Gerhard Ziegler

Numerical Differential Protection

Principles and Applications

SIEMENS

Second Edition

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by Gerhard Ziegler

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Foreword
to the First Edition

Differential protection provides absolute selectivity and fast operation, and is applied in numerous variations for the protection of electrical machines, transformers, busbars and feeders at all voltage levels.

Substantial progress has been made with numerical technology which has made this measuring principle even more attractive for the user, such as for example the integrated CT ratio adaptation and the large degree of CT saturation tolerance. The application of digital data exchange over interference free fiber optic cables has simplified the protection of cables and overhead lines in urban and industrial networks substantially, while also improving the security. Digital communication networks are finding increasing application for the transfer of protection data in overhead line networks. Thereby, the differential protection may also be applied on longer lines well exceeding 100 km as well as complex system configurations with multiple line terminals.

The book at hand initially conveys the basic principles of differential protection with analogy and digital technology. Special note will be taken of current transformers, data transfer and digital communication. Subsequently the various types of differential protection and the practical applications will be covered, using the Siemens SIPROTEC product range. In principle, the explanations however also apply to the devices of other manufacturers. Practical examples are calculated for illustration purposes.

This book is aimed at students and young engineers, who require an introduction to the topic of differential protection. However, users with practical experience, seeking an entry to digital technology of differential protection may also find this book to be a useful addition to their library. Furthermore, it may also be used as a reference for special application problems.

Nuremberg, March 2005 Gerhard Ziegler

Foreword
to the Second Edition

Differential protection is a fast and selective method of protection against short-circuits. It is applied in many variants for electrical machines, transformers, busbars, and electric lines.

Initially this book covers the theory and fundamentals of analog and digital differential protection. Current transformers are treated in detail including transient behaviour, impact on protection performance, and practical dimensioning. An extended chapter is dedicated to signal transmission for line protection in particular to modern digital communication and GPS timing.

The emphasis is then placed on the different variants of differential protection and their practical application illustrated by concrete examples. This is completed by recommendations for commissioning, testing and maintenance.

Finally the design and management of modern differential protection is explained by means of the latest Siemens SIPROTEC relay series.

A textbook and standard work in one, this book covers all topics which have to be paid attention to for planning, designing, configuring and applying differential protection systems. The book is aimed at students and engineers who wish to familiarise themselves with the subject of differential power protection, as well as the experienced user, entering the area of digital differential protection. Furthermore it serves as a reference guide for solving application problems.

For this second edition all contents have been revised, extended and updated to the latest state of protective relaying.

Nuremberg, August 2011 Gerhard Ziegler

Contents

1 Introduction

Differential protection was already applied towards the end of the 19^{th} century, and was one of the first protection systems ever used.

Faults are detected by comparison of the currents flowing into and out of the protected plant item. As a result of the fast tripping with absolute selectivity it is suited as main protection of all important items of plant, i.e. generators, transformers, busbars as well as cables and overhead lines.

The protected zone is clearly defined by the positioning of the current transformers. The back-up protection function for external faults must therefore always be implemented with an additional time graded protection (over-current or distance protection).[1]

1.1 Protection principle

Differential protection calculates the sum of all currents flowing into and out of the protected object. Apart from magnetising currents and capacitive charging currents, this current sum must always be equal to zero (Kirchhoff's current law) if the protected object is un-faulted. Internal faults are therefore detected by the appearance of a differential current. For security against mal-operation due to CT transformation errors, the pick-up threshold of the protection is increased in proportion to the total current flow (stabilising or restraint current). Thereby, the protection sensitivity is automatically matched to the prevailing short circuit conditions.

Implementation of differential protection is simpler in the case of protected objects that are not geographically spread out (generators, transformers, busbars), where the current transformers are situated close together. In this case, the current transformers may be connected to the protection device directly via control cables.

In the case of HV cables and overhead lines, the measured currents must be transmitted over large distances to the corresponding opposite line end, for the comparison to take place. Utilising pilot wire connections (special protection cables), distances of approximately 25 km may be spanned. With modern relays, using digital communication via fiber optic cables, differential protection may also be implemented on long overhead lines of over 100 km.

[1] In most cases simple back-up protection is integrated in numerical devices, so that a separate device is not necessary for applications in distribution networks. A back-up protection for faults on the protected object must always be provided by a separate device in order to achieve hardware redundancy. This is particularly true for the transmission network.

High impedance differential protection is a particular variant of differential protection. It is adapted to the non-linear transformation characteristic of current transformers and achieves stability during CT saturation by means of a high series resistance at the differential relay.

Due to its simplicity, high impedance differential protection is relatively common in Anglo-Saxon influenced countries. It is suitable for protection of galvanically connected units such as busbars, generators, motors, compensating reactors and auto- transformers, but not for normal transformers with separate windings. A disadvantage lies in the fact that all current transformers must be identical.

1.2 Numerical differential protection

Towards the end of the 1980's, the numerical technology was introduced to protection applications. [1-1]

A number of general advantages are:

- Modern relays are multi-functional and, apart from the protection functions, capable of executing additional tasks such as operational measurement and disturbance recording.
- Due to integrated self-monitoring, event driven maintenance, instead of costly preventive routine maintenance may be applied.
- Devices may be operated locally and from remote with a PC via serial interface.
- All important measured values are indicated with the integrated measuring function. External measuring instruments during commissioning and testing are therefore not normally required.

