# ЭЛЕКТРОТЕХНИЧЕСКИЕ КОМПЛЕКСЫ И СИСТЕМЫ
# ELECTRICAL FACILITIES AND SYSTEMS

***Долгицер А.***
***Dolgicers A.***
*Dr. sc. ing.*
*Asoc. professor,*
*Power Engineering Institute*
*Riga Technical University*
*Riga, Latvia*

***Козадаев Е.***
***Kozadajevs Je.***
*mag. sc. ing.*
*Researcher*
*Power Engineering Institute*
*Riga Technical University*
*Riga, Latvia*

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## IMPROVEMENT OF THE SENSITIVITY OF DIFFERENTIAL PROTECTION OF POWER TRANSFORMERS

This paper presents the development of microprocessor based device for improving the sensitivity of differential protection of power transformers. Power transformers failure may lead to high scale system's operations disruption and heavy economic losses, that's why the lever of requirements for power transformer protections is so high. Differential protection is usually used as a main protection against internal faults such as inter-windings faults, inter-coil faults or coil-core faults. For safe protection against incomplete winding faults protection device must be capable to detect differential current from such a low value as 0.01% from nominal. However, transformer for relay protections needs are produced with error classes 5P and 10P meaning error rate 5 and 10% correspondently. The idea for a new device is to use information obtained from measurement current transformers. The microprocessor based device may "teach" itself by forming some error correction table in it's memory on the basis of core outputs compare during normal operation. In case of fault device may operate with much higher sensitivity thus sensing fault on it's early stage.

*Key words*: Differential protection of power transformers, current transformer, sensitivity of relay protection, internal faults.

## ПОВЫШЕНИЕ ЧУВСТВИТЕЛЬНОСТИ ДИФФЕРЕНЦИАЛЬНОЙ ЗАЩИТЫ СИЛОВЫХ ТРАНСФОРМАТОРОВ

Силовые трансформаторы являются ответственными и дорогостоящими элементами энергосистемы, их повреждения способны принести значительный экономический ущерб, привести к системным авариям. В качестве основной защиты от внутренних повреждений, как межвитковых и межкатушечных замыканий, замыканий на корпус и сердечник, используется дифференциальная защита. Для надежной защиты

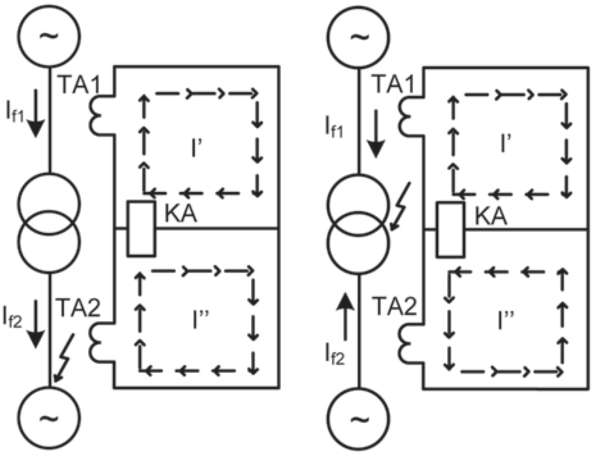
трансформаторов от неполных замыканий может потребоваться защита с чувствительностью 0,01% от номинального тока. На сегодняшний день трансформаторы тока, используемые для дифференциальной защиты, не могут обеспечить такую точность. Идея предлагаемого устройства заключается в использовании информации, получаемой от измерительных трансформаторов, для коррекции погрешности основных данных от измерительных токовых трансформаторов. Микропроцессорное устройство релейной защиты может быть «обучено», т. е. по результатам наблюдений, выполненных в нормальном режиме, в памяти устройства может быть сформирована таблица поправок с помощью которой в аварийном режиме устройство сможет действовать с более высокой эффективностью.

*Ключевые слова.* Дифференциальная защита силовых трансформаторов, токовые трансформаторы, внутренние короткие замыкания, чувствительность защиты.

## I. Introduction

Power transformers are highly valued power system's elements, transformers failure may lead to high scale system's operations disruption and heavy economic losses. Transformer damages are often linked with long term customer disconnections or available power limitations. That's why the lever of requirements for power transformer protections is so high. Between transformer damages internal and external damages are distinguished. Under the term "internal damage" are understood any kind of damage, that is located inside the transformer's shell or tank. Internal damage may cause winding destruction, fire and transformer's blow-up, which leads to complete transformer destruction. Protection against internal faults is a matter of high importance. Differential protection is usually used as a main protection against internal faults such as inter-windings faults, inter-coil faults or coil-core faults [1].

