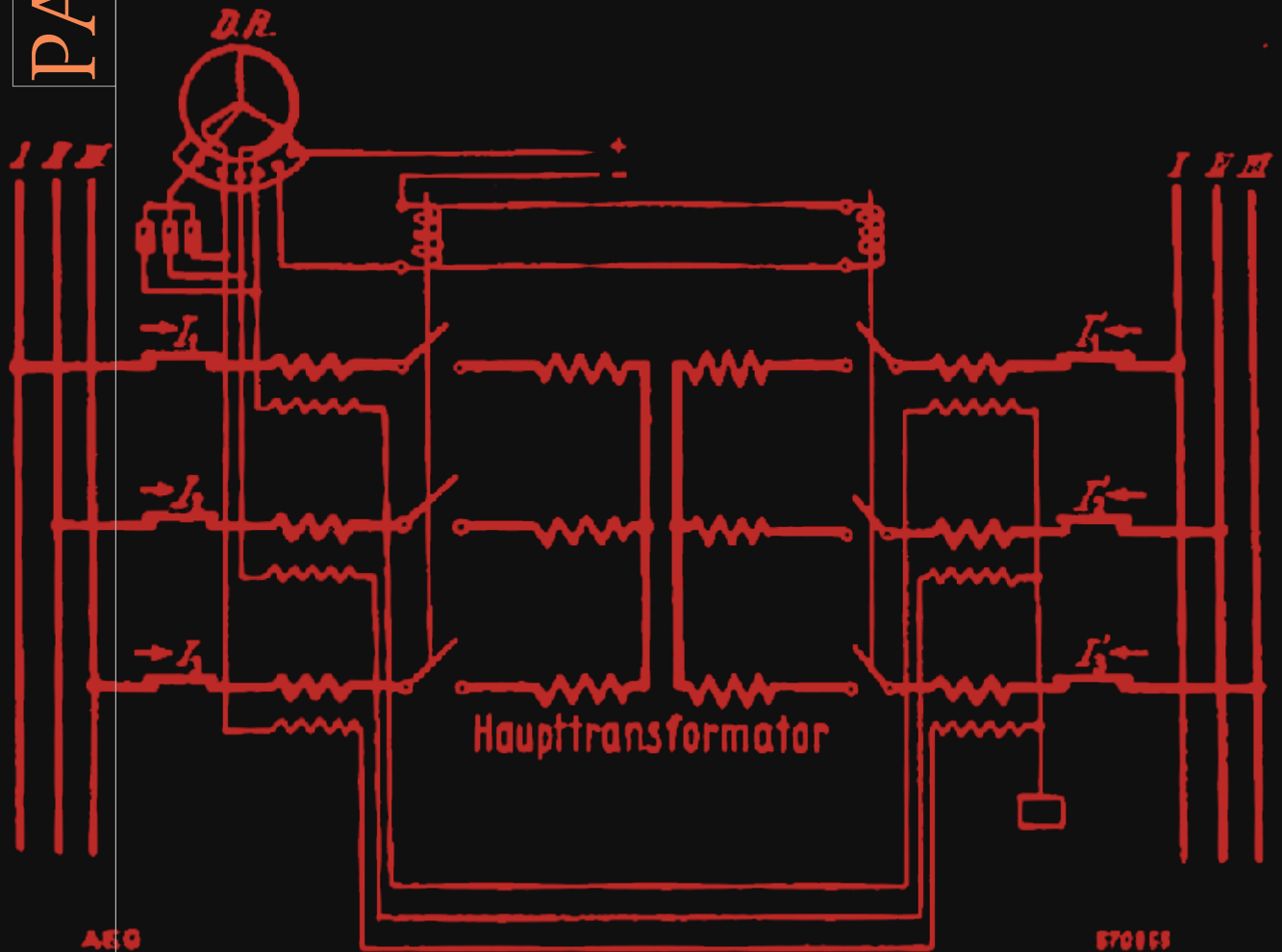
