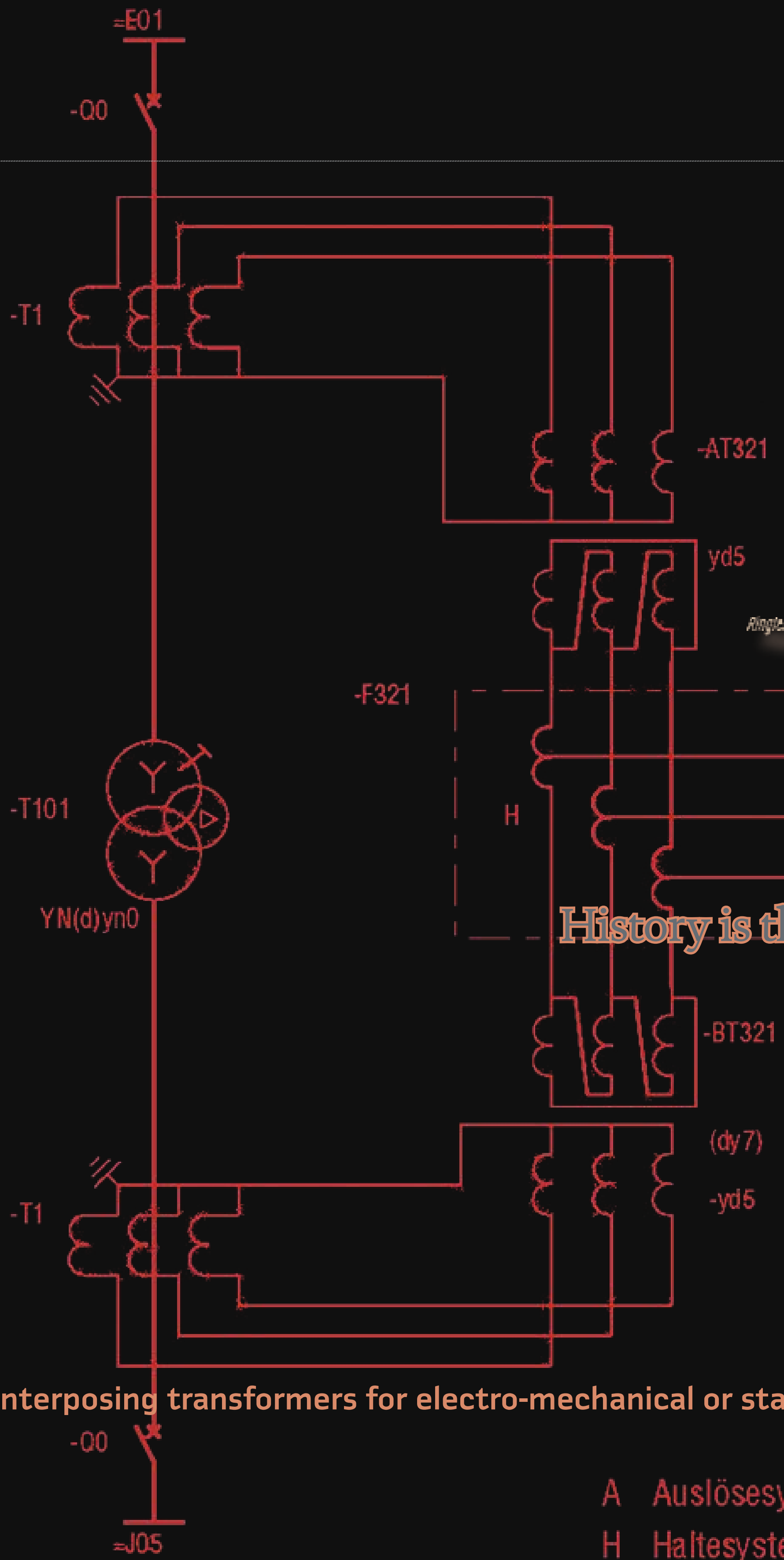
History is the tutor of life

Differential



Interposing transformers for electro-mechanical or static protection

Busbar Protection DRS-BB, ELIN, 2001

by Walter Schossig

Protection History

Protection for Multiple Busbars (Siemens)

Differential Protection

Further Steps

Differential protection has become popular - but open issues still exist.