To understand the basics of such protection let's discuss the simplified schematics on the fig. 1.




a) b)

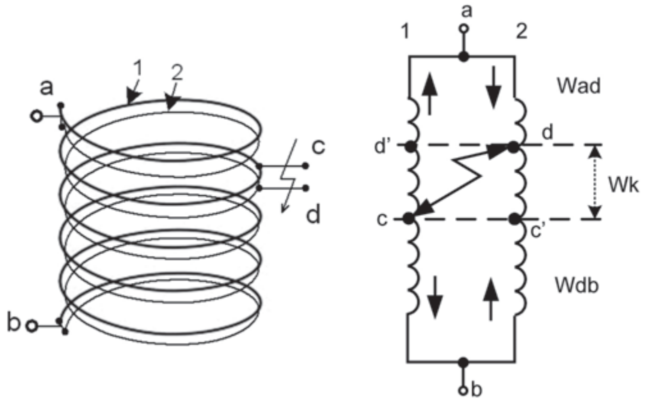
Fig. 1. Basic principle of differential protection's operations

The current transformer TA1 is inserted into the primary windings circuit of the protected power transformer, another current transformer TA2 is used to monitor current in the secondary winding's circuit. Both current transformers are selected in such way, that in case of nominal load of protected transformer they secondary currents are equal. Fig1.a shows circuit operation in cases of normal load or external damage. The current relay KA is fed by difference of currents from TA1 and TA2, in case of external fault or load this currents are equal by amplitude and opposite by direction, so resulting current in the KA coil is equal to zero and no output is produced. Complete opposite situation is observable in case of internal fault. Both currents are directed toward fault and as shown on Fig 1.b.

KA will receive near double fault current and with KA trip the disconnection signal for power switches will be produced. Reader may come to conclusion, that protection device, based on differential principle will be absolutely selective and will benefit an unlimited sensitivity. In the real world protection sensitivity is limited by the number of factors, partially linked with protected transformer, such as magnetizing current, (especially rapid changes in it) or change of real transformation ratio occurring when the voltage regulator changes the taps during it's operation and partially inflicted by the current transformers errors. Let's designate the current in the KA under normal regime conditions or in case of external fault as unbalance current. In the ideal case the unbalance current $I_{nb}$=0, the real value of this current is basic factor of determinacy for protection trip current and a basic limiter for protections sensitivity.

## II. Estimation of required protections sensitivity

Let's find an estimation of required protections sensitivity. The hardest task for the differential protection is opening of so called incomplete winding faults, which may occur in the multi-wire transformer windings, when a coil is formed from multiple parallel wires (such design is preferable for high current transformer coils for technology reasons) [1]. Let's discuss transformer's winding made of two parallel wires (Fig 2.a) with common terminals *a* and *b*. Any insulation damage will cause short circuiting between windings of different parallel branches (points *c* and *d*) and, in common case, between different winding (at last one winding shift will occur). Faults current is limited by resistance of two contour's *cad* and *cbd* (see Fig 2.b) formed by parallel winded wires and may be estimated




a) b)

Fig. 2. Transformer's winding formed by two parallel wires

by the method proposed by L. Leites considering the short-circuited part of common winding as a separate winding [3]. Damaged leg of transformer may be represented by schematic shown on Fig. 3. To simplify equations let's consider, that before the fault transformer didn't carry any load. Two opposite EDF $E_K$ and $E_K'$ are inserted between points of fault c and d both equal to multiplication of single wind voltage $U_w$ by number of faulted winds $W_k$, power network is represented by the EDF $E_n$ behind resistance $Z_N$. Let's use superposition method [4] representing real regime as combination of two partial regimes, in our case prefault and fault. Schematic, representing the fault regime is shown on the Fig. 4.