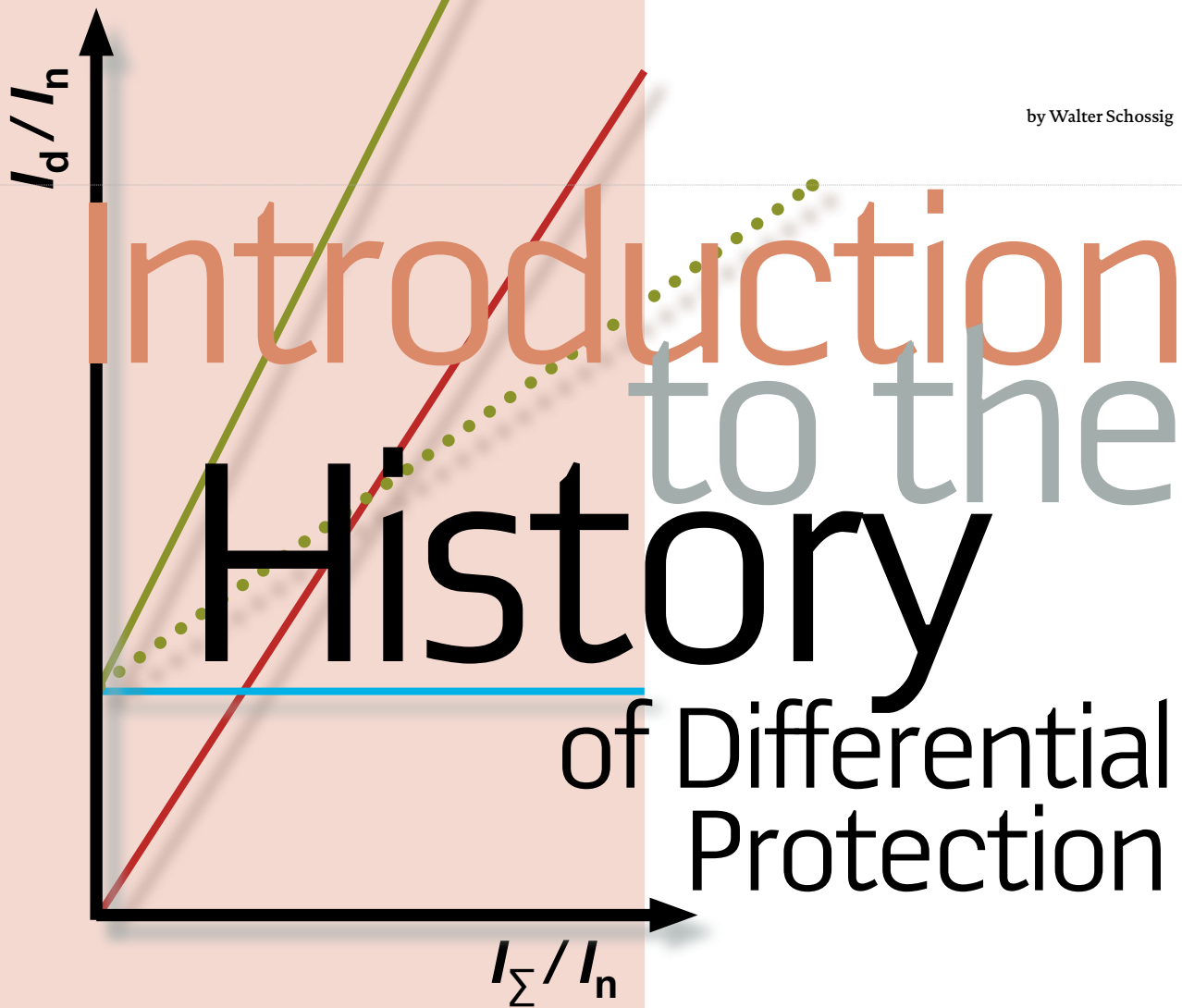


