# Schutz von Regeltransformatoren

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Transformatoren müssen wegen ihrer hohen Anschaffungs- und Ausfallkosten gegen interne Fehler geschützt werden. Als schneller selektiver Schutz wird der Differentialschutz mit Stromstabilisierung verwendet. Er hat die Aufgabe, beim Auftreten von internen Fehlern den Transformator schnell und selektiv abzuschalten und dadurch eine Ausweitung des Schadens zu verhindern. Dazu ist es nötig, dass der Schutz in der Lage ist, auch solche Fehler festzustellen, die aus den Klemmengrößen nur schwer erkennbar sind. Ein solcher Fehler ist z. B. ein Windungsschluss ohne Erdberührung. Obwohl in der kurzgeschlossenen Windung ein immens hoher Strom fließt, verursacht dieser Fehler in den Leiterströmen des Transformators nur geringfügige Veränderungen. Liegt die aus diesen Veränderungen in den Leiterströmen resultierende Stromdifferenz unterhalb der Selektivitätsgrenze im Auslösediagramm des Differentialschutzes, so bleibt ein Auslösesignal des Schutzes aus. Eine der Fehlertoleranzzonen im Auslösediagramm des Transformatordifferentialschutzes ist bei Regeltransformatoren die Zone, welche die Stromdifferenzen berücksichtigt, die sich aufgrund des Regelprozesses mit einem Stufenschalter bilden. Dadurch ergibt sich ein Bereich, in dem der heutige Schutz nicht anspricht.

Ein weiterer Punkt ist die Vorgehensweise beim Schutz von Regelbänken (zwei miteinander verbundene Transformatoren). Es wird zurzeit jede Beschaltungsart untersucht und ein jeweils eigenes („typbezogenes") Schutzkonzept entwickelt, was jedoch wegen der Anzahl der benötigten Schutzgeräte und Stromwandlergruppen nicht unbedingt kostengünstig ist. Regeltransformatoren bzw. Regelbänke kommen in letzter Zeit angesichts des steigenden Bedarfs an Leistungsflussmanagement zunehmend in unterschiedlichen Bauformen zum Einsatz.

Um diese Nachteile zu überwinden, wird in der vorliegenden Arbeit ein adaptives Verfahren für den Differentialschutz von Regeltransformatoren bzw. Regelbänken vorgestellt. Dieses Verfahren soll zu einer erheblichen Verbesserung der Empfindlichkeit des Schutzes gegenüber den bisher verwendeten Verfahren und zur Vereinfachung der Schutzkonzeption führen. Durch typbezogene komplexe analytische Funktionen, bestehend aus der Windungsanzahl der Wicklungen (einschließlich der Regelwicklungen als Variable) und weiteren Regelgrößen (z. B. Winkel), können Regelbänke und -transformatoren beschrieben werden. Diese Regelgrößen werden in Anlehnung an die Stellung des Stufenschalters bestimmt und online korrigiert. Insofern ist die Fähigkeit des Schutzes zur Erfassung der Stufenschalterstellung und zu einer adaptiven Anpassung der Primär- und Sekundärströme als Funktion dieser Stellung eine Voraussetzung für die Implementierung des Konzepts.

Nach einer Einführung in die Problematik wird eine Reihe von Regeltransformatoren unterschiedlicher Art betrachtet, deren analytische Adaptionsfunktionen hergeleitet und präsentiert werden.

Um diese Adaptionsfunktionen zu überprüfen sowie das gesamte Konzept zu testen, wurde ein einfaches Modell für Regeltransformatoren entwickelt. Die Elemente der aus den Transformatornenndaten errechneten Matrizen werden nach einem mathematischen Verfahren in Relation zur Stufenschalterstellung modifiziert.

Die vorgestellte theoretische Betrachtung wird mit einem Überblick über praktische Realisierungsaspekte abgerundet, die Erfassungsmöglichkeiten der Stufenschalterstellung werden auch angesprochen. Des Weiteren wird ein Realisierungsvorschlag gemacht und die Machbarkeit anhand einer Implementierung auf einem digitalen Signalprozessor überprüft.

Am Schluss werden Simulationsergebnisse präsentiert, dadurch wird Folgendes nachgewiesen: Erstens die Fähigkeit der typbezogenen Adaptionsfunktionen, die Regeltransformatoren zu beschreiben, und zweitens die Fähigkeit des Konzepts, einen empfindlichen selektiven Schutz für den Regeltransformator zu gewährleisten.

In der Arbeit wird auch auf das Thema “Signalaufbereitung im Differentialschutz von Transformatoren” eingegangen, es werden Filteralgorithmen analysiert und miteinander verglichen und Verbesserungsmöglichkeiten vorgeschlagen.