Particular advantages are also obtained specifically for differential protection:

- Digital measuring techniques have substantially improved filters for the inrush stabilisation and intelligent measuring algorithms provide additional stabilisation during CT saturation.
- With conventional devices, additional matching transformers were required to adapt different CT ratios and transformer vector groups. Numerical relays implement this adaptation internally by computation.
- Phase segregated measurement can be implemented with moderate effort and therefore achieves the same pick-up sensitivity for all fault types as well as reliable pick-up in the event of multiple faults.
- Communication links are also covered by the continuous self-monitoring.
- Decentralised construction of the busbar protection with communication via fiber optic cables and PC-based configuration achieved a significant reduction in complexity.

2 Definitions

The following terms are used in this document.

If they correspond to the definitions of the International Electrotechnical Vocabulary Chapter 448: Power System Protection (IEC 60050-448), then the corresponding reference number is given:

Protection (in USA: Relaying)
The provisions for detecting faults or other abnormal conditions in a power system, for enabling fault clearance, for terminating abnormal conditions, and for initiating signals or indications. [448-11-01]

Protection relay (in USA: protective relay)
Measuring relay that, either solely, or in combination with other relays, is a constituent of a protection equipment. [448-11-02]

Protection equipment (in USA relay system)
An equipment incorporating one or more protection relays and, if necessary, logic elements intended to perform one or more specified protection functions. [448-11-03]

Protection system
An arrangement of one or more protection equipments, and other devices intended to perform one or more specified protection functions. [448-11-04]

NOTE 1: A protection system includes one or more protection equipments, instrument transformer(s), wiring, tripping circuit(s) and, where provided, communication system(s). Depending on the principle(s) of the protection system, it may include one end or all ends of the protected section and, possibly, automatic reclosing equipment.

NOTE 2: The circuit breaker(s) are excluded.

Protected section
That part of the system network, or circuit within a network, to which specified protection has been applied. [448-11-05]

Digital (Numerical) protection (relay)
Fully digital relays utilising microprocessor technology with analog to digital conversion of the measured values (current and voltage) and subsequent numerical processing by computer programs. Earlier the designation “computer relay” has been used.

In Europe, it has sometimes been distinguished between “digital” and “numerical” relays. The term “digital” has been used with the earlier relay generation using micro-processors instead of discrete static measuring and logic circuits. The term “numerical” has been reserved for the modern computer type relays. [A-15]

In the US, the term “digital” has always been used in this meaning of “numerical” protection.

Nowadays, both terms are used in parallel.

Unit protection

A protection whose operation and section selectivity are dependent on the comparison of electrical quantities at each end of the protected section.

NOTE: In the USA, the term “unit protection” designates the protection provided for an electrical generator.

Longitudinal differential protection (generally designated as differential protection)

Protection, the operation and selectivity of which depends on the comparison of the magnitude or the phase and magnitude of the currents at the ends of the protected section. [448-14-16]

Transverse differential protection

Protection applied to parallel connected circuits and in which operation depends on unbalanced distribution of currents between them. [448-14-17]

Biased (stabilised) differential protection (in USA: percentage differential relay)

Differential protection, with a pick-up threshold that increases proportional to the increasing through current (sum of the absolute values of the currents from all the line ends).

Operating (tripping) current (of a differential relay)

Current difference that tends to initiate operation (in general tripping).

Restraint (stabilising) current (of a differential relay)

Current proportional to through current that tends to inhibit differential relay operation.

Variable slope characteristic

Operating characteristic of a differential relay with an increasing slope (percentage) dependent on increasing restraint current.

High impedance differential protection

Current differential protection using a current differential relay whose impedance is high compared with the impedance of the secondary circuit of a saturated CT. [448-14-22]

Low impedance differential protection (generally designated differential protection)

Current differential protection using a current differential relay whose impedance is not high compared with the impedance of the secondary of a saturated CT. [448-14-23]

Phase comparison protection

Protection whose operation and selectivity depends on the comparison of the phase of the currents at each end of the protected section. [448-14-18]

Discriminative zone

The selective part of a multi-zone busbar protection, generally supervising current flow into and out of a single section of busbar. [448-14-24]

Check zone

The non-selective part of a multi-zone busbar protection, generally supervising current flow at the complete station. [448-14-25]

NOTE: Tripping of the busbar protection is conditional on the operation of both the check and a discriminating zone.

Restricted earth fault protection (in USA: ground differential protection)

Protection, in which the residual current from a set of three-phase current transformers is balanced against the residual output from a similar set of current transformers located on the earthing connection, if any, of a neutral point. [448-14-29]

NOTE: This term is also used when the neutral of the protected plant is unearthed i.e. neither a second set of three-phase current transformers nor a CT in the neutral connection is needed to restrict the protected section.

Partial Differential Protection

Protection circuit which is often used in regions with Anglo-Saxon history. It is applied to busbars with bus section coupler and parallel in-feed. Current relays are connected to measure the differential current between the in-feed and the section coupler. One time grading step can be saved in the grading of the overcurrent relays. (see section 3.5)

Pilot wire protection

Protection associated with telecommunication using metallic wires. [448-15-04]

Short circuit loop (fault loop)

The circuit path in the energy system to and from the fault location as seen from the source.