Differential protection became an important protection technology in the twentieth century.



First solutions for cable and transformer differential protection





Biography

Walter Schossig (VDE) was born in Arnsdorf (now Czech Republic) in 1941. He studied electrical engineering in Zittau (Germany), and joined a utility in the former Eastern Germany. After the German reunion the utility was renamed as TEAG, now E.ON Thüringer Energie AG in Erfurt. There he received his Masters degree and worked as a protection engineer until his retirement. He was a member of many study groups and associations. He is an active member of the working group "Medium Voltage Relaying" at the German VDE. He is the author of several papers, guidelines and the book "Netzschuttechnik (Power System Protection)". He works on a chronicle about the history of electricity supply, with emphasis on protection and control.

THE LAST ARTICLES OF THIS SERIES IN PACW COVERED DISTANCE PROTECTION. The main protection in the HV- and EHV- but also in the MV-grids in Germany, Austria and other countries. Other countries like UK, United States and Russia prefer overcurrent, phase and signal comparison protection since the beginning up to today. For the protection of transformers, generators and motors differential protection is the main choice worldwide.

Forerunners of Differential Protection

Already at the end of the 19th century some engineers talked about differential protection- it was the comparison of voltages and currents in single phases. A first proposal in 1896 compared the voltages of the two phases of a DC system with the neutral phase. A balance beam relay with coils on both sides was balanced as long as the voltages were equal (German patent DRP 92442 Figure 1)

According to a proposal of Elektrizitäts-AG Schuckert, DRP 113521, in three-phase systems the currents of different phases are compared (one relay and two coils for each phase). Each coil moves a side of the beam. During symmetrical conditions the currents are equal. This scheme was used for the detection of unsymmetrical short-circuits and of breaks of a line.

Schuckert proposed in 1900 another differential relay using balanced beams. Now the current of one phase operates one side; the other two phases on the other side. A change of load in a single phase trips the relay (DRP 122503). So far this relay can be described as a phase balance relay, it utilizes the zero sequence system. AEG had already published in 1899 a paper in the German magazine "Elektrotechnische Rundschau" regarding a differential relay.

In 1898 Kallmann described in the magazine ETZ his idea for a "differential scheme for direct indication of deviation of currents". This system was used for announcement only.

Differential Protection as Selective Protection

A differential protection that compares the currents on both sides of power system equipment was patented by Charles Hestermann Merz and Bernhard Price (England). „Improvements in the Method of and Means for Protecting Apparatus on Alternating Current Systems" was patented in the UK (patent 3896) on 16 February 1904 and on 31 May 1904 in Germany (DRP 166224)- the year 1904 became the year of birth of differential protection. On both sides of a line or a transformer now current transformers are installed. The secondary windings are connected in a manner that during normal operation the current is zero. The connection of the

transformers is realized with pilot wires. For the protection of lines relays were installed on both sides, each tripping a circuit breaker in the case of a fault (Figure 2) For the protection of transformers only one relay was necessary that trips both sides. In case of a fault between the measuring transformers the currents on both sides became different and the relay trips. A disadvantage of this system is that if the transformers operate under no-load condition; this causes a high voltage in the circuit. To solve this a bridge circuit was used (Figure 3).

The cumulative circuit of the current transformers and relays in the diagonal connection was introduced by Kuhlmann, AEG in 1904.

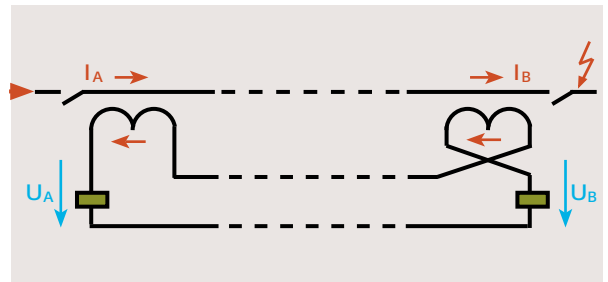
First Applications

A first major application was the 20-kV-cable-grid of Country of Durham Electrical Power Distribution Co. in northern England (1906/1907). AEG acquired the patent of Merz and Price in 1907. The first application was in the mine Luisenthal (Saar) and at EW Westfalen (both in Germany) a short time after that. Other known applications are the power station Rosherville (1911); Victoria Falls and Transvaal Power Co. Ltd. (South Africa; generators & transformers 1911/12).

Figure 4 shows a high sensitive differential relay working with a moving-iron measuring element. The outer yoke was made from alloyed sheet steel with high initial permeability. It carries (on sharpened terminals) the excitation coils. A blade like a Z increases the field strength with a small move. Now with a small own consumption a huge torque is possible. The weight of the blade was 8 grams only; a small spring retracts the trolley pole.

Another transformer protection scheme common until 1918 used windings of the coils connected in series with the current transformer windings and bypassed with fuses. The scheme can be compared with the Cleveland-scheme with a fuse as mentioned in another part of this history series. AEG later developed a three-phase universal device (Figure 6). This device could be ordered for the different needs as cable, transformer or generator protection. It operates according to the electromagnetic principle. A circular magnetic yield carried the three spread out (120°) pole piece of the windings. When

2 Differential protection of Merz-Price, 1904



the current achieves the level a trident shaft rotating armature moves and releases a drop indicator. A reset was possible manually. The setup of the startup value was achievable with moving the element along the scale. The device for transformer protection was equipped with a make contact, which switched on a timer. This timer was set up to 2 s and thus limited the impact of the inrush current.

The current differential protection was quite common in England. This was different in other countries like the US, where overcurrent protection was used. Nevertheless, differential protection schemes became quite popular later on.