The beginning of differential protection, first solutions for stabilization due to saturation of measuring transformers and transformer taps were covered in the last issue of PAC World. The problem of reliability in case of external faults and the different behavior if working as line differential or transformer differential, the problem of inrush-detection, the usage of interposing transformers and zero-sequence current elimination have been an important topic since the 30s of the 20th century. The digital relays solved a lot of problems, but there are still some open issues.

Harmonic Restraint

Overriding an operating current with a timing element caused unacceptable delays. A bypass was used to eliminate the timer in case of the startup of an additional overcurrent protection used in that case. When transformers with granular transformer magnetic sheet steel were introduced, the high operating currents did not allow this bypassing anymore.

In 1943 AEG provided a fast protection device consisting of two complete differential relays. One relay was used as the starting relay of another one (Fig. 2). This configuration was based on two patents of Gutmann (DE 889031 and DE 896676). The differential current flows through the starting elements. D2 is bypassed in this first step and it trips with a time delay. It has been shown that the third peak of the current was only 40%. The K-Relays (dashed line), which could trip independently, was set at 0.5 s. This configuration was quite stable, but was a huge effort. This effort could be decreased in 1950 with a simple auxiliary circuit instead of the second differential relay. This auxiliary circuit uses the differential relay two times. In 1944 AEG developed the high-speed differential relay QS2 (Fig. 5).

Blocking with second harmonics (harmonic-restraint) was invented by Kenneddy,L.F. and Hayward,C.D.in 1938. In the differential relays provided by BBC in 1961 (Fig. 1) stabilization was reached with a contact system mechanically tuned to the frequency of the operating current. The curve is distorted (Fig. 4). The force of the current on the iron system of the relays is with the nominal frequency, while the force of the sinusoidal alternating current is according to the doubled nominal frequency. The contact system vibrates due to the impact of the sinusoidal current. The impulses are too short to activate the contactor, but in case of a fault the contact will be closed immediately, even in case of switch onto fault. It trips after 0.1 to 0.15 seconds. Three-winding transformers used the DM2s. The difference (Fig. 3) of two currents has been compared with the current of winding 3. Only when

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 Thueringer 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.

two systems tripped it was a fault in a transformer. Because these devices were single-pole devices, six were used for one three-winding transformer.

Implementation of Rectifiers

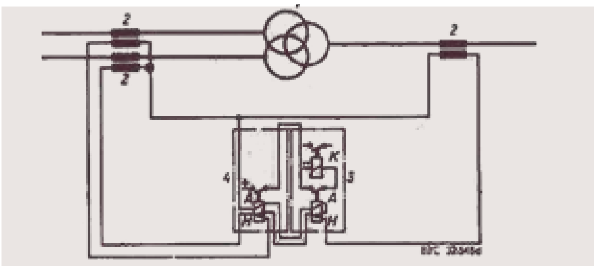
AEG first introduced dry-disk rectifiers in distance protection in 1937. They proposed their usage in differential relays two years later. The approach was based on the estimation of an average value in moving-coil relays. Because the disturbing operating current has a sharp curve, relays measuring average values should be more insensitive than the common electro-magnetic relays working with root mean square used at the time. This approach of Engelhardt was not that successful, because the ratio of the average values of the operating currents´(form factor) was not big enough to achieve a secure starting at small fault currents (0,3 In) and to achieve stability at the same time. The practical examination of this interesting approach was postponed. 10 years later it was used for a second time, but with additional delaying elements.

In 1950 Neugebauer, Siemens, showed that every mechanical ratio can be emulated with a rectifier and a polarized relay in the diagonal as an indicator (Fig. 6).