Short circuit (fault) impedance

The impedance at the point of fault between the faulted phase conductor and earth (ground) or between the faulted phase conductors themselves. [448-14-11]

Source impedance

For a particular fault location, the impedance in the equivalent circuit of the fault current path between the point where the voltage is applied to the measuring relay and the EMF in the equivalent circuit producing the fault current in the same path. [448-14-13]

Fault resistance

The resistance at the point of fault between the faulted phase conductor and earth (ground) or between the faulted phase conductors themselves.

Phasor

In this book, the phasor representation is used for electrical signals:

$$\underline{A} = A \cdot e^{j\varphi} = A \cdot (\cos\varphi + j\sin\varphi) = B + jC$$

$$A = \sqrt{B^2 + C^2}$$

Thereby A represents the *RMS* value of current, voltage or power and φ is the phase angle referenced to the time $t = 0$.

The representation is extended for impedances which are not time dependent.

Vector

This designation is often used instead of phasor (in this case, A may also represent the peak value of the electrical AC signal)

α- and β-plane

The operating characteristic of the differential protection may be visualised in the complex plane (polar characteristic) using the current ratios $\underline{\alpha} = \underline{I}_A / \underline{I}_B$ and $\underline{\beta} = \underline{I}_B / \underline{I}_A$. In this context $\underline{I}_A$ is the current at the local terminal and $\underline{I}_B$ the current at the remote terminal. This is primarily applied to feeder protection.

Polar Characteristic

Representation of the operating characteristic of the differential protection in terms of the ratio of the compared currents. (Refer to α- and β-plane)

Current sign convention for differential protection

In this book, currents that are flowing into the protected object will be designated as positive. Therefore the vectorial current sum for internal faults is $\underline{I}_1 + \underline{I}_2 + \ldots$ $\ldots + \underline{I}_n$.

According to this convention the vectorial current sum corresponds to the differential current.

Polarity of current transformers

If no indication to the contrary exists, the following polarity rules for transformers and instrument transformers apply in this book (Refer to section 5.5, Figure 5.10).

Primary winding, secondary winding and possible further windings are wound in the same direction.

Voltages on the windings have the same polarity, i.e. they are in phase.

The currents have opposite polarity, i.e. they flow through the windings in opposite directions ($i_1 \cdot w_1 + i_2 \cdot w_2 + ... + i_n \cdot w_n = 0$).

Conductor/phase designation
In this book the standardised IEC designation L1, L2, L3 is generally used. In equations or diagrams, where clarity demands, the designations a, b, c are alternatively used.

Earth current (in USA: ground current)
Current (I_E) flowing from a neutral point to earth and current flowing through earth.

Zero sequence current
According to the computation with symmetrical components, the zero sequence current is one third of the sum of the phase currents, i.e. one third of the neutral current $I_0 = 1/3 \cdot I_N$. In three-phase HV systems (no neutral conductor), the neutral current corresponds to the earth current, therefore also $I_0 = 1/3 \cdot I_E$.

Residual current
Current (I_N) equal to the vector sum of the phase currents. [448-14-11]

Through fault current

A current due to a power system fault external to that part of the section protected by the given protection and which flows through the protected section [448-14-13]

3 Mode of Operation

The principle of differential protection is initially described in this section. Subsequently different protection principles and measuring techniques are covered in the further chapters. Current transformer response and signal transmission are then covered in detail as the reliability of the complete protection system is reliant thereon. Based on this, the application specific protection systems for generators, motors, transformers, feeders and busbars are described. In each case, application related questions are discussed.

3.1 Introduction

The differential protection is 100% selective and therefore only responds to faults within its protected zone. The boundary of the protected zone is uniquely defined by the location of the current transformers. Time grading with other protection systems is therefore not required, allowing for tripping without additional delay. Differential protection is therefore suited as fast main protection for all important plant items.

Due to the simple current comparison, the principle of differential protection is very straight forward. Stability in the event of external faults however demands an adequate dimension and matching of the current transformers. To ensure acceptable cost for the current transformers, the differential protection must however tolerate a fair degree of current transformer saturation. Determining the degree of saturation and providing adequate stabilisation against the false differential currents arising, are therefore important additional tasks of this measuring principle.

Generators, motors and transformers are often protected by differential protection, as the high sensitivity and fast operation is ideally suited to minimise damage. On feeders the differential protection is mainly used to protect cables, particularly on short distances where distance protection cannot be readily applied. On applications over longer distances of up to 25 km, the interference on the pilot wires by the earth fault current must be considered. Additional screening and isolation may be necessary. Numerical differential protection with serial data transfer via fiber optic communication is not affected in this manner, and distances of more than 100 km may be bridged. With the introduction of digital data networks by the utilities, serial data connections between all important substations have become available. This provides a further application opportunity for differential protection. The interfaces, protocols and procedures for the information exchange between protection device and data transfer system must be exactly matched and must correspond with the appropriate standards (open communication). When transferring data, using multiplexing, together with other services, the time response of the data channel must also be considered, in particular in the case of communication path switching. Furthermore, the availability of the communication system must generally be checked. The differential protection with digital communication improves the protection quality in the transmission system, as the measurement is strictly per phase allowing phase selective tripping with subsequent AR. This also applies to difficult fault constellations, such as for example multiple faults on double circuit lines which cannot be cleared phase selectively by the distance protection. The differential protection is ideally suited for the increasing number of three terminal lines.