Differential protection systems became known in Germany as "pilot-wire protection" in 1907. Another idea was to compare the currents of parallel lines because due to the primary impedances of the line there is a certain ratio. This transverse differential protection (another name was "8-protection" because the form of the circuit was as an "eight") (Figure 10) was patented by Wedmore (UK) in 1908 (Brit. Pat. 11797).

The big advantage: no pilot wire was necessary. Of course, the operation of such a protection scheme is possible with permanently operated double circuit lines only.

To protect more than two parallel lines Richard Bauch, SIEMENS introduced in 1918 the transverse differential protection with polygon connection (DRP 330667; Figure 11). Please note that the picture shows the comparison in one phase only. In normal operation the relays are currentless

6a

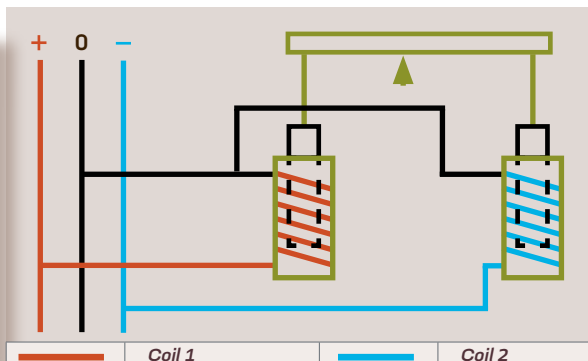


Differential relay, AEG

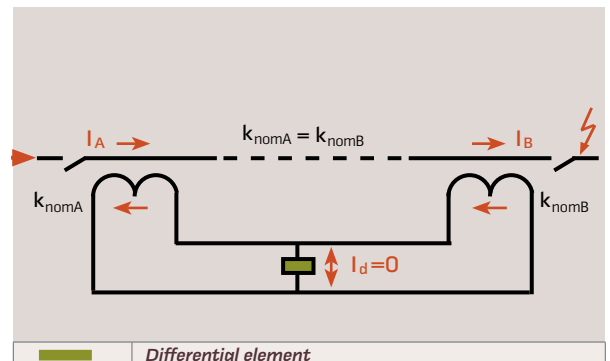
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1 First differential protection



3 Bridge Circuit



Transmission line differential protection systems became also known as "pilot-wire protection".

because both currents are about the same size and have the same direction. The currents circulate in the "eight" or in the polygon. Only in case of unbalance a current flows through the relays. To allow an operation with single-system-lines, F&G patented (DRP 264541) another approach in 1912. A single conductor cable is electrically divided. During normal operation a certain ratio of currents occurs and they cancel each out. In case of a fault the relay tilts. Biermanns (AEG) proposed a "power differential relay". It works as a contact wattmeter with two drive systems in an Aaron-circuit, both operating an aluminum-disk. Both are excited with the difference of currents and show in normal case the iron losses of the transformer. They are quite sensitive to react on decreases, e.g. caused by failures in iron; but they are even fast enough to detect a short-circuit in a winding before demolitions can occur. This wattmetrical relay started already with a power at the fault location with a value of 0.5% of the nominal power of the transformer. Additionally a normal current differential relay was used, it should operate in the case of a collapse of voltage and if the wattmetrical relay became less sensitive. The power differential relay did not operate instantaneously, but with the time of the current differential relay and its timer. Figure 12 shows the circuit.

The English Clothier und Leeson published a "split pilot system" in 1929. The single core, necessary for the comparison of the currents was splitted in the middle of the coil of the differential transformer. The relays were connected to the secondary winding of this measuring transformer. (Figure 7)

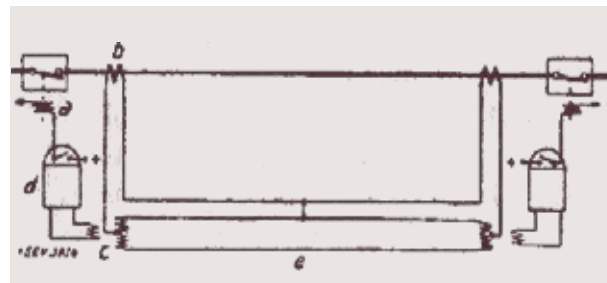
Since during normal operation the same part of current is flowing in every half-coil, the fields compensate each other. In

the middle of the pilot wire there is no difference of voltage, so the current flowing over the transversal connection is zero. In case of a fault the differential current flows through the transversal connection and the winding of the differential relay, it starts up. With this segregation the relay is insensitive for interferences on both cores.

