

When the first circuit breakers were developed, engineers started to look for ways to trip them automatically when a short circuit fault occurred in the zone of protection.



Protection

This article discussed only the industry's initial approach to protection and selectivity

History

the Start of Protection (Latin proverb)

History is the tutor of life.

Start of Protection Systems

When circuit breakers were first developed, engineers started to find out how to trip them automatically if short circuits occurred in distribution and generation assets. The initial approach was to interrupt short circuit currents however this technique subsequently evolved to satisfy the requirement for selective tripping of the asset. Past research into frequent explosions of oil circuit breakers has shown that breakers experience problems both in situations where the fault was cleared too quickly and in situations where there was too long a delay in tripping. Moreover, the assets being protected had thermal ratings that constrained their operation under fault conditions.

Fusible Link as Primary Protection

At the end of the 19th century assets in substations mostly operated with DC voltage. Fusible links were used to protect generators, lines, motors and other loads against overload and short circuits. The fuses were made out of lead, silver and tin. The fusible strip (wire or bond) was open. When the operating voltage in the substations increased, the fusible links were covered with porcelain and clay to protect the operators. The fuses were open on both sides and were called tube fuses. First patents were published by Weston in 1882 (lead alloy DRP

24057); by Blathy in 1890 (chamber fusible link DRP 54249); by Wurts (Electric Safety Fuse Box US-Pat. Nr. 434169). In 1899 Smith and Baughman published a patent (American patent 636577) for a fusible link that provided an indication of operation (i.e. a small indicator flag operated if the fusible link opened). (Fig.)

From Tripping Device to Relay

The fusible link offered several benefits such as the interruption of sudden short-circuit current at a low price. The main disadvantage is that they have to be changed after each operation. To counteract this disadvantage, a measuring element was added to the circuit breaker that initiated a trip when the fault current reached a defined level.

At the World Trade Show in Paris in 1900 the company "Helios von Froitzheim" demonstrated how a machine could be used to open a high voltage circuit breaker to trip a 3000 kVA machine. The arc-extinction was realized with air-blast. As illustrated in Fig. 2, the magnet opened a latch in the event of an overcurrent and air was blasted out of a tube that was made of gum. Most circuit breakers in 1900 were oil-filled breakers with a stored-energy spring operating mechanism. The spring was charged during switching on. It is important to know that these circuit breakers had a trip-free mechanism

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 reunification 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 "Netzschutztechnik (Power System Protection)" He works on a chronicle about the history of electricity supply, with emphasis on protection and control.

(during switching on in case of a fault tripping was possible). In 1899 the American Sharpstein, S.H established the circuit breaker requirement "... if they switch onto fault the circuit breaker should be opened in any way and automatically".

Up to this time in the United States, the majority of schemes used two circuit breakers connected in series (one with tripping device, one to switch on the line or motor connected). This requirement for two breakers was resolved by Emmet & Hewlett in the US in 1901 and in Germany by Vogelsang, M. in 1901, V&H with a horn and oil circuit breaker.

The tripping devices (directly using measuring values) and relays (connected to current transformers) at this stage measured currents only (Fig. 5) The tripping devices operated at high voltage levels and were attached to the bushings of the circuit breakers. The turn of the current coil directly monitored the circuit being protected. These devices were primary tripping devices and operated either mechanically or electrically (with an isolated bar)(Fig. 6). It was obvious that current in itself was not a unique indicator for a fault and consequently definite time relays (DT relays) were developed where the tripping time decreases with growing current. The first technique for such devices used an induction procedure. Thermal relays with a bimetal strip began to be used in the 1920's. Since such devices could easily replicate thermal conditions they were useful to discriminate against thermal overload. (Fig. 7). The first overcurrent relays and tripping devices in Europe were developed to achieve the characteristic curve of a fusible link.

The disadvantage of using DT relays for time graded protection was that the tripping time depended on the number and power of generators used. In normal case this is highly appreciated. The tripping time for those devices was not inversely proportional to the current, it was faster. That resulted in small selective time intervals and a lack of protection selectivity. The time interval required was 0.5s to 1.5 s while the actual relay trip time, decreases upto 0.1-0.2 s. To achieve selectivity with short circuit currents the time-

delayed trip was developed. The IT overcurrent relays provided a fixed delay time that was not dependent on the current level. This allowed for fixed time settings and series protection schemes for assets (e.g. transmission lines or transformers) that discriminated towards the direction of generators and that were more effective than the the protection offered by the IT relays. Stillwell patented a time relay in 1899 that was later used in Germany (Fig. 8).