The prime objective of busbar differential protection is fast, zone selective clearance of busbar faults to prevent large system outages and to ensure system stability. Mal-operation must be avoided at all cost as these could result in extensive supply interruption.

Extremely fast operating times of less than one cycle along with a high degree of stability against current transformer saturation have been state of the art for quite some time. Security against mal-operation due to hardware failure is achieved by AND combination of several independent tripping criteria.

In large substations the busbar configuration is often complex with numerous busbar sections as well as several bus-sectionalisers and bus couplers. This demands numerous measuring circuits and a complex isolator replica for the co-ordination of the bus section specific current differential protection. The switching of analog measuring circuits, that is necessary in conventional systems, is not required in the numerical busbar protection, where this is done by logic allocation of signals via an isolator replica within the software. A de-centralised configuration with bay units and communication via fiber optic reduces the previously very comprehensive substation cabling to a minimum.

The statements made so far refer to the “normal” current differential protection based on low impedance measuring technique.[1]

Apart from this the high impedance differential protection also exists. In this case, the measuring relay in the differential path has high impedance in comparison with the secondary impedance of a saturated current transformer. Stability is thereby automatically achieved in the event of through-fault currents with current transformer saturation. The current of the non-saturated CT in this case will not flow via the measuring relay but rather through the saturated CT which acts as a low impedance shunt.

This technique is frequently used outside continental Europe to protect galvanically connected circuits, primarily generators, motors and busbars as well as restricted earth fault protection on transformers. This method requires special current transformer cores (Class PX according to IEC 60044-1, formerly Class X to BS 3938) having the same ratio.

[1] In numerical relays the differential circuit only exists within the software. The differential protection however corresponds to the low impedance measuring technique.

During internal faults, when all CT's are feeding current to the high impedance relay, large voltage peaks in the CT secondary circuits arise. These must be restricted by means of a varistor. This measuring technique is not suited for the protection of multiple busbars, as the current transformer secondary circuits must be switched over. Some users apply this technique to dual busbar systems using the isolator auxiliary contacts for direct switching over of CT secondary circuits. The high impedance differential protection is however primarily used when isolator replicas are not required e.g. for one-and-a-half circuit breaker applications.

3.2 Basic principles

The basic principles, which have been known for decades, are still applicable and independent of the specific device technology. [3-2]

The differential protection compares the measured values with regard to magnitude and phase. This is possible by direct comparison of instantaneous values or by vector (phasor) comparison. In each case the measurement is based on Kirchhoff's laws which state that the geometric (vector) sum of the currents entering or leaving a node must add up to 0 at any point in time. The convention used in this context states that the currents flowing into the protected zone are positive, while the currents leaving the protected zone are negative.

3.2.1 Current differential protection

This is the simplest and most frequently applied form of differential protection. The measuring principle is shown in Figure 3.1. The current transformers at the extremities of the differential protection zone are connected in series on the secondary side so that the currents circulate through the current transformers during an external fault (Figure 3.1a) and no current flows through the differential measuring branch where the differential relay is situated. In the event of an internal fault (Figure 3.1b) the fault currents flow towards the fault location so that the secondary currents add up and flow via the differential branch. The differential relay picks up and initiates tripping.

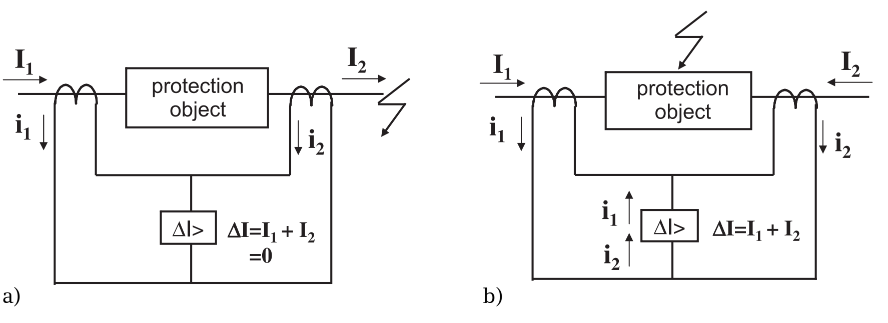
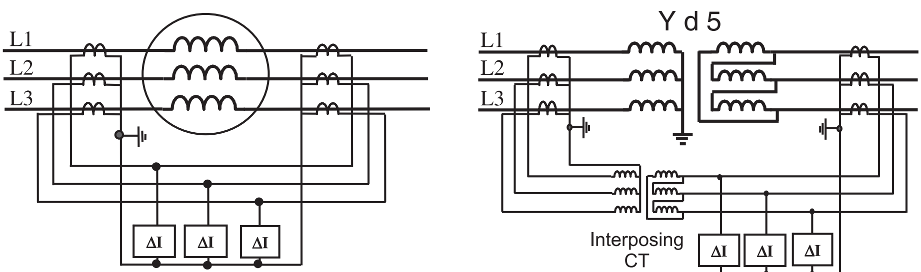


Figure 3.1 Measuring principle: External fault or load (a), Internal fault (b)

This simple circuit principle (non-biased current differential protection) may be used on all non-distributed protection objects where the current transformers are located in close physical proximity to each other.