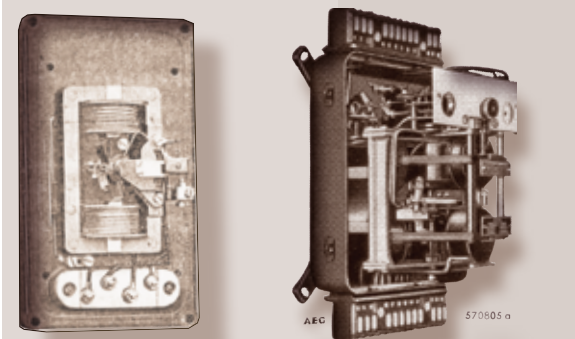
Stabilization

The issues, that with the classical differential protection false tripping may occur in case of short circuits outside the zone of protection was recognized by Waldemar Petersen, AEG in 1920. The main reason for that was the different saturation of measuring transformers caused by increasing short-circuit currents and their DC-components. Additionally the tuning of the current transformers on both sides was disturbed by the tap changers used more and more. This impact was reduced with additional tappings for the interposing transformers and vector group replication; they had to be switched with every tap changing. This was not possible with a lot of operations or even with automatic tap changing anymore. Due to this AEG proposed a quotient measuring relay in 1930. This relay was not started up with the magnitude of the differential current anymore; it evaluates the ratio of differential current and through-fault current. With that, the device was stable in case of outside faults. This quotient measuring relay used the electromechanical principle as well. Additionally to the difference-system it used a 3-pole restrained-system excited

7 Split pilot system

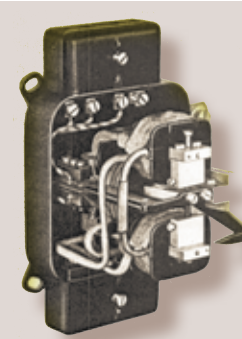


4 High sensitive relay (Siemens)

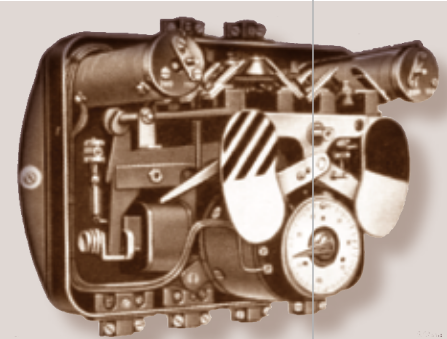


5 Relay QS1, AEG quotient measuring

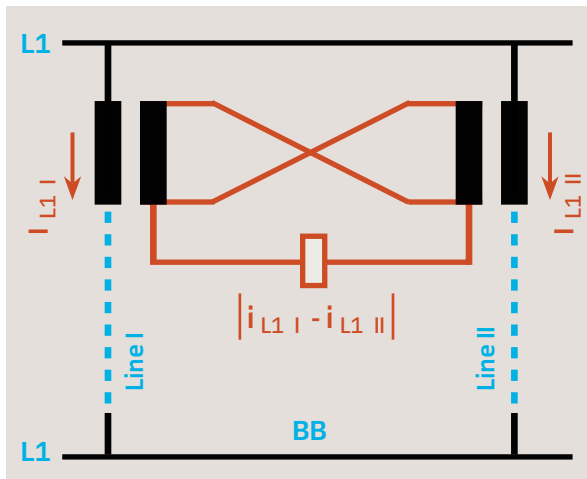
8 RW10, single pole, Siemens



9 Pfannkuch-cable-protection, AEG, 1920



10 Transverse Differential Protection, Wedmore, 1908 (Phase a shown)



by the restrained current (through-fault current) to generate a torque (Figure 5). The solution of SIEMENS implemented in RW10 interrupts the tripping if a fixed value 1.5 of maximal load current was exceeded. (Figure 13,8)

ASEA presented their stabilized differential relay RBD in 1925. An interesting proposal was made by P. Barry (France) in 1925 – to use an interposing transformer with the same number of ampere-turns on the low-voltage side of the transformers, where the CTs have a high number of ampere-turns. This could decrease the impact of the different magnetically characteristics so far, but increases the sensitivity of the protection (Figure 15). Barry uses here an older scheme, the measuring transformers connected against each other. To avoid open secondary windings he used resistances to have a load. This resistances needed a lot of energy and decreased the sensitivity further.