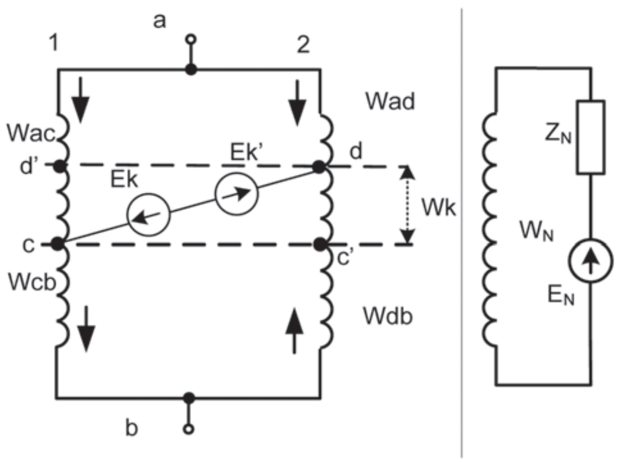



Fig. 3. Equivalent schematic of one transformer's leg

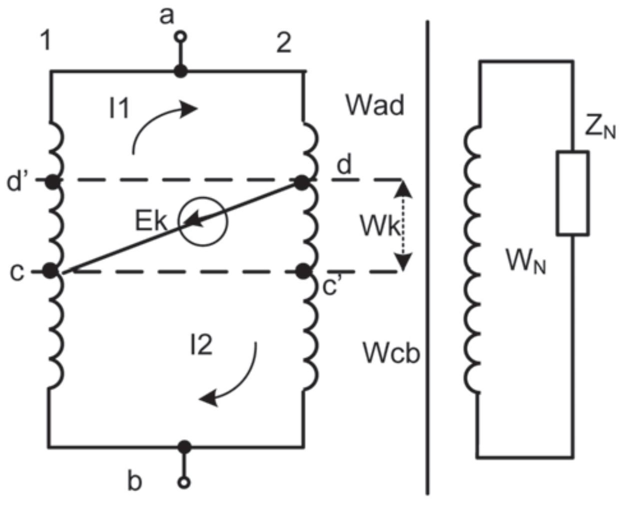
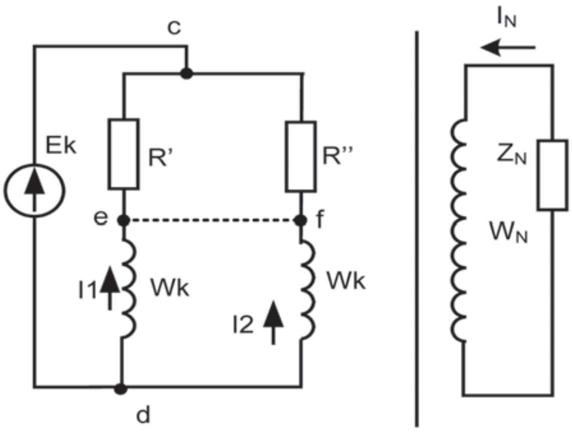



Fig. 4. Fault regime of transformers coil




a) b)

Fig. 5. Simplified schematics of fault regime

Should be noted, that winding's parts *вс* and *вс′*, as well as *ad* and *ad′* are *bifilar* and may be represented by only active resistances and it is possible to simplify Fig. 4 schematics coming to Fig.5. Where

$$R' = 2R_{ad}+R_k \quad (1)$$

and

$$R'' = 2R_{ad}+R_k. \quad (2)$$

By separation of active resistance $R_k$ of short-circuited winds $W_k$ and considering voltage $U_{de}$ equal to $U_{df}$ Fig. 5 a may be further simplified to Fig. 5b, where $Z_e$ marks equivalent resistance of network and transformer relative to $W_k$. Let's introduce parameter

$$\alpha = \frac{w_{ad} + \frac{1}{2} w_k}{w_{ad} + w_k + w_{cb}}, \quad (3)$$

with meaning of relative distance from the start point of winding to the point of failure. Thus

$$R' = 2\alpha \cdot R_v \quad (4)$$

and

$$R'' = 2\,(1-\alpha)\,R_v\,, \tag{5}$$

where $R_v$ denotes active resistance of single windings wire. For winding made of m parallel wires

$$R_v = R_{ab}\cdot m,\ R' = 2\alpha\cdot m\cdot R_{ab} \tag{6}$$

and

$$R'' = 2\,(1-\alpha)\cdot m\cdot R_{ab}\,. \tag{7}$$

Current in the place of fault may be found as

$$I_k = \frac{U_k}{Z_e + \dfrac{R'\cdot R''}{R'+R''}} = \frac{U_k}{Z_e + \alpha(1-\alpha)2m\cdot R_{ab}}. \tag{8}$$

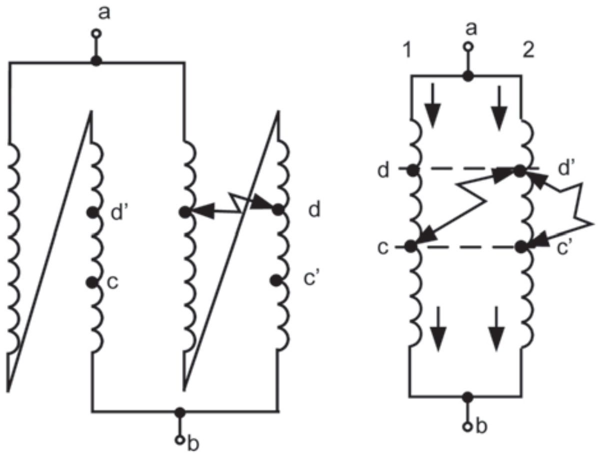
The topmost value of $I_к$ corresponds to

$$\alpha_{\max} = \frac{w_k}{2(w_{ad}+w_k+w_{cb})}, \tag{9}$$

and $(1-\alpha_{max})$, smallest value is $\alpha_{\min} = \frac{1}{2}$, i. e. fault is in the middle of the winding. The fault component $I_N$, which determines operation of differential protection may be found as

$$I_N = \frac{I_k\cdot W_k}{W_N}. \tag{10}$$

According to the works of Alexander Zasypkin [5] calculus of $I_N$ currents for transformers produced by ZTZ factory with rated power from 25 to 1000 MBA yielded $I_N$ in range from 6% to 30% of transformer's nominal current. Meanwhile the fault current is not less than $(\alpha+(1-\alpha))\cdot I_{nom}$ and poses a real danger for transformer. Thus for safe protection against incomplete winding faults protection device must be capable to detect differential current from such a low value as 0.01% from nominal. Must be mentioned, that failing to detect incomplete winding fault timely will lead to inter-coil insulation burn-off and transition from incomplete winding fault to the full coil fault between coil levels or coil – coil fault with typical IN varying from 10% to 150% of nominal current (see Fig. 6).