The simplest arrangement results with generators or motors (Figure 3.2a), in particular when the current transformers have the same ratio.

The transformer protection requires interposing current transformers for the vector group and ratio correction of the currents used for the comparison (Figure 3.2b).



a) Generator/Motor b) Transformer

Figure 3.2 Differential protection, three phase basic principle

For busbar protection, the currents from a number of feeders must be summated (Figure 3.3). In the case of load and external faults, the vector sum of the feeder currents is equal zero, so that no differential current flows in the relay. During internal faults, the currents however add up to a large differential current.

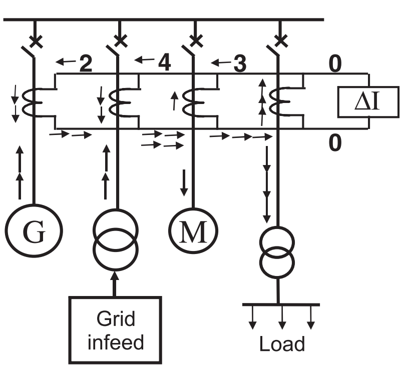


Figure 3.3 Busbar protection
(load or through fault condition)

For feeder differential protection, the current transformers at the two terminals of the protected object are far apart. In this case, the connection circuit according to Figure 3.4 is used (three core pilot differential protection). Three pilot wire cores are required for the connection between the two stations, which typically are provided as a “twisted triplet” via a communication cable. Current differential relays

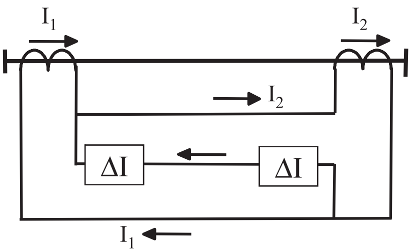


Figure 3.4
Line differential protection

are connected at both terminals in the differential core which, in the event of an internal fault, trip the circuit breakers in their respective stations. No further trip command communication between the stations is therefore required. In practice, the current transformer secondary currents (1 or 5 A) are converted to 100 mA by interposing current transformers to reduce the burden of the pilot wire cores. The current differential protection may be used over distances of approximately 10 km due to this reduced current transformer burden. Over short distances of 1 to 2 km, control cables (2 kV isolation) may be used.

When the pilot wire cables are in close proximity to power cables or overhead lines, adequate screening against fault currents via earth is required. On longer distances, high voltages of several kV may be induced in the pilot wires. This affects the isolation of the pilot wires against earth, and requires special pilot wire cables with higher insulation (e.g. 8 kV) and may necessitate barrier transformers to prevent the high voltages from reaching the protection relays (refer to section 6.1.1).

To further reduce the number of pilot wire cores required, the interposing current transformers are also summation transformers, whereby the phase currents are combined to a single (summated) composite current.

Current comparison with digital measured value transmission

The principle of current differential protection was so far described, based on the classic mode of 50/60 Hz analog measured value transmission via pilot wire communication. With numerical protection, the application of serial data transfer is increasingly used.

Thereby the measured values are digitally coded and transmitted via a dedicated fiber optic core or via a digital data communication system. Despite the numerical measured value transmission and processing, the basic principle remains the same.

The digital feeder differential protection 7SD52 and the decentralised numerical busbar protection 7SS52 are examples for this.

The comparison protection circuits described above are also designated as “longitudinal differential protection”. For the sake of completeness the transverse differential protection that was used previously, must also be mentioned. It compared the current at the terminals of two or more circuits connected in parallel. This type of protection is hardly ever used anymore with lines in particular because the circuits must be connected in parallel for this type of protection and may not be operated independently. Only with generators that have parallel (split) windings in each phase brought out to separate terminals, the transverse differential protection is still used against turn faults.

3.2.2 Biased (stabilized) differential protection

So far, for the sake of simplicity, a fixed pick-up threshold was assumed for the relay measuring the current in the differential circuit. In practice however, a false differential current resulting from transformation errors of the current transformers must be considered.

In the linear range of the current transformers, this error is proportional to the through current. In the event of large fault currents, CT saturation may be the result, causing a rapid increase of this false differential current.

Additionally, transformer tap changers will cause a false current due to the modification of the transformation ratio.

Figure 3.5 shows the differential current measured by the relay, related to the through current ($I_{through}$) during load or external faults.