To eliminate the disturbing currents at transformers with continuous control Schulze, H., Auma, proposed in 1929 a possibility to consider the tap changes; BEWAG in Berlin

Improved stability of differential protection is achieved by adding a biased relay.

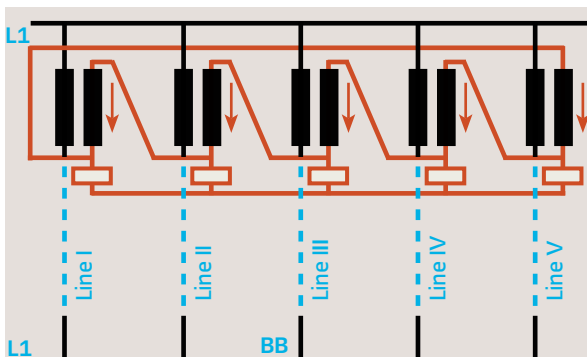
operates a "differential watt protection." To allow an adaptation for different vector groups and tapplings, SIEMENS introduced interposing transformers for the different vector groups with own tapplings (DRP 315272). When the produced power became more the short-circuit currents increased and so far the false currents as well. To avoid false trippings Albert Edward McColl proposed a restrained winding. (percentage differential relay, Figure 14) Two electromagnets affect an arm of balance. One electromagnet uses the geometrical sum of currents for restraining (biased relay) and the other one uses the geometrical difference for tripping. Now the tripping current proportional to the through-fault current has to be larger to trip, that's why the name "percentage-relay". The restraining impact could be changed (*change of number of windings or the arms*) to achieve the behavior required. According to a British Patent (133187) Wedmore built another differential relay. Now the action of the tripping coil was influenced by the total current in the transformer. The bigger the current, the bigger the startup. This avoids false tripping and is still used today.

Inrush Restraint

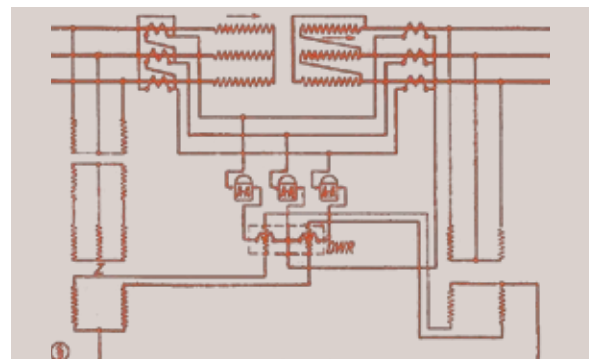
With the return spring on the other side the relay holds the contact normally closed. If the geometrical sum is bigger than the geometrical difference, it opens the contact. If we have this contact in a serial connection with a "normal" current relay (*operating with the normal fault current*) this relay is blocked in case of an ratio relay. The relay becomes a biased relay. The only difference between the percentage relay and this restraining relay is the direction of spring power $\pm C$ (*percentage relay + C; biased relay - C. C has the dimension of Amps that are necessary to overcome the elastic force.*)

Brit. Patent 104571 and the SIEMENS engineer Geise, Fr.

11 Transverse Differential Protection (Polygon Connection), Bauch, 1918 (Phase a shown)



12 Wattmetrical differential relay, (Siemens) interposing voltage transformer



Multiple parallel lines can be protected by a single relay.

proposed biased relay as an addition to differential relays in 1932. It was introduced in Germany with the name "stabilized differential relay", other known names are "quotient differential relay" (AEG); "percent differential relay" (BBC) and "relays with restraining element" (SIEMENS). The impact of the slowly decaying inrush currents could be eliminated with a timing element (0-5...2 seconds) only (*estimation of the value with 10 trials plus 0.3 seconds*). The idea of a "harmonic restraint" was born. But it took up to the 50's of the last century to present rectifiers and filters to block the protection to achieve security for switching on and to allow fast tripping (50...100 ms) on the other side. Geise, F. (SIEMENS) used saturated transformers which blocked the DC-component of the inrush current. Hoel proposed an swinging contact adjusted on the nominal frequency of the grid in 1944; this idea was patented by Stoecklin, J., BBC (CH) in 1944 (DRP 849444).

The transversal protection, proposed by Bauch, R. in the 1920's was extended with biased relays to avoid false trippings with external faults or different impedances of lines. Another idea was the usage of instantaneous values to compare the direction of currents- this proved a failure in field experience.