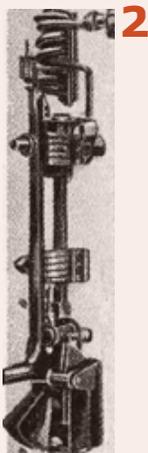
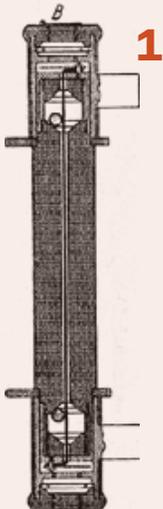
A special issue had been oil circuit breakers .In a protection scheme setup recommendation for the circuit breaker, published in 1919, a time delay of 1 second was required. The recommendation noted that the setting should be adhered to in order to avoid a significant reduction in the rotation speed of motors. On the other hand they recommended using conditional short-circuit current. The first solution for 3-phase protection systems was built using two induction cups that were excited by the current. The time delay was achieved by air damping with a bantling made of leather (Fig. 19).

To achieve a fixed time delay the timing element consisted of a mechanical timer, an oil flask or a leather bantling. In the case of a fault an electromagnet tripped the spring. The types of overcurrent relays used up to now are shown in Table 1. Vogelsang,M., V&H realized the first zero voltage tripping device in 1904. AEG realized a 3-phase zero voltage relay for high voltage circuit breakers in 1906.

Use of Measurement Transformers

The current transformer was invented by Benischke,G. in 1898 and made it possible to connect secondary relays. At that time the relays worked normally with 5A. See Fig. 9 for voltage and current transformers are from 1899.

Measurement transformers with an accuracy of 1% were available by 1907. Electromechanical relays, especially the hinged armature type, needed more operational energy. Their nominal current was 5A. The required nominal current was reduced to 1A with the use of power rectifiers and permanent magnet moving-coil elements. This had the advantage of requiring a reduced relay burden in the instrument rooms. In



3 Tripping Relay, BBC, 1930



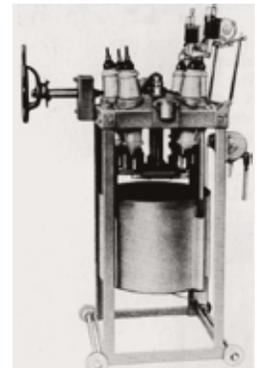
4 Tripping Device, Sachsenwerk, 1930



5 IT and DT Relays



6 10 kV Oil Circuit Breaker (kettle let down)



The circuit breaker – in most of all cases oil circuit breakers in 1900 - used a stored-energy spring mechanism.

1926 Arnold proposed using relays with a nominal current rating of 1A but up to today still new substations with 5A are built. AEG introduced current transformer tripping with time fuse in 1908 (Cleveland-Relay) - the current transformer is short-circuited up to the moment when the current level of the fuse is reached. Rogowski proposed Steinhaus a circuit for measuring of currents without iron already in 1912. The Rogowski-coils were seldom used at that time since they were unable to satisfy the relay burden requirements.

Configuration of Measurement Devices and Auxiliary Relais

The first used hinged armature type relays had a high intrinsic consumption and the resetting ratio was less than 0.8. These hinged armature type relays were widely used as auxiliary relays. Rotating armature relays had a lower intrinsic consumption and achieved a resetting ratio of approximately 0.85. (Fig.13, Fig.14)

In grids with parallel lines or with rings and with generators in parallel it is not reachable to achieve selectivity with overcurrent relays.

Dedreux, C. patented (DRP Nr. 59 192) a delayed overcurrent tripping device in 1891. Delayed and non delayed overcurrent relays were developed in 1900. The operating principles continue to be used today (Fig. 11). These relays (DT, IT, IDTM) were used as primary tripping devices and as secondary relays. A tripping device trips the circuit breaker mechanically; a relay switches an electric circuit. Both operate with values that occur during a disturbance. An

overcurrent relay trips the coil of a circuit breaker if a certain level is exceeded. The measuring winding of tripping device is flushed by the primary current and the trip is transmitted over a linkage to the circuit breaker. Using relays for tripping and the relay itself auxiliary voltage is necessary.