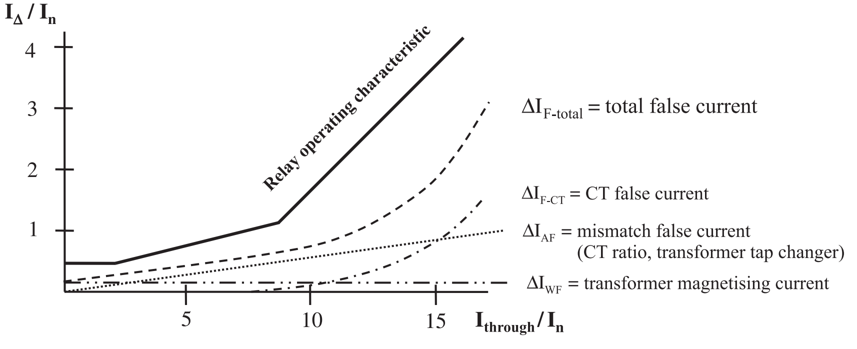


Figure 3.5 False differential current during load and external faults with adapted relay characteristic

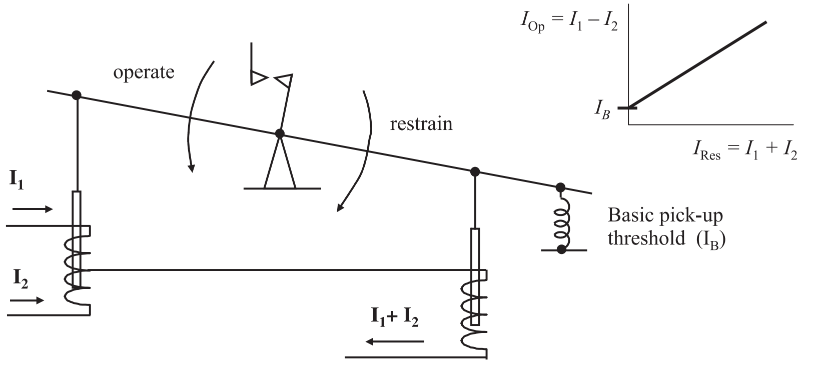


Figure 3.6 Biased differential relay according to McCroll

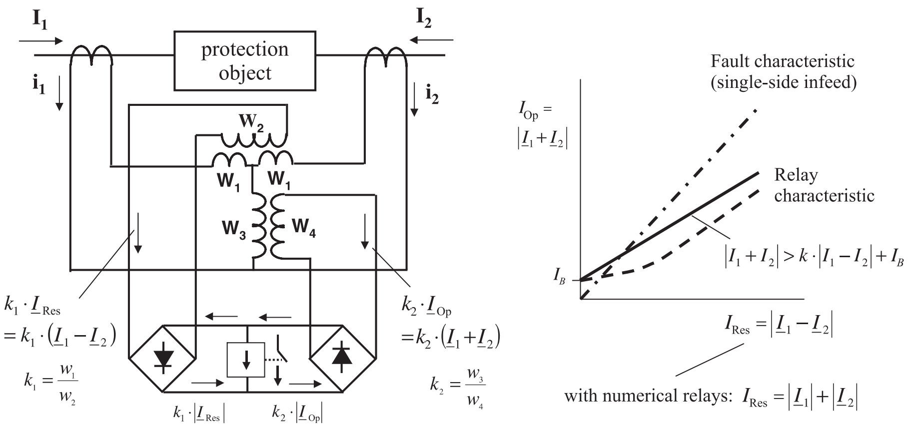


Figure 3.7 Differential protection with bridge rectifying circuit in the measuring path

It is apparent that the pick-up threshold should be increased when the through current increases. This results in high sensitivity during load and small fault currents, while at the same time providing improved stability against mal-operation with large currents when CT saturation is expected.

In the early days of protection this was achieved by increasing the pick-up threshold proportionally to the through current. This method was already suggested in 1920 as a biased differential relay [3-1, 3-2]. The principle of operation is shown in Figure 3.6: Biased differential relay according to McCroll.

Electromechanical and static relays implemented this method using a rectifier bridge comparator Figure 3.7. The measuring path was implemented with a polarised moving coil relay having high sensitivity and later with an electronic trigger circuit.

Bias (stabilisation) was provided by the signal $\underline{I}_{\text{Bias}} = k_1 \cdot (\underline{I}_1 - \underline{I}_2)$ which corresponds to the “sum” of the CT currents in the event of a through current. In this regard, the chosen sign convention for the currents must be observed; it designates the currents as positive when they flow into the protected object. Operation is effected by the “difference” of the CT currents $\underline{I}_{\text{Op}} = k_2 \cdot (\underline{I}_1 + \underline{I}_2)$.

The following states result:

	$\underline{I}_{\text{Bias}} = k_1 \cdot (\underline{I}_1 - \underline{I}_2)$	$\underline{I}_{\text{Op}} = k_2 \cdot (\underline{I}_1 + \underline{I}_2)$
External fault	$\underline{I}_{\text{Bias}} = 2 \cdot k_1 \cdot \underline{I}_{\text{F}}$	$\underline{I}_{\text{Op}} = 0$
Internal fault with single end in-feed	$\underline{I}_{\text{Bias}} = k_1 \cdot \underline{I}_{\text{F}}$	$\underline{I}_{\text{Op}} = k_2 \cdot \underline{I}_{\text{F}}$
Internal fault with in-feed from both ends	$\underline{I}_{\text{Bias}} = 0$	$\underline{I}_{\text{Op}} = 2 \cdot k_2 \cdot \underline{I}_{\text{F}}$

The pick-up criterion is:

$$I_{\text{Op}} > I_{\text{Bias}} \quad \text{i.e.} \quad k_2 \cdot |\underline{I}_1 + \underline{I}_2| > k_1 \cdot |\underline{I}_1 - \underline{I}_2|$$

By means of a restraint spring on the pick-up relay, a minimum pick-up threshold B can also be applied.