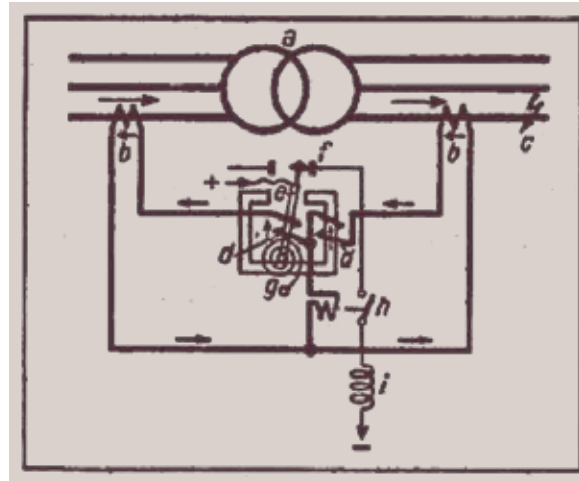
We can estimate in general, that the usage of transverse differential protection for lines is inappropriate because the lines have to be parallel all the time and have to be on the same busbar. Nevertheless, this protection is used up for the protection of equal part-windings in generators and large capacitor banks.

Other Comparison Protection Systems

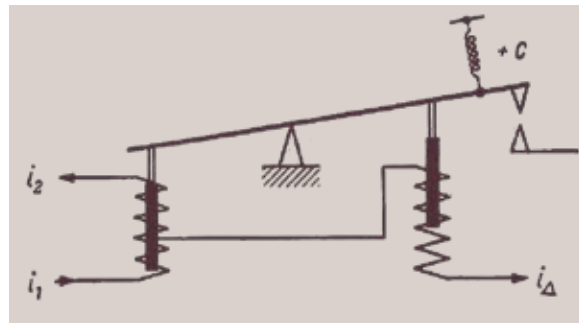
The usage of differential protection for lines is not very common in Germany. One of the reasons is the need for an additional wire (beside the line) and that the proper work of this core is essential for the reliability of the whole protection system. Due to this effort and the danger of damaging of the pilot wire the value of the protection system was estimated as illusory and as a "fakery of a protection that does not exist in reality". Another reason against a wide usage was the impact of the disturbing capacity of the pilot wire, especially at long lines. Resonances are possible and the results in a protection system difficult to detect. Compensation trials with coils and transformers were proved of failure. In any case the long pilot wires with their high resistance are a high burden for the current transformers. That's why differential protection is quite common in systems with short distances - generators, transformers, transducers and motors.

When distance protection was not available, the engineers searched for other fast tripping protection devices especially for cable grids. The already mentioned divided-conductor protection (split-pilot protection) was developed in the 1920's and did not need the pilot-wire. Pfannkuch, AEG, developed the Pfannkuch-cable-protection in 1920 (Figure 9, 17). It was used for voltages up to 60 kV; a number of pilot wires were on perimeters of the main wire with a poor isolation. This requires a special measuring transformer, the Pfannkuch-transformer (Figure 16). The difference voltage between the main core and the testing wires was around 60...160 Volts. The protection was realized with an active-power relay. It was set up in that

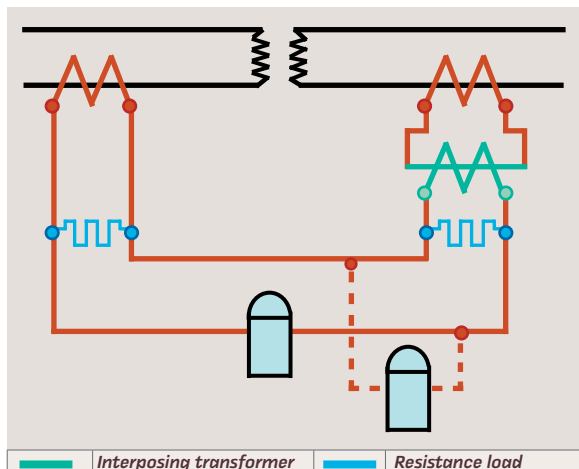
13 Stabilized differential protection 3-pole, RW10, Siemens



14 Percentage differential relay, McColl, 1917

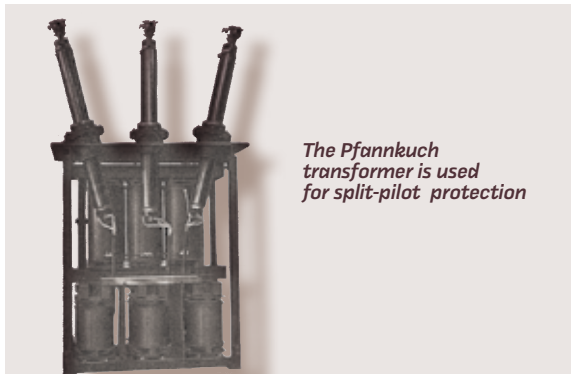


15 Figure Differential Protection with Interposing Transformers (according to Barry)



Different methods were invented to improve the performance of differential protection relays.