The measuring transformer Tr1 emulates the geometrical sum, while Tr2 in the diagonal uses the difference current $|i1 - i2| = i\Delta$. Depending on what is bigger - the sum or the difference, the differential current flows in different directions through the moving-coil relay Dr, that closes a contact in one or the other direction. The impact of stabilization varies with the tap $k = |i1 + i2|$. Problems occurred here as well with cold-rolled sheets in transformers (high and slowly decreasing operating currents).

A real solution was proposed by Gutmann, AEG, in 1950 using moving-coil relays in a rectifier circuit. An inductive diverter resistor increases the impact of harmonics on the "bias"-side but decreases the impact on the "trip"-side with the differential current. The result of this simple principle was not sufficient to stabilize the differential relays. Further research by ABB resulted in a separation of differential protection and blocking. The established quotient relay QS4 could be used further and an additional blocking element RO1h was used.

3 Single phase basic scheme for three-windings Transformers , DMs and DM2s, BBC, 1961



This add-on could be realized in such a manner, that it only observes the curve of the current. Further improvement was possible with the idea of Halama (Fig. 11). A high-pass filter between the diverter resistor and the input of the rectifier changes the ratio of magnitudes in a manner that increased zero-crossing occurs. The RO1h allowed a fast response on operating currents and the abandonment of timing elements or damping. This allows a fast differential protection and was presented in 1957 as the stable fast differential relay RQ4 (Fig. 7). It was used in 1957 in the first 380 kV connection in Western Germany (Rommerskirchen-Hoheneck, RWE).

Choice and Usage of Interposing Transformers

The ratio of the main instrument transformers on the high and low sides of a transformer is not the same as the actual transformation ratio of the transformer. The vector groups also have to be considered. In 1916 Siemens patented (DRP 315 272) interposing transformers for adjustment of vector group and ratio for differential protection. Taps and secondary replica of primary equipment allowed correct behavior during internal and external failures (Fig. 8). But even transformers with vector group Yy0 the additional tertiary winding requires a delta-connection to eliminate the zero-sequence components in case of external single-phase failures. The standard circuit shown on page 70, was developed in the 1960s. A variant of OERLIKON to eliminate the position of tap changer is shown in (Fig. 9). The secondary windings of current transformer on

Differential relay, with Blocking (DMs, BBC, 1961)

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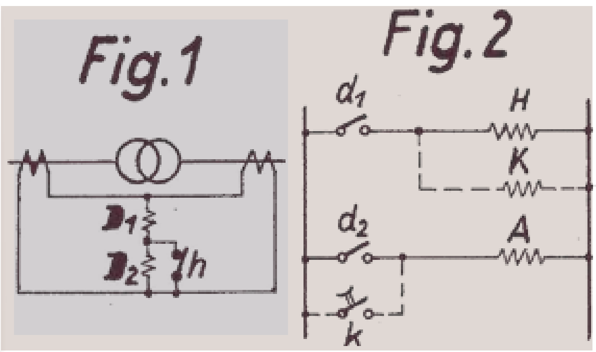
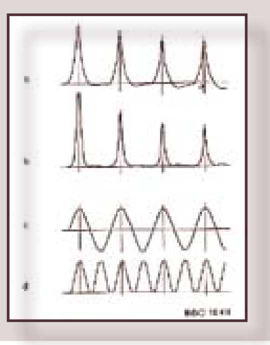
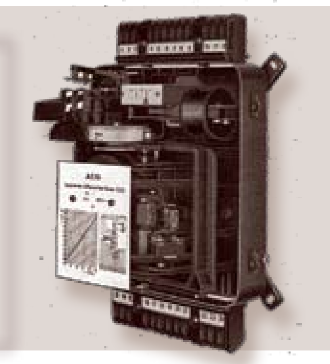
2 Differential relay with starting relay, Gutmann, AEG, 1943



4 Curve of inrush



5 High speed differential relays QS2, AEG, 1944



Differential protection allows fast and selective 100% protection of transformers, generators, motors & lines.

both sides of the transformer were bypassed with reactance coils D1, D2 with linear characteristic. Reactance coil D2 was mechanically connected with tap changer S, the reactance of the coil was related to the position of the tap changer.