## ▪ Protection of Regulating Transformers

**Dipl.-Ing. Tammam Hayder**

Increased energy demand, deregulation, privatization of the power supply industry and cross-border energy transport often cause utilities to operate and stress transmission systems to, and occasionally beyond, the capabilities they were originally designed for. Maintaining reliable, secure and economical operation of interconnected networks under these conditions requires that transmission operators improve their control and management of network power flows and provide voltage stability. Today, new power electronics applications such as unified power flow controllers (UPFC) are available to control network power flows. Since regulating transformers have proved efficient in controlling the power flows and regulating the voltage, they are more and more widely used.

In this changing environment of energy production, transmission and distribution high demands on the protection equipment are required, concerning sensitivity, security and reliability. Especially the policy of integrating protection functions into the control and monitoring systems challenges protection engineers 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 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 thesis presents an adaptive adjustment concept for differential protection of regulating transformers.

### Protection of regulating transformers - state of the art

Regulating transformers may be of the “in-phase” type or the “phase-shifting” type. The in-phase type provides means for increasing or decreasing the circuit voltage at its location under load without changing the phase angle. The phase-shifting type changes the phase angle and usually also the voltage magnitude under load. A regulating transformer may be used alone in a circuit or in conjunction with a power transformer. Or the regulating-transformer function may be built into a power transformer.

The current approach to the conception of differential protection for regulating transformers is as follows: For power transformers with regulating winding (mostly in-phase type), the percentage slope of the differential relay should be high enough to accommodate the full range of voltage change, as already mentioned 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 [IEEE C37.91, 2000]. Thereby the protection sensibility is significantly impaired.

In the case of a regulating transformer in conjunction with a power transformer, a concept of protection for every arrangement should be developed. The most commonly used circuit for a two-core design, “phase-shifting” type is the symmetrical phase shifting transformer (PST). This configuration consists of an auxiliary unit, whose secondary winding is connected serially into the transmission path and a main unit which is equipped with a fully tapped low-voltage winding. This PST is protected by dual, redundant protection systems including a percentage-differential relay with harmonic restraint and an individual current transformer for each system. So far, several tests had to be carried out to determine the current transformer connection and ratio requirements and to adjust the relays [IEEE C57.135, 2001].

### 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 design consisting of two transformers) on the regulating transformer in relation to the tap changer position enables the attainment of two goals: the improvement of the protection sensitivity and the simplification of the protection conception. 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.

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).

### Derivation of analytical adaptive functions

The well-known equivalent circuit (positive-sequence) of 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 the case of a single-core regulating transformer, the internal connection of windings should be analysed. In the case of a double-core regulating arrangement, one has to distinguish between two types according to the connection of the auxiliary unit: If the winding on the load side of the auxiliary unit is galvanically separated from the main unit, the complex ratio of turns can be calculated by multiplying the ratio of turns of both units with each other. In the other type, a winding of the auxiliary unit is connected into the transmission path and to the main unit. 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. In this thesis, a catalogue containing adjustment functions for several common designs of regulating transformers has been compiled.

### Modelling of regulating transformers

Two models have been used in this thesis:

a) A geometrical model whose elements are derived from the geometrical arrangement of the transformer. 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.

b) 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 $p$:

This model is successfully implemented in the simulation program EMTP-ATP as a routine named BCTRAN. In order to model internal faults, new elements can be added which are computed using mathematical equations modelling the faulted transformer. A model for a regulating transformer can be created in the following two steps:

1. The matrices [R] and [L] modelling a regulating transformer with nominal position of the tap changer (position 0) are calculated using the BCTRAN routine of ATP.
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 period of changing between the two positions can be modelled by means of the switching sequence of the tap changer.

**Conception of adaptive differential protection for regulating transformers**

The concept uses the well-known tow protection methods: restricted earth fault protection and biased differential protection. In applying the differential protection a variety of considerations must be taken into account. After the elimination of zero sequence currents the ratio and the phase of signals on either side of the windings must be corrected. In place of constant correction factors the concept arranges software blocks for correction (ratio and phase) with an open input interface for adjustment functions depending on the type of the regulating transformers. Such an open platform allows an easy implementation of new functions. Prerequisite for the adaptive system is the recording of the position indicating signal. There are several possibilities for receiving the tap position. One possible way is via a direct connection with 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.