It is interesting to note, that the first overcurrent relay was a DT-relay, driven by Ferraris disk. This allowed an adaption of the lead stripe fusible links that were used up to then.

The first AEG relay (3 phase design) used two currents from different conductors to act on one disk made of aluminum.(Fig. 15). Using the circular magnetic yoke, all relays used this circular box as shown in Fig. 5.

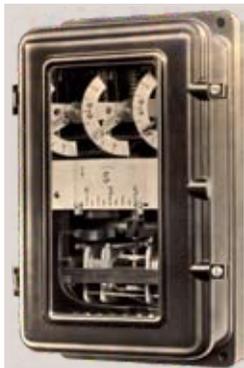
Charles Brown proposed an overcurrent relay (Fig.22) with a time delay in 1902. He used a Ferraris disk to achieve this. It raised a weight when turning. When the weight (7) changed, the startup value could be changed. With the length of the hairline (6) on the drum (5) the time to closing the contacts (8) could be changed.

The independent overcurrent relay RA s4 made by S&H (Fig. 17) achieved a current independent delay with the synchronized Ferraris disk. An armature working in the stray field cleaved the disk if the current is below the level. If the current level exceeds the setting; it unblocks and couples the armature with the disk. Changing the force on the spring changes the startup current (upper scale). Changing the way of the contacts changes the delay (lower scale). When the short-circuit current is cleared; the armature falls back to its starting position. At an

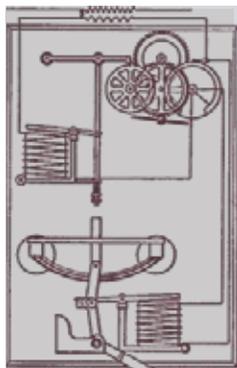
Table 1 Overcurrent Protection

Protection	Abbreviation	
Thermal Overcurrent	IT	Inverse Time Relay
Independent Overcurrent	DT	Definite Time Relay
Thermal Overcurrent with limited Time	IDMT	Inverse Time-Relay with Definite Minimum Time Relay

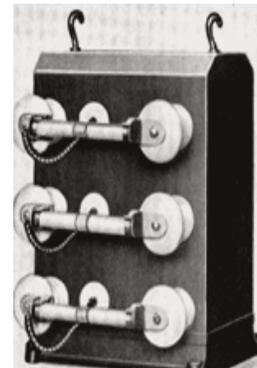
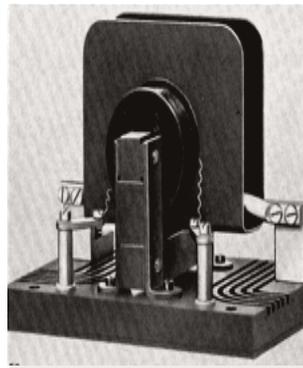
7 Bimetal Relay, R1325, 1932



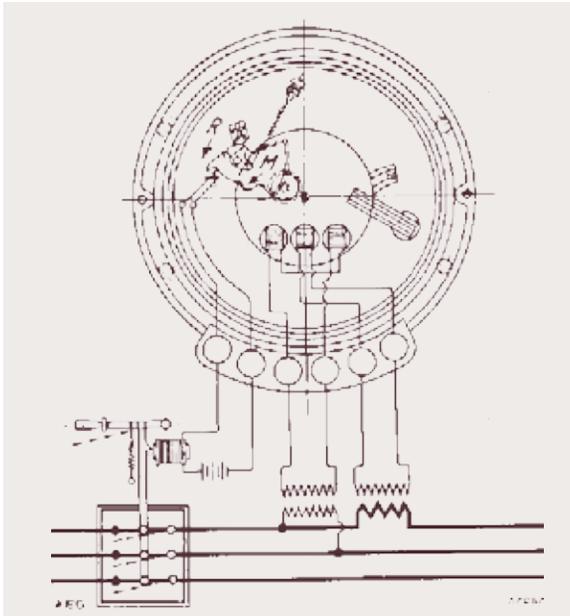
8 Independent time relay (Patent Stillwell, 1899)



9 Current Transformers, Voltage Transformers, AEG, 1899



10 Common Maximum and Reverse-Current Relay, AEG 1903



extra charge a slave pointer was available, which was resettable from the outside and showed the duration of the disturbance.