Calculating and connecting interposing transformers is a little bit tricky. There are many ways for something to go wrong (Fig. 10). The "*380-volts-method*" was a fast and secure method to detect failures. A three-phase short-circuit on the low-voltage side of the transformer and feeding on the primary side with low voltage was measured with 9 ammeters (three ammeters on every side and in the differential tree, with an internal and an external fault. Wrong connections could be easily detected.

Busbar Differential Protection

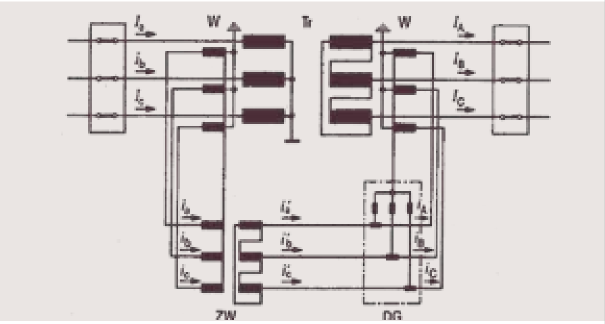
To need to protect busbars was not recognized as important in the first years. Failures on the busbar were detected by the protection in the infeed (transformer or generator). The long busbar fault clearing time was a problem for the stability of the generators and the grids and could cause huge damages in a substation. The first busbar differential relays worked as shown in Fig. 15. This simple scheme - one overcurrent relay without time element was sufficient- showed deficiency. The advantage was doubtful and a lot of customers avoided using it:

- direct interconnection of current transformers causes problems in operation, testing of relays and changes
- there is no stabilization for external faults
- it was only suitable for single busbar systems
- a switchover of current transformer was not possible due to overvoltages and contacts in the main current circuit are not appreciated.
- three different differential circuits are necessary in a three-phase system - a huge effort in a single busbar system

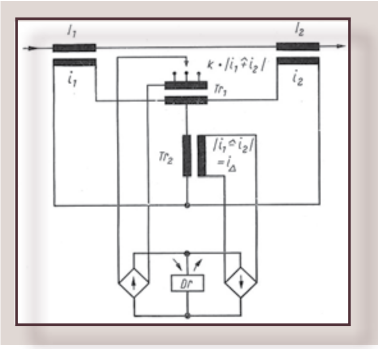
In 1939 Smith,R.M. und Sonnemann,W.K. of Westinghouse described together with Dodds,G.B.of DLC (US) the usage of a quotient differential relay as a fast busbar protection. A lot of disturbance records documented numerous short circuit examinations. Interpretations and discussions showed that the busbar issue is most of all a current transformer issue and not a relay issue. If all current transformers would work the same, a simple overcurrent relay as described would be sufficient. In reality transformer failures occur, so it is practically impossible to avoid it. This failure is caused by saturation of transformers and additional magnetization caused by a superimposed DC-component. A short-circuit outside the busbar with primary differential currents more or less equal to zero, causes high currents on the secondary side and would cause a false tripping.

This happens especially when a high short circuit current flows through the instrument transformers of the faulty line which is supplied by a huge number of small lines with different small single contributions. In that case all current transformers work on an operating point of their characteristic. To avoid this, a solution known from transformer differential protection was used - quotient differential system with bias