a) b)

Fig. 6. Transition from incomplete winding fault to the complete winding fault (a) and coil-coil fault (b)

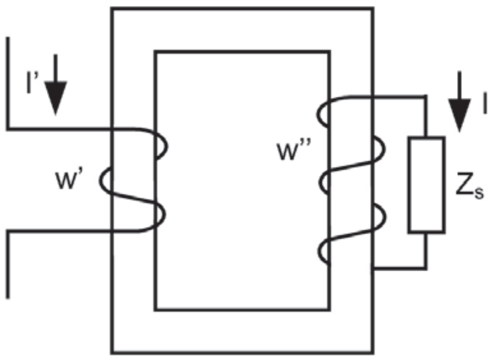
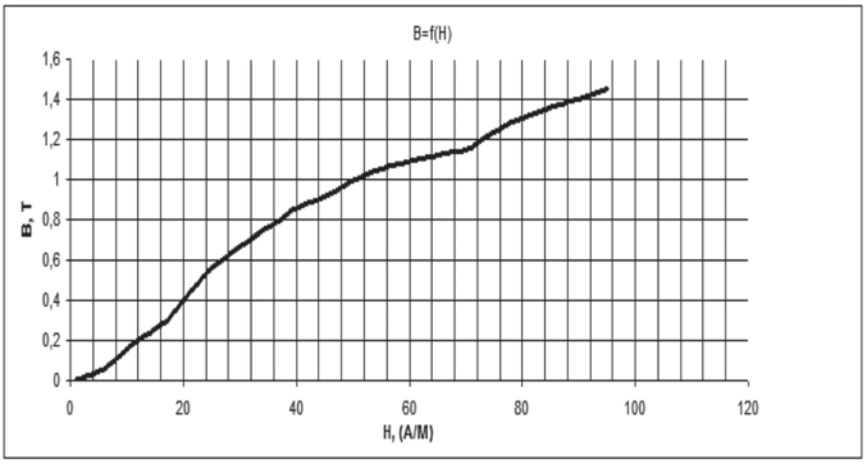



Fig. 7. Current transformer

**III. Current transformer's errors and unbalance current**

Let's discuss a steel core based current transformer loaded with load resistance Zs (see Fig. 7). In case of ideal transformer secondary current is proportional to the primary as $I'' = \frac{I'\cdot w'}{w''}$, but in case of real transformer non-linearity of transformer steel should be taken into consideration.



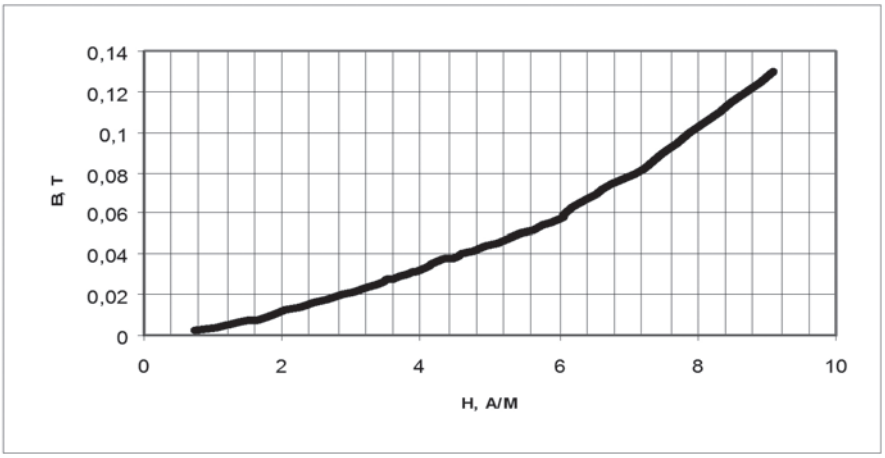



Fig. 8. Magnetizing curve for steel 3411

Chart on Fig. 8 shows typical magnetizing curve (flux density B as function of magnetizing force H) for type 3411 transformer steel. The dependency curve is highly non-linear at beginning (H from 0 to 40–45 A/M corresponding to flux densities below 0.15 Tesla), then curve shows relatively low disturbance until saturation at levels above 1 Tesla. Error characteristics of current transformer with core made from such steel will be close to the ABB produced current transformer's characteristics (see Fig. 9) [6].