Selective Protection

The selective protection was developed in the 19th century. The Niagara plants needed a selective line protection for their 11-kV-grid. The technical director Stillwell created it in an innovative manner. He used common elements like overcurrent and time-relays. He used a GE fan motor as a directional unit. The stator field was interfused through the voltage, the rotor was flown through the current. The reverse-current-relay for the double line was invented (Fig. 20). An automatic operating circuit breaker, using overcurrent

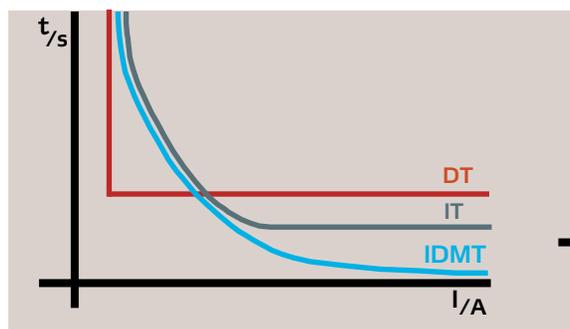
The first time grading in opposite directions was first used in 1918, the principle was known since 1900

and reverse-current relays was proposed at the Paris fair in 1900. The two-pole relay operated an oil circuit breaker with compressed air.

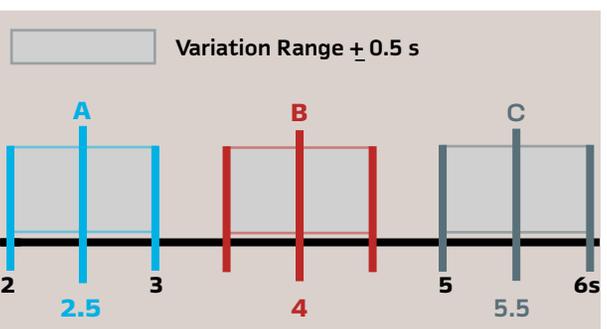
The first reverse-current-relays for alternating current (AC) had the same name as those for DC. H. Probst invented the AC reverse-current-relay, influenced by the use of small shunt-motors. He said that there were a lot of objections against this idea; some even said that he did not know the first thing about electrical engineering. Nevertheless he invented the reverse-power-protection. Before claiming the patent by AEG Gerhard published in 1903 a paper in the ETZ magazine describing a reverse-power protection. The relays are supplied with current and voltage by the measuring transformers; closing a parallel circuit which operates the tripping devices. This was the first reference of transformer-operated tripping devices. Contrary to later devices the relay was supplied by the voltage transformer in parallel despite the fact that the voltage is not available during a fault condition. Current transformer-operated relays are supplied by current transformers in series. The main use of this directional relay was to trip the faulty generator in the case of parallel operating transformers using the criteria "change of power direction". Auxiliary power from the grid was required to operate both the secondary relays and the shunt trip. Henri Owen Tudor proposed the accumulator in a patent in 1886 (Fig. 16).

Transformer operated tripping devices were used in less important stations. Please note that in the first stations two

11 Characteristic Curve of Overcurrent Relays



12 Time Grading of Overcurrent Protection Waterside Station New York, 1901



Dedreux, C.

proposed

a delayed

overcurrent

tripping

device

in 1891

DRP Nr.59 192

current transformers were used one for the relay and one for the tripping device. In the Cleveland-protection, developed in 1908, the current transformer was connected with the tripping device of the breaker mechanism. To achieve a delayed tripping; a time-fusible-link was connected in parallel; unblocking the current after the link melted. To achieve selectivity, a time delay was sometimes necessary. The term "selectivity" was already used in telephone systems to differ between intermittent and permanent currents. The introduction of overcurrent protection in 1901 was without time grading. Later they used clocks as timing elements (Fig. 21; Fig. 18)

Merz und Price proposed the longitudinal current differential protection in 1903. This will be described in a later article. The use of a hinged armature in an overcurrent relay was published in 1902 in by SIEMENS and Brown, C. E.L. However BBC claim the patent on a current-dependent relay (DRP No. 143556). AEG supplied overcurrent relays with two phases on one Ferraris disk one year later and published a patent with "common maximum and reverse-current-relay" for generator protection. It was an aluminum disk driven by a three-limb magnetic core. The outer limbs were excited by the voltage, the center limb by the current (Fig. 10). Under normal current direction the relay had a huge delay at high overcurrents but tripped immediately under reverse current conditions.

