Fig. 13. Short circuits of phase L1 with ground on different windings of type-3 regulating transformer for tap changer position 1 and fault resistance 0.1 Ω, f1: short circuit on PW(MT) at 1.2% of turn number, f2: short circuit on PW(AT) at the terminal to load site and f3: short circuit on SW(AT) at the terminal to the regulating winding of the main transformer. (a) Single-line diagram of the simulated system. (b) Differential and bias currents. (c) Fault characteristic on the bias-differential current characteristic of the protection.

V. Investigation of Technical Feasibility

This section describes the operating response of a prototype adaptive differential unit based on a TMS320C6713 DSP on an evaluation board. Fig. 16 shows the prototype system. The algorithm of the differential protection of the transformer with the Fourier-Filter has been implemented on a DSP with the C-code, the tap changer has been modelled as interrupt routine, which at arbitrary time can be activated. The current signals simulated by EMTP–ATP are sampled with a Matlab routine and transferred to the evaluation board through a universal serial bus (USB) interface. The sampling rate is 800 samples/cycle. The adaptation functions in Table II have been implemented successfully as components. According to the regulating transformer type, an adaptation function can be downloaded after the main program and saved in the flash memory. This approach makes the configuration of the relay more flexible. As an example, the regulating transformer type has been investigated (Fig. 17). Current signals during a TCP(MT) changing period of the tap changer on the

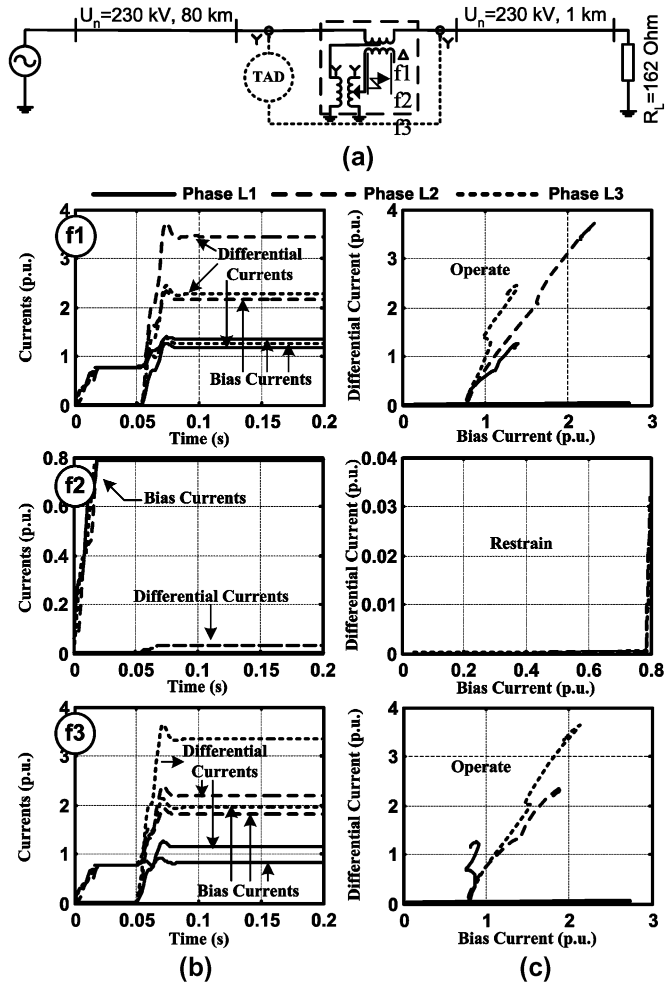

Fig. 14. Turn-to-turn short circuits on SW(AT)-phase L1 of type-3 regulating transformer, 20% of winding is short-circuited over fault resistance 0.1 Ω and different tap changer positions, f1: by tap changer position −16, f2: by tap changer position 1 and f3: by tap changer position +16. (a) Single-line diagram of the simulated system. (b) Differential and bias currents. (c) Fault characteristic on the bias-differential current characteristic of the protection.