Good current transformer design exploits linear areas of core magnetizing curve in the most optimal way. Nowadays two main types of current transformers are produced – for purposes of relay protection and for measurements which are mostly tailored to the needs of commercial metering. Measurement transformers are available with precision class 0.2 and 0.5 and maximal measurable current up to double nominal. Transformer for relay protections needs are produced with error classes 5P and 10P meaning error rate 5 and 10 % correspondently. Measurable current for such type of transformers is up to 40 times of nominal. As a test object transformer from widely used series TPL-10 with nominal current 75A was selected. Design of this transformer incorporates two separate cores – one for protection and another for measurement purposes, molded in hard epoxy enclosure with common primary winding. Factory characteristics of TPL-10 are shown on Fig. 10, curve 1 [9]. As long as difference between measuring and protective core measures in parts of percent direct measuring of currents will not produce trustable results, since error of best ammeters (0.2% from 5A) is compatible with measurable difference. To solve this problem differential schematic was selected (See Fig. 11). Both cores are loaded with equal resistance of 4.5 Ohm which corresponds to allowable by precision current up to 150 A. Sensitive ammeter measures differential current, assuming measurement core as reference we can think this current as some form of protective core errors estimation. Chart on the Fig. 12 shows this differences current in dependence from primary current. As reader can see, protective

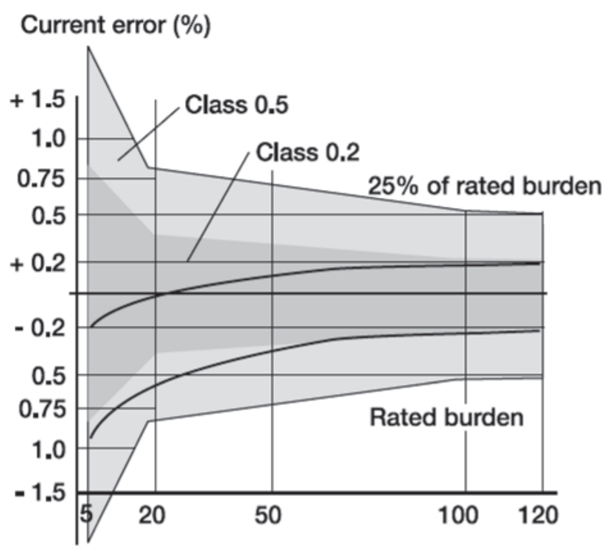
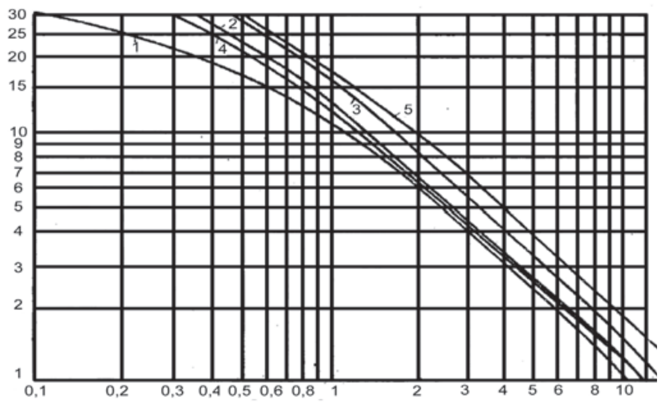



Fig. 9. Error boundaries for current transformers




Secondary load, Ohm
Fig. 10. Factory characteristics of TPL-10 type current transformers

core has quite moderate error in the area of currents under nominal, but even a 2–3% of error seriously limits protection ability to discover incomplete winding fault timely until it transits to the more severe damage. Modern protective devices do incorporate some technics to adjust to limitations caused unbalance current, one of such technics is to use functional restrain characteristics like one shown on Fig. 13, where necessary to trip differential current is changed accordingly to absolute value of load current, but such technics can't solve problem of unsatisfactory protection sensitivity limited by current transformers error.

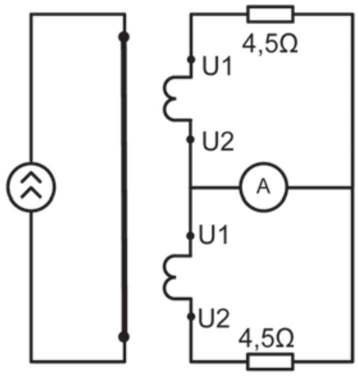



Fig. 11. Schematic, used to measure difference between current transformer's cores