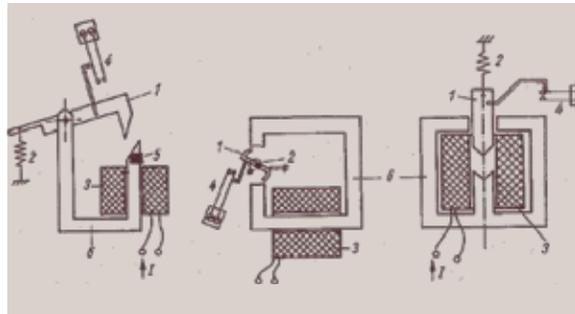
Krämer, Chr., F&G patented a "relay for automatic opening of alternating current circuits" in 1904 (DRP 174218). They used a Ferraris disk as a time-element of the voltage drop relay as selective short-circuit protection. The principle of distance protection is published in a general summary in this paper; this is the invention of the distance protection.

ASEA designed and built their first protection relay in 1905, the overcurrent-time-protection type TCB. The need for protection for ring system operation was becoming more important in 1908. The first ideas used voltage drop relays without directional elements. An AEG patent in 1908 (DRP 210 152) described a solution that used a short circuit voltage setting to block the timing element. This was of course only possible if all relays had the same time setting and the stations inside the ring had only one circuit breaker.

The idea for an automatic recloser was patented by Bollinger, Emag, in 1913. In the 1930's the dead time was 3 minutes to allow motor starters to reset or to switch off motors manually. V&H provided in 1925 an "automatically on-off-switch" which switches on the station 3 minutes after tripping automatically. Two or three reclosings were common, sometimes operated by dropping weights.

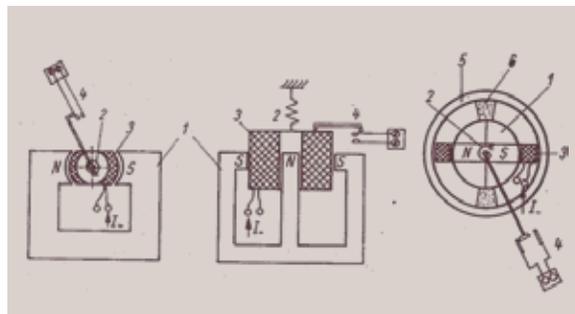
Schrader, W., V&H, patented a relay for automatically working overcurrent tripping devices in 1914. Contrary to known extra-high current relays this device did not wait until a certain level of current was reached; it reacted after certain increases of amplitude in a certain time - the first di/dt-relay. The first time grading in opposite directions was used in 1918 although the principle had been known since 1900. Today it is known as directional overcurrent protection. The time for

13 Electromechanical Relays



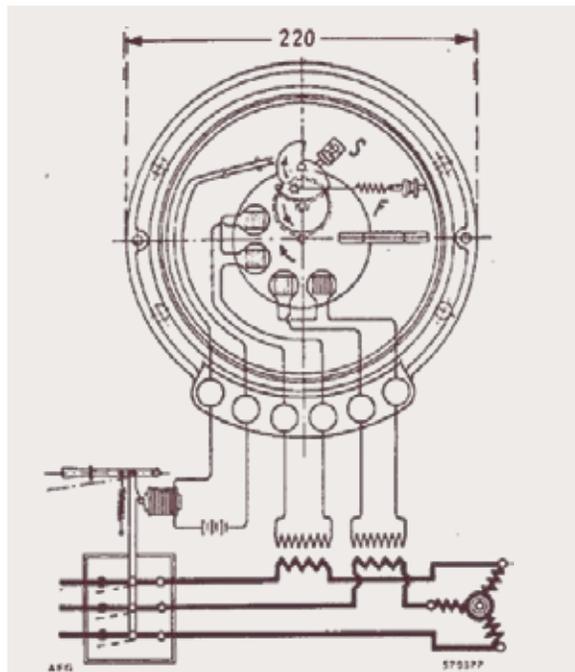
13 (Clapper-Type-Armature; Rotating Armature; Immersion Armature) 1- Armature 2- Spring Return Device 3- Field Coil 4- Set of Contacts 5- Short-Circuiting Ring 6-Yoke