16 Combined 60 -kV - Pfannkuch - and voltage transformer



manner that in case of a normal energization of the cable nothing happens. But if in case of a beginning failure the isolation of the cable starts to carbonize the relay trips due to the active power and warns before a puncture. Now the relay changes its setup. A second startup trips the oil circuit breaker.

These devices have been used for the first time in Berlin (30 kV; 1920/22), Cologne (25 kV 4 km; 1921) Buenos Aires (1922; 27.5 kV; 62 km) and Constantinople (1922; 10 kV; 4 km). In 1924 AEG commissioned in Japan (*central station Kyoto-Dento to the substations Toji, Gojo, Daibutso, Shimabar and Sujakuno*) a 20 km 22 kV cable for Kyoto-Electric Light Co. and used Pfannkuch's system for protection.

Further developments of this protection have been supported by Rottsieper at the cable manufacturer "Kabelwerk Oberspree" in Berlin. Since there have been some problems with this cable protection systems; the new distance protection became more popular at this time. Nevertheless, distance protection is difficult to use with short cables. That is why directional power comparison relays were used since 1933. This could be done with the directional elements in the distance relays or with separate directional relays. Of course there are pilot wires needed as well but they could be realized as low voltage cable with small insulation and profile ("*telephone cables*"). The big advantage compared with the other systems

was, that it was not longer necessary to transport measuring values with magnitude and phase angle; only DC signals. The problem of measuring transformer burden and the length of line was not that restricted anymore. Failures near the stations caused an uncertainty (missing voltage for estimation of direction); power swing and out-of-step of power stations on both sides caused to false trippings.

AEG developed current-direction comparison-protection (SV-protection) in 1936. This protection used polarized relays (as known in telecommunications). These relays were excited by transformer's current and their contacts switch-over with the frequency of the short-circuit current. Pilot wires were used to detect in a circuit with an auxiliary voltage if on both sides the same positive and negative alternations occur (=external fault) occur or if they are in opposition (location of fault was supplied by both sides = internal fault). This works in case of single infeed (Figure 18, 19a, b) and for two sources as well. The first applications of this protection were reported in Brandenburg, Eisenach and Darmstadt (Germany).

Höchststädter developed his Lypro-protection in 1913. It needed only one pilot wire, connected in such manner that the Ampere-windings of the main current and of the pilot wire cancel out each other. Other systems, as the Glaser-protection, Ferranti-Howkins-protection and Kalecore-cables should just be mentioned because they were not developed further. More important became the directional-comparison protection, comparing the direction (*power-line-carrier*)-transmission. This system was proposed in 1933 by Neugebauer, SIEMENS.

In 1924 Biermanns, AEG introduced a principle of different protection function for main and backup without pilot wires. For double lines he proposes transversal differential protection (immediate trip in case of failures on line) and distance protection to detect busbar failures. Smith, R.M.; Sonnemann, W.K. und Dodds, G.B. (US) describe their busbar protection based on quotient differential protection in 1939.

Further developments will be covered in the next edition.

Any comments or questions please send to:

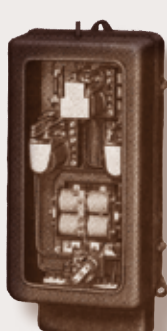
walter.schossig@pacw.org
www.walter-schossig.de

19a

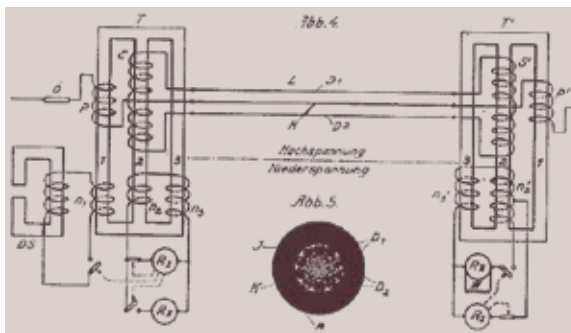


SV-Protection
AEG, 1936

19b



17 Pfannkuch-Cable-Protection



18 SV-Protection, circuit, AEG, 1936