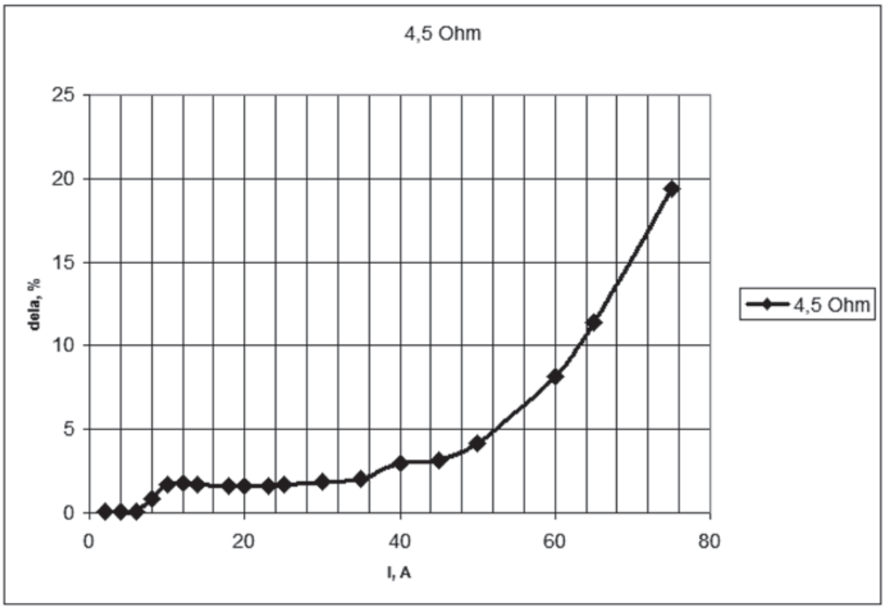



Fig. 12. Difference between secondary currents of measurement and protection cores in dependency of primary current

Significant improvement in sensitivity may be achieved by usage of measuring cores, but such usage is not allowable because such cores are not designed for high current and will saturate putting into jeopardy the whole operation of protective device.

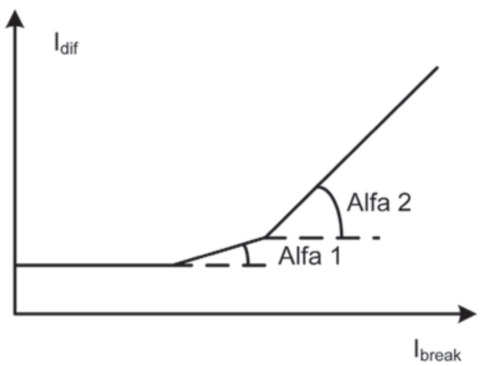



Fig. 13. Restrained operational characteristics of differential protection

Significant improvement in sensitivity may be achieved by usage of measuring cores, but such usage is not allowable because such cores are not designed for high current and will saturate putting into jeopardy the whole operation of protective device.

**IV. Usage of measuring current transformers for error correction**

As mentioned, simple usage of metering cores for protection purposes is not allowable due to unavoidable saturation, such saturation often considered as necessary to protect measuring equipment from damage by overcurrent. But information obtained from measurement current transformers may be used (of coarse when such information is relevant) to correct main current transformer's errors. The microprocessor based device may "teach" itself by forming some error correction table in it's memory on the basis of core outputs compare during normal operation. In case of fault device may operate with much higher sensitivity thus sensing fault on it's early stage.

Let's discuss proposed technics on example of developed by RTU transformers protection device [10].

Simplified structure of device is presented on the Fig. 14. Currents from primary and secondary side of protected power transformer are accepted by the set of intermediate current transformers *1a–1c* for primary side and *1d–1e* for secondary, after that current is transformed into proportional voltage and filtered by two sets of analogue filters *2a–2c* and *2d–2f*. Voltages from A phase from both sides of protected transformer are received thru intermediate transformers *1g* and *1h* and are filtered by analogue filters *2g* and *2h*. All analogue signals are converted to digital form by ADC module *3*, later digital filtration is incorporated. Numerical filters *4a* and *4c* are used to separate orthogonal components of fundamental harmonics from primary and secondary side currents, filters *4в* and *4d* are separating second harmonics components from currents. Maxi-selector *6* is used to determine larger amplitude and if it is above threshold level $m_2max$ comparator *7* produces binary signal $m_2$. Threshold constant is never less, than 0.17 from absolute value of primary current value $|\dot{I}'|$, produced by module *10*. Module *5* in connection with orthogonal components filter 4f produces real value of power transformer transformation ratio, allowing to compensate transformation ratio changes occurring when taps are changed by voltage regulator.