The principle equation for the biased differential protection is thus obtained:

$$\left|\underline{I}_1 + \underline{I}_2\right| > k \cdot \left|\underline{I}_1 - \underline{I}_2\right| + B \quad \text{whereby} \quad k = k_1/k_2 \tag{3-1}$$

Later, the measuring circuit was further refined, and supplemented with an additional diode resistor combination. Thereby, the restraint with small currents sets in slowly and only starts increasing strongly above a threshold value (variable restraint) as illustrated by the dotted characteristic in Figure 3.7. Numeric protection then implemented a characteristic made up of several sections. This allows better adaptation to the area of false current measurement that must be excluded.

In newer protection devices, the threshold B is no longer added to the restraining side, but is provided as a separate setting value: $I_{\text{Op}} > B$. As a result the biased characteristic $I_{\text{Op}} > k \cdot I_{\text{Res}}$ is no longer displaced by the initial value B, but instead passes through the origin of the coordinates. Consequently an increased sensitivity with small currents is achieved (refer to Figure 3.14 below).

The described measuring principle may also be applied to protection objects having more than two terminals (three winding transformer or busbar protection). Thereby the sum of the current magnitudes (arithmetic sum) is used for the restraint[1] while the magnitude of the geometric (vectorial) sum of the currents is used for operation:

$$I_{\text{Res}} = \left|\underline{I}_1\right| + \left|\underline{I}_2\right| + \left|\underline{I}_3\right| + \ldots + \left|\underline{I}_{\text{n}}\right| \tag{3-2}$$

$$I_{\text{Op}} = \left|\underline{I}_1 + \underline{I}_2 + \underline{I}_3 + \ldots + \underline{I}_{\text{n}}\right| \tag{3-3}$$

The conditions stated above apply as pick-up criterion:

$$I_{\text{Op}} > k \cdot I_{\text{Res}} \quad \text{and} \quad I_{\text{Op}} > B \tag{3-4}$$

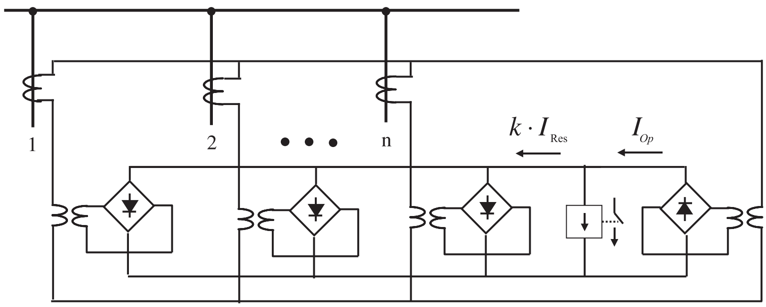
The bias factor k (%bias /100), which defines the slope of the bias characteristic, can be set in the range from $k = 0.3$ to 0.8, depending on the application and the dimensions of the current transformers. The threshold B may be set to $10\% I_{\text{N}}$ for a generator, while 130% of the maximum feeder current is typical for busbar protection.

This is referred to at length in the section regarding the individual protection systems.

The corresponding circuit based on analog signal processing is shown in Figure 3.8. The magnitude computation is achieved with the rectification.

In the event of an external fault, the operating current I_{Op} must be zero, i.e. the current vectors must add up to zero. The restraint current corresponds to the sum of the current magnitudes.

[1] With numerical relays, this formula also applies to two ended differential protection.



$$I_{Op} = |\underline{I}_1 + \underline{I}_2 + ... + \underline{I}_n| = |\Sigma\, \underline{I}| \qquad I_{Res} = |\underline{I}_1| + |\underline{I}_2| + ... + |\underline{I}_n| = \Sigma |\underline{I}|$$

Figure 3.8 Multi-terminal differential protection – schematic

In case of an internal fault, the operating current is the result of the summated current vectors. In its simplest form, when the in-feeds and consequently also the associated fault currents are all approximately in phase, the vector and the magnitude sums are equal i.e. $I_{Op} = I_{Res}$.

Under normal circumstances (low resistance fault and phase-equivalent in-feeds) the following may be noted:

External fault	$I_{Res} = 2 \cdot I_{F\text{-thru}}$	$I_{Op} = 0$	$I_{F\text{-thru}}$ is the fault current flowing through the protected object
Internal fault	$I_{Res} = I_{F\text{-int}}$	$I_{Op} = I_{F\text{-int}}$	$I_{F\text{-int}}$ is the sum of the fault currents at the fault location

In the event of internal faults with relatively large fault resistance it must however be considered that part of the load current may still be flowing through the protected object during the fault. The through flowing load current is superimposed onto the fault currents flowing into the protected object. The ratio I_{Op}/I_{Res} correspondingly reduces.

Example 3-1:

Short circuit with fault resistance (Figure 3.9)

$I_{Op} = 2300 - 300 = 2000$

$I_{Res} = 2300 + 300 = 2600$

$I_{Op}/I_{Res} = 0.77$

In expansive transmission systems or in the event that power swings or even out of step conditions arise, the fault currents flowing into the fault location may however have substantial phase angle differences. In this case the vectorial sum of the currents is smaller than the sum of the current magnitudes and therefore $I_{Op} < I_{Res}$. For a two ended in-feed, the conditions according to Figure 3.10 will result.