## Simulation results

A lot of simulations have been carried out with the models presented above. Five different types of transformers have been simulated. Their rated data are provided by the transformer manufacturers. First, the accuracy of the derived adjustment functions have been checked. In a further step the stability of the restricted earth fault protection and the biased differential protection in case of external faults has been investigated. Furthermore, different short circuits in windings with the earth and turn-to-turn short circuits in windings have been simulated. The following conclusions can be drawn:

- When checking out the adjustment functions, there remained a small difference current. Its amount depends on the fact on which side of the transformer the tap changer is installed. If the tap changer is installed on the primary winding then the residual difference current is bigger (about 0.06 p.u. of the rated current) because of a magnetising current; otherwise the residual current is less than 0.005 p.u. of the rated current.
- Both protection functions are stable in case of external faults. The position of the tap changer does not have a significant impact.
- Both the restricted earth fault protection and the biased differential protection have responded to different short circuits with earth and turn-to-turn short circuits in windings of the five simulated types. The increase of the earth fault protection indicators and of the fault characteristics in the relay diagram depends on several parameters: winding, place of fault, position of tap changer and fault resistance.

  Simulations of turn-turn short circuits 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-turn short circuits.

## Investigation of technical feasibility

In this investigation a Texas Instruments DSP 225 MHz has been used on the evaluation board. The algorithm of the differential protection of the transformer has been implemented on the DSP with the C-code. Simulated current signals have been sampled with a Matlab routine and transported to the evaluation board through an USB interface. The implementation of adaption functions as components which can be downloaded after the main program was successful. The execution time of currents adjustment by changing the changer position amounted to less than 0.1 ms.

## Signal processing in digital protection relays for transformers

Input signals to differential protective relays on transformers are not pure sinusoidal signals; they are contaminated with noise which must be eliminated in order to obtain signal quantities of interest. A filter must save the fundamental frequency components and up to the fifth harmonic components. There are two types of digital filtering algorithms for protective relays: a) algorithms with a data window and b) algorithms based on estimation of the signal parameters. The algorithms of the first type are mostly finite impulse response filters (FIR) whose output signal is related to the input signal by a convolution sum. The most common FIR filters in digital protective relays for transformers are one-cycle Fourier-filters and one-cycle Walsh- filters. The benefit of the Walsh filter lies in the simplicity of the calculating, but in terms of accuracy and speed the one-cycle Fourier filter was found to be a good compromise for a digital implementation of the differential relay for power transformers. Algorithms of type b) are more complex than those of type a). Two filters of this latter family have been found suitable for the digital protection of transformers, the recursive least square filter (RLS) and the Kalman filter. In this thesis the Kalman filter has been used as a test case for recursive estimator filters.

The current attitude towards the use of Kalman filters in comparison to Fourier filters is that an application of the filter is justified only when the covariance of white noise cannot be assumed constant. Tests have shown the behaviour of an eleven-state Kalman filter and a one-cycle Fourier filter in the presence of new types of noise which could appear in a modern power system. In this thesis a test signal comprising several sinusoidal components and faults in a transformer simulated with EMTP-ATP have been considered.

- In case of a signal affected by white noise (constant covariance): Both filters appear to be capable of eliminating the noise, but a little improvement is obtained when the Kalman filter is used. Above all, the estimated fundamental frequency component has less standard deviation.
- Signal affected by decayed DC-component: In contrast to the Fourier filter, the Kalman filter is capable of rejecting the DC component.
- Signal affected by nonharmonic sinusoids: A quality improvement is clearly obtained by employing the Kalman filter.

In two cases the necessity for an improvement of the Kalman filter has been identified and solutions have been developed:

- In case of variations in the system frequency of more than ± 50 mHz from its normal value, the Kalman filter becomes instable: One possibility is the use of an extended Kalman filter, which is simply an extension of the linear Kalman-filter theory to non-linear systems. The eleven-state filter must be extended to a twelve-state system in which the system frequency is considered as a system variable [Kim, 2005] and the relationships of the observed current signals become non-linear. The quality of the output signals obtained by using the recommended adopted Kalman filter is clearly an improvement, not only in comparison to the linear Kalman filter, but also in comparison to the Fourier filter.

- A significant problem in using the Kalman Filter is the long rise time after the occurrence of a fault in the transformer. The reason is the covariance matrix *P* which becomes smaller after a few iterations. To avoid this, the matrix *P* must be reset to a high value when a fault occurs. A fault indicator is a jump in the difference current. This jump can be detected with a Hinkley detector [P-Mathonna, 1984].

In view of additional quality in power systems, a Kalman filter with the improvements recommended above could be a better alternative to a Fourier filter in differential protection relays for transformers.

## Conclusions

A significant improvement of protection sensitivity can be achieved with an adaptive current balance of primary and secondary currents on the regulating transformer in relation to the tap changer position. 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. The adaptive functions can be verified by means of the developed models.

In this thesis, the Kalman filter has been extended by using non-linear system relationships, in order to improve the filter stability in case of frequency variations. A Hinkley detector has been integrated which detects the jump of the difference current, so that the covariance matrix *P* can be reset to a high value when a fault occurs. Thereby the rise time of the filter upon the occurrence of a fault in the transformer is significantly reduced.