Module *8* perform scaling of currents accordingly to

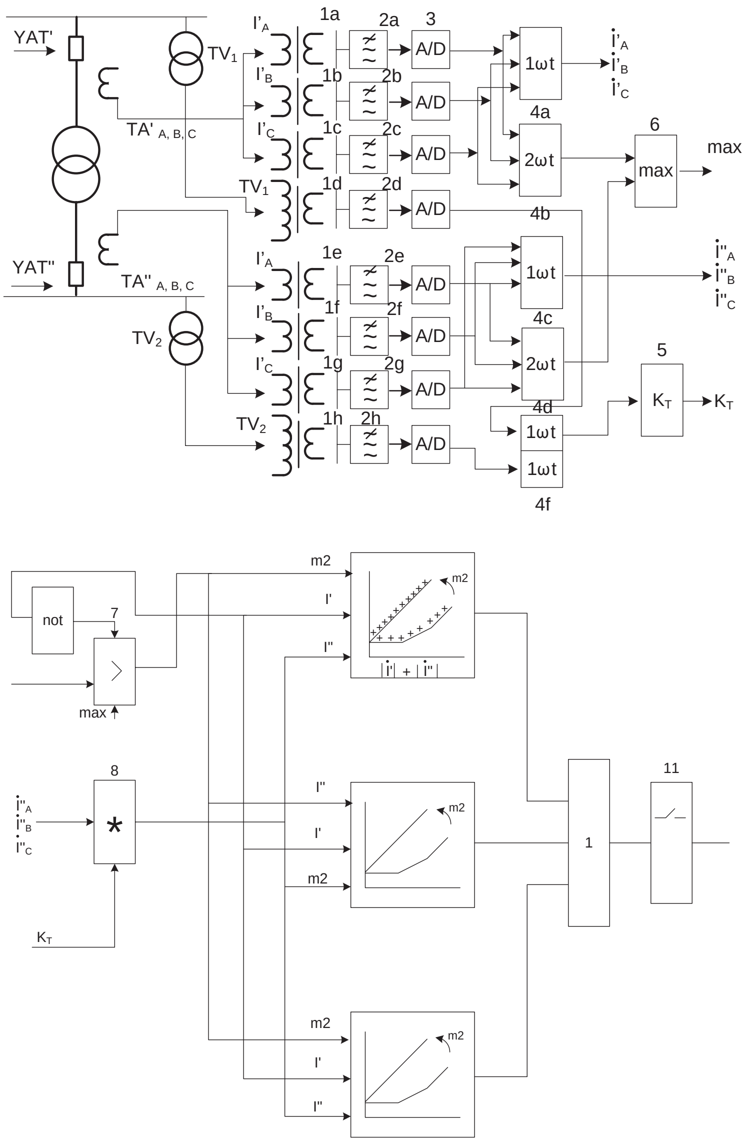



Fig. 14. Simplified structural schematic of protective device

the real transformation ratio found by module *5*. Scaled orthogonal components of currents are processed by the set of three main characteristics modules *9a*, *9b* and *9c*. In absence of *m2* signal each module 9 realizes restrained trip characteristics combined from three lines. Module of vectorial subtraction $|\dot{I}'-\dot{k}t\dot{I}''|$, is used as a tripping value and sum of current absolutes $|\dot{I}'| + |kt\dot{I}''|$ as a restraining. Such design makes possible to easily adopt protective device to unbalance current of particular current transformers set. Special role is assigned to the binary signal $m_2$ Presence of this signal marks the surge of magnetizing current as shown by Alexander Drozdov in his work [7] during magnetizing currents surge second harmonics amplitude is no less, than 0.17 from amplitude of fundamental harmonics. In case of $m_2$ goes high main characteristics module switches to the low sensitivity characteristics in form of straight line. Trip of any of modules *9* sends signal to the output relays module *12* and formation of disconnection impulse for power switches of protected transformer.

Proposed upgrade of this device (see Fig. 13) adds to the protection's structure (of Fig. 12) additional current channels 1 *i*, *j*, *k* and 1 *l*, *m*, *n*, additional analogue filters set 2 *i*, *j*, *k* and 2 *l*, *m*, *n*. Also additional channels are added to the ADC module *3* and fundamental harmonicsc filters 4 *∂* and 4 *h* are also added. Such additions will allow to obtain information about measuring transformers currents in form of orhogonal components *a*, *b*, *c* and *i''a*, *i''b*, *i''c*.

Under the normal condition protective device is "learning", the comparisement module *13* is forming a corrections tabular function $K_c = f(|\dot{I}|)$, this module has two inhibit inputs, one is activated by the $m_2$ signal preventing " bad learning" caused by the magnetizing current surge. The second inhibiting input is activated by the signal from threshold module *14* and stops "learning" if current thru current transformer is above 120% – 150% from the nominal preventing "poisoning" of correction table by data from saturated measurement core. After some time in operation corrections table containing values of correction multiplier $K_C$ as tabular function from current's value is formed in the non- violent memory of device and device may start operate using corrected values of currents $I'$ and $I''$. Should be noted, that correction table contains discrete values of $K_C$ and device needs an interpolation module able to produce value of $K_C$ any intermediate value of current. To ensure minimal trip time of protective device interpolation module must operate in the shortest possible time, that's why a linear interpolation model in the space of $I$, $R_e(\dot{K}_c)$, $J_m(\dot{K}_c)$ was chosen.

## V. Conclusions

Usage of measuring transformers as correction source for main current transformers allows to reduce "appearing" value of unbalance current from 2–3% to 0.2–0.3% from nominal. As result protective device will become much more sensitive towards inter-winding fault, maintaining good robustness level in case of other types of fault.

*Список литературы*


1. *Федосеев А.М.* Релейная защита электроэнергетических систем: Учебное пособие для вузов [Текст] / А.М. Федосеев; 2-е изд., перераб. и доп. – М.: Энергоатомиздат, 1992. – 528 с.
2. *Вольдек А.И.* Электрические машины: Учебник для студентов высш. техн. учебн. заведений [Текст] / А.И. Вольдек. – 3-е изд., перераб. – Л.: Энергия, 1978. – 832 с.
3. *Лейтес Л.В.* Электромагнитные расчеты трансформаторов и реакторов [Текст] / Л.В. Лейтес. – М.: Энергия, 1981 г. – 392 с.