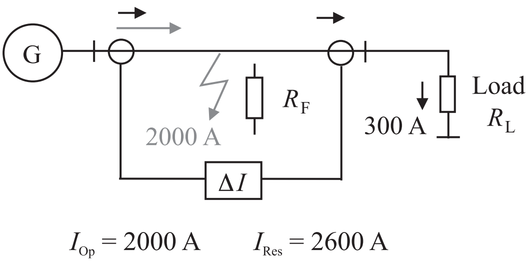


Figure 3.9 Internal fault with fault resistance, current distribution

If for the sake of simplicity, the two currents are assumed to have equal magnitude, then the following applies:

$$I_{Res} = 2 \cdot |I_F| \quad \text{and} \quad I_{Op} = 2 \cdot |I_F| \cdot \cos\frac{\delta}{2}.$$

When $\delta = 30°$, the lower ratio $I_{Op}/I_{Res} = 0.87$ results.

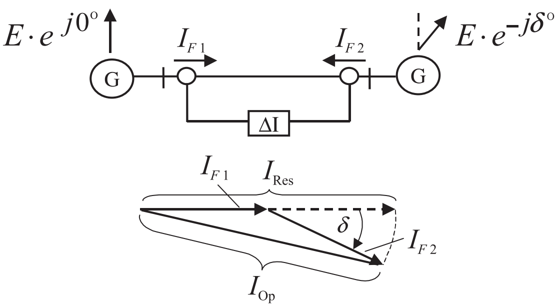


Figure 3.10 Internal fault with phase shift between in-feeds

The observed effects may of course also be compounded. The bias (stabilisation) factor k should therefore not be set above 0.8. On the contrary the current transformers should be chosen such that a setting above 0.7 is not necessary.

Note 1: In the protection literature and relay manuals, very often the through flowing current is taken as reference and counted positive. In this case, the operating current corresponds to $\underline{I}_{Op} = |\underline{I}_1 - \underline{I}_2|$ (differential current) and the restraint current to $I_{Res} = |\underline{I}_1 + \underline{I}_2|$ with traditional relays or $I_{Res} = |\underline{I}_1| + |\underline{I}_2|$ with numerical relays. This rule, which fits for protection of two-terminal objects, however is impractical in the case of multiple end protection objects like busbar protection. Therefore the sign rule, that currents flowing into the protection object are counted positive, is uniformly applied in this book (also corresponds to the Siemens relaying conventions).

Note 2: In this book, the restraint quantity corresponds to the sum of the current magnitudes $I_{Res} = |\underline{I}_1| + |\underline{I}_2|$. The I_{Op}/I_{Res} locus for internal faults is in this case a straight line with 45° inclination (100% slope) in the operating/restraint diagram (see Figure 3.7). This also applies to all Siemens relays.

Some relay manufacturers only use one half of the current sum as restraint quantity: $I_{Res} = (|\underline{I}_1| + |\underline{I}_2|)/2$, even with multi-terminal protection, i. e. $I_{Res} = (|\underline{I}_1| + |\underline{I}_2| + |\underline{I}_3| + \ldots + |\underline{I}_n|)/2)$. In this case, the internal fault locus has a 200% slope! This has to be kept in mind for comparing relays of different make and setting the bias factor (slope percentage).

3.2.3 Differential Protection with two pilot wire cores

The pilot wire differential protection (twisted pair pilot wires) was developed for the application with communication cables having twisted pilot wire pairs (telephone cables). It is primarily used outside continental Europe, where the twisted pairs are often leased from telephone companies.

Two variants are in essence possible:

- opposed voltage principle (tripping pilot scheme)
- circulating current principle (blocking pilot scheme)

Both variants were developed and applied in practice [A-13, A-22]. The relays supplied by Siemens, described in detail in section 9.2, operate with the opposed voltage principle.

Voltage comparison (opposed voltage principle)

With this technique, the current at each line terminal is routed through a shunt resistance (R_Q) thereby producing voltages U_1 and U_2 each proportional to the corresponding current Figure 3.11. These two voltages are then compared via the pilot wire pair. The connection is chosen such that in the event of load current or external fault current flowing through the line, the voltages are in opposition and no current flows via the pilot wire pair. During internal faults, the two voltages however are in phase and drive a current through the pilot wire loop. This current, which is only a few mA referred to nominal current of the current transformers, results in tripping via the sensitive current relay (ΔI).

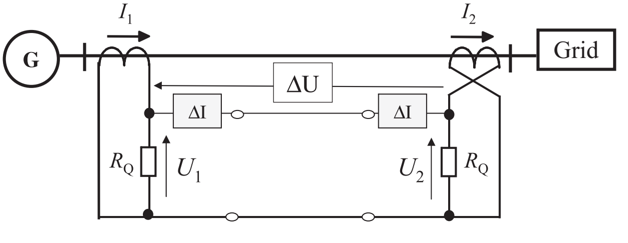


Figure 3.11 Line differential protection, voltage comparison principle