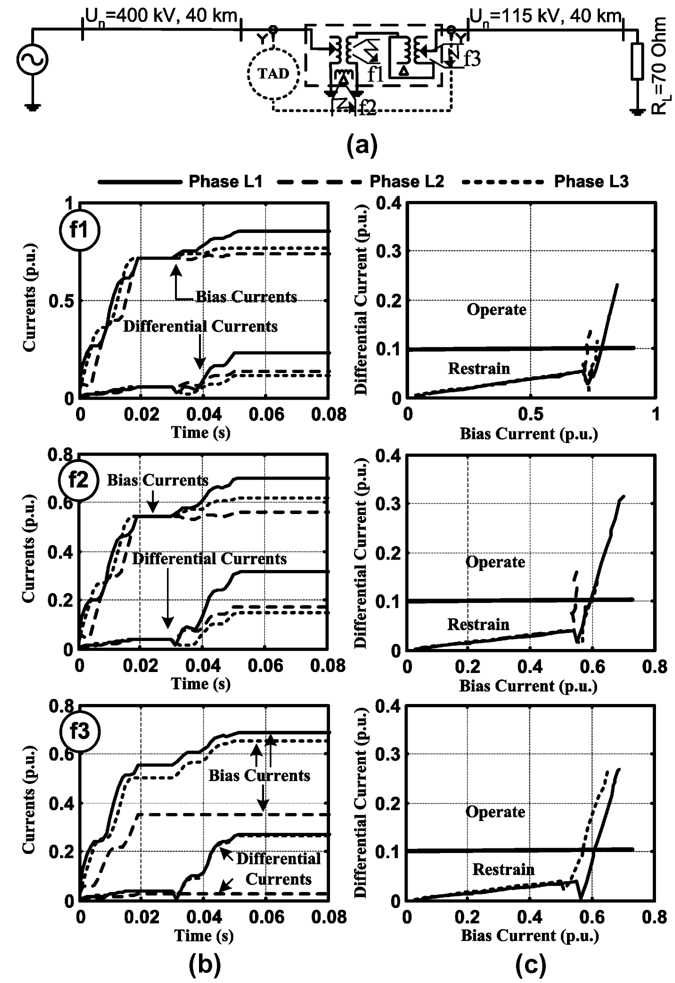

Fig. 15. Turn-to-turn short circuits on phase L1-different windings of type-5 regulating transformer over fault resistance 0.01 Ω and different tap changer positions, f1: 1% of SW(MT)-turns is short circuited by TCP(MT) = 0 and TCP(AT) = +12, f2: 3% of TW(MT)-turns is short circuited by TCP(MT) = +12 and TCP(AT)= +12 and f3: 4% of SW(AT)-turns is short circuited by TCP(MT) = +12 and TCP(AT) = +12. (a) Single-line diagram of the simulated system. (b) Differential and bias currents. (c) Fault characteristic on the bias-differential current characteristic of the protection.

main transformer from +11 to +12 position have been prepared and loaded to the board. Fig. 17(b) shows that the filter output (50-Hz component) is different in dependence to starting time of adjustment, a fact that should be considered. The execution time of current adjustment by changing the position amounts to less than 0.1 ms [Fig. 17(c)].

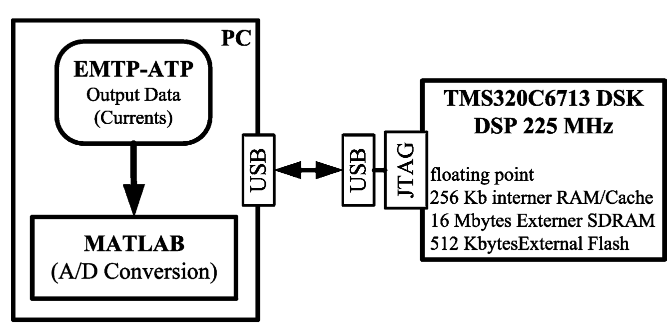

Fig. 16. Software implementation.

VI. Conclusion

An algorithm for adaptive differential protection of regulating transformers is described in this paper. In the configuration phase of the relay, an adaptive function depending on the type of the regulating transformer will be implemented. Secondary currents are adjusted online in relation to the tap changer position, so that the primary and secondary currents are balanced. The adaptive functions are derived analytically and can be verified by means of developed models presented in this paper. The proposed algorithm assumes the ability of the protection to record the tap changer position. Simulation results on various faults and regulating transformer types indicate that with the proposed algorithm a significant improvement of protection sensitivity can be achieved. Up to now, a dependence on tap changer position is given only in a few cases with low relevance. A low priced test system has been established, which makes it possible to examine protection algorithms in real time using output signals of ATP/EMTP.

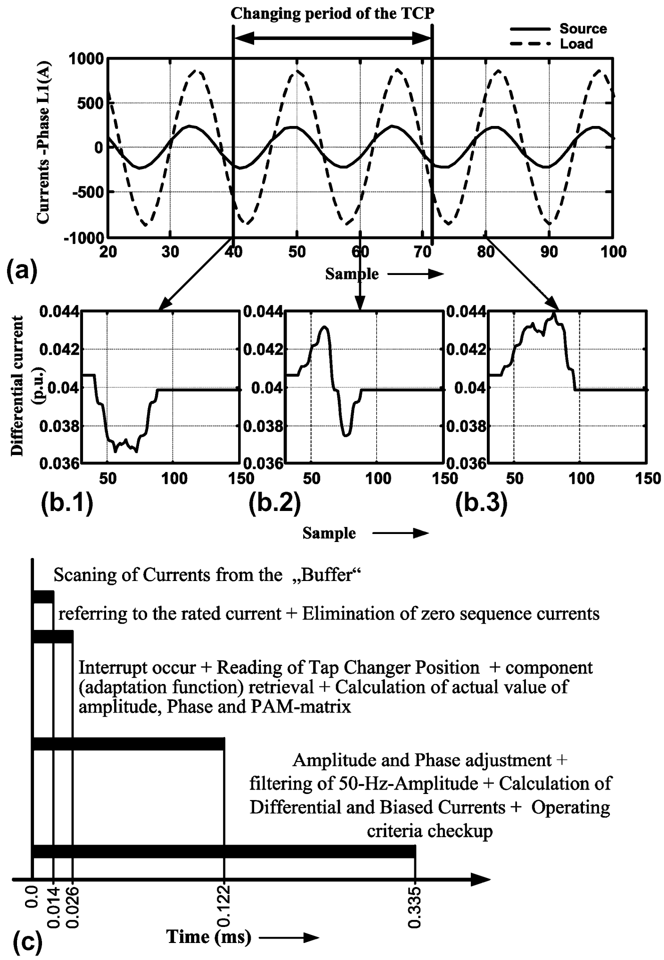

Fig. 17. Application of the testing system: type-1 regulating transformer by changing of TCP(MT) from $+11$ to $+12$, TCP(AT) $= +12$. (a) Sampling input currents. (b) Differential current by different starting time of the adaptation process. (c) Operating expense of the adaptation algorithm.

With this test system, the technical feasibility of the proposed algorithm has been investigated. The execution time is acceptable and the possibility for flexible implementation of the adaptation functions has been tested.

Furthermore, such an adaptive adjustment concept turns the differential protection relay into an universal relay for transformers. The development of an individual protection concept for every type of regulating arrangement and the use of several differential relays with current transformer groups for every relay is no longer necessary.

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