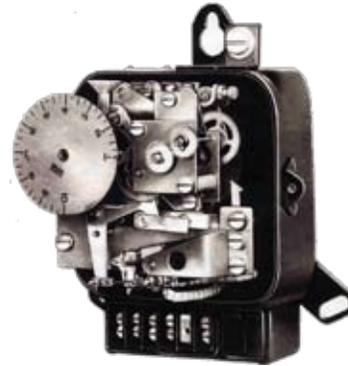
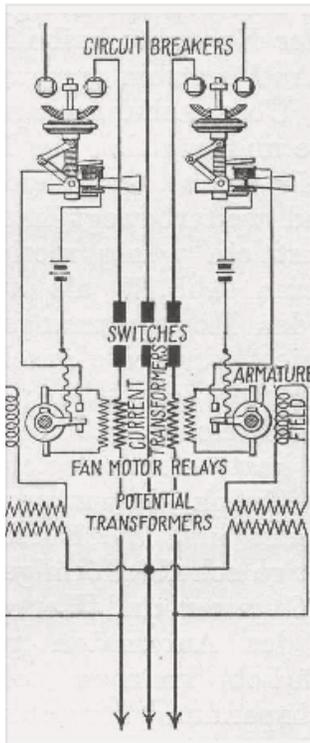
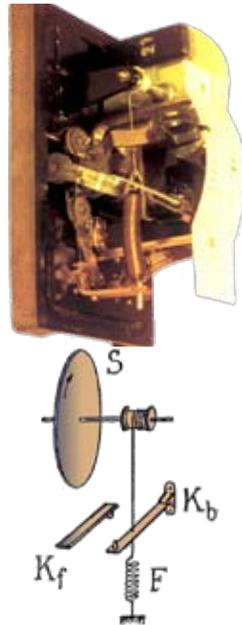
14 Permanent Magnetic Relays



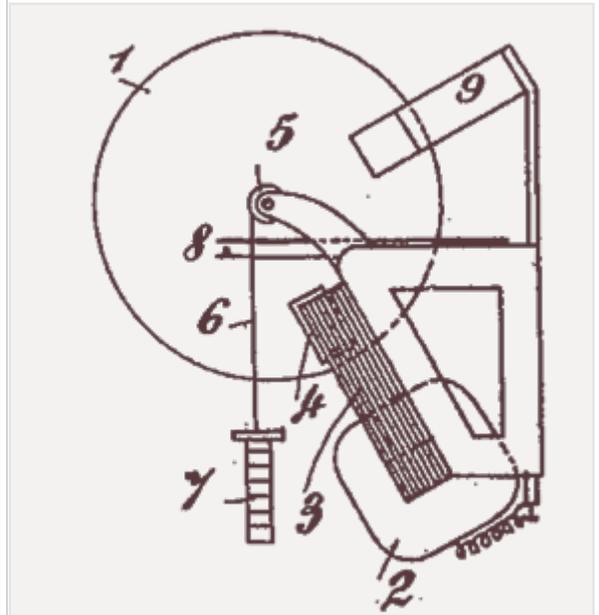
14. (Moving Coil with Outside Magnet; Plunger Coil; Moving Coil with Core-Magnet) 1-Permanent Magnet 2-Spring Return Device 3- Operating Coil 4- Set of Contacts 5- Magnetic Return 6- Non Magnetic Space

15 Two-Pole Overcurrent Relay AEG, 1903



16 H. O. Tudor**17 Relay RA4, S&H****18 Relay Rs104, S&H****19 IDMT- Relay, AEG, 1905****20 Reverse-current-relay Niagara, GE, 1899****21 RA1, S&H, 1925**

Überstromrelais RA1

22 Overcurrent Delay Relay BBC, 1902

protection operation close to power plants was very high up to 12 seconds. Biermanns, AEG, used dependent overcurrent protection as line protection already 1919. The circuit breakers and relays used at this time required a selective time interval in the range of 0.5 up to 1.5 seconds (Fig. 12).

Pfannkuch.W of AEG developed a cable protection relay using a pilot wire in the main wire - the patent "Pfannkuch-Protection" (DRP 398482). Höchstädter,M. proposed another cable protection ("Lypro") in the same year. These relays could detect two-phase short-circuits and earth-faults. This split-conductor protection caused a stir, later they were substituted

by distance relays with advanced features. Another approach to achieve fastest tripping times with rugged devices (not high accuracy) was to observe that the fault current has the same direction on both sides. Common operating times of 0.5 s were already achieved in the US in the 1920's; in Germany 2 s and more were quite common.

Further initiatives in distance, differential and generator protection will be covered in later articles.

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