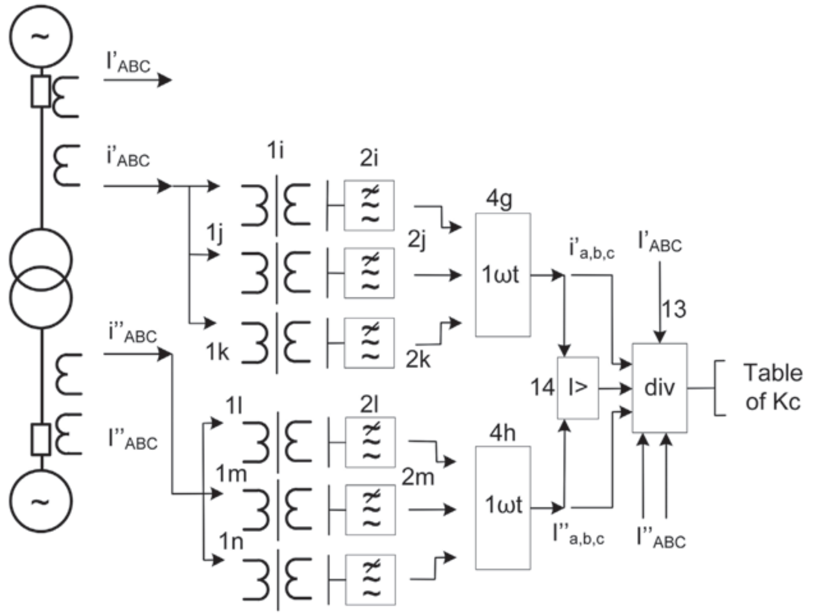




Fig. 15. Proposed additions to upgrade device structure

4. *Атабеков Г.И.* Основы теории цепей [Текст] / Г.И. Атабеков. – М.: Лань, 7-е изд., 2009. – 592 с.

5. *Засыпкин А.С.* Релейная защита трансформаторов [Текст] / А.С. Засыпкин М.: – Энергоатомиздат, 1989. – 240 с.

6. *ABB* Instrument transformer application guide. – ABB, 2011.

7. *Дроздов А.Д.* Электрические цепи с ферромагнитными сердечниками в релейной защите [Текст] / А.Д. Дроздов. – Энергия, 1965. – 240 с.

8. *Привалов И.И.* Аналитическая геометрия [Текст] / И.И. Привалов. – М.: Наука, 1966. – 272 с.

9. *Справочник* по релейной защите [Текст] / Под общ. ред. М.А. Берковича. – М.: – Госэнергоиздат, 1963. – 512 с.

10. *Sauhats A.* Transformatoru aizsardzība un automātika [Text] / A. Sauhats, A. Vasiļjevs, S. Leščenkovs. – Rīga, 2003. – l. 17.

*References*

1. *Fedoseev A.M.* Relejnaja zashhita elektrojenergeticheskih sistem: Uchebnoe posobie dlja vuzov [Tekst] / A.M. Fedoseev. – 2-e izd., pererab. i dop. – M.: Energoatomizdat, 1992. – 528 s.

2. *Vol'dek A.I.* Elektricheskie mashiny: uchebnik dlja studentov vyssh. tehn. uchebn. zavedenij [Tekst] / A.I. Vol'dek. – 3-e izd., pererab. – L.: Jenergija, 1978. – 832 s.

3. *Lejtes L.V.* Elektromagnitnye raschety transformatorov i reaktorov [Tekst] / L.V. Lejtes. – M.: Jenergija, 1981. – 392 s.

4. *Atabekov G.I.* Osnovy teorii cepej [Tekst] / G.I. Atabekov. – M.: Lan', 7-e izd., 2009. – 592 s.

5. *Zasypkin A.S.* Relejnaja zashhita transformatorov [Tekst] / A.S. Zasypkin M.: Energoatomizdat, 1989. – 240 s.

6. *ABB* Instrument transformer application guide. – ABB, 2011.

7. *Drozdov A.D.* Elektricheskie cepi s ferromagnitnymi serdechnikami v relejnoj zashhite [Tekst] / A.D. Drozdov. – Energija, 1965. – 240 s.

8. *Privalov I.I.* Analiticheskaja geometrija [Tekst] / I.I. Privalov. – M.: Nauka, 1966. – 272 s.

9. *Spravochnik* po relejnoj zashhite [Tekst] / Pod obsh. red. M.A. Berkovicha. – M.: Gosjenergoizdat, 1963. – 512 s.

10. *Sauhats A.* Transformatoru aizsardzība un automātika [Text] / A. Sauhats, A. Vasiļjevs, S. Leščenkovs. – Rīga, 2003. – l. 17