8 Replica of transformer vector group with interposing transformers

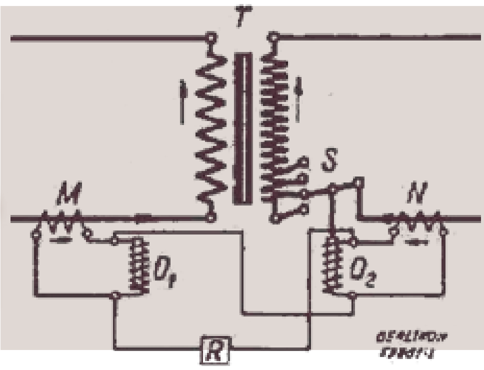


6 Differential protection with moving-coil, Siemens

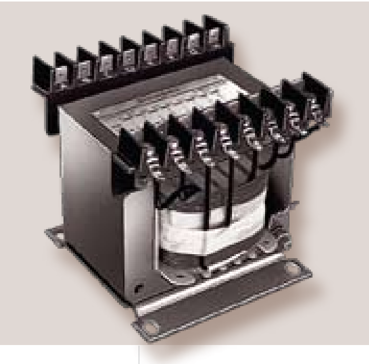


7 Make-proof relay RQ4, 1957

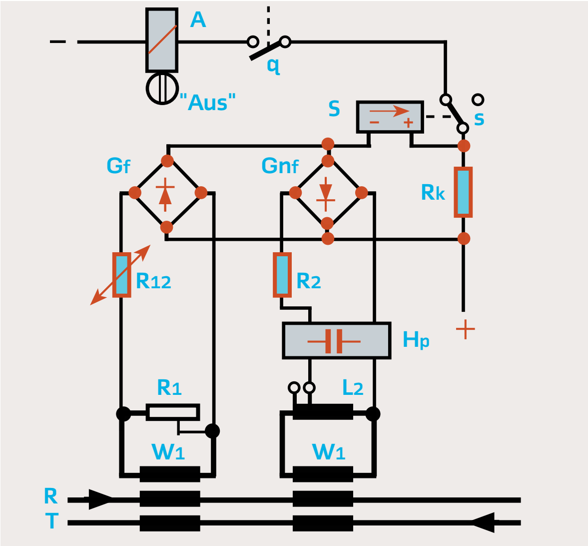
9 Tap changer with differential protection, OERLIKON



10 Interposing transformer 4AM5, Siemens



11 Lockout of differential protection, AEG



A Tripping relay | q Differential relay | S Lockout relay | Hp High-pass

> Interposing transformers are no longer necessary, which simplifies commissioning.

system. The difficulty in busbar protection is that every feeder should have its own bias system – which was not possible. The use of several quotient differential relays was proposed to solve this problem. The tripping contacts of up to three bias systems shall be connected in series. Lines with a huge difference between smallest and biggest short circuit currents shall be protected with differential relays with current dependent startup quotient. To restrict fault current, off-state resistances were used. The resistance should not be that big in order to avoid disturbing the protection operation.

A new quotient differential relay was also described, in which the three bias systems work with similar coils. They are connected in such a manner that the coil of the biased system excites with another coil another bias system, even if only one bias system has a current. This system was quite stable, which was confirmed by many trials. The fist stabilized busbar differential protection for a 110-kV-substation was developed by Siemens in 1957. Difficulties could be solved by new elements like mixing transformers and moving-coil relays. To extend differential protection for substations with multiple busbars was relatively simple. In the secondary circuits of the mixing transformers M the maximum current was 300mA- a switching with conventional auxiliary relays was possible. In the 110-kV-grid of the German HEW (Hamburg) within 3 years twenty busbars were protected in 9 substations with RN23 and RN24 relays.

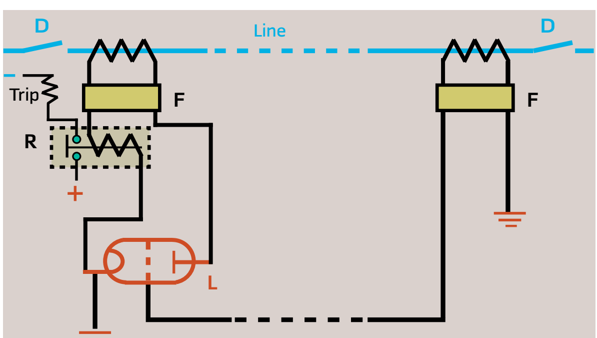
Further Developments of Differential Protection

The French utility EDF decided in 1947 to abstain from differential protection and to use Buchholz-protection with additional frame ground protection instead. Frame leakage protection means isolated installation to detect earth faults. Later they came back to established differential protection systems. Seeley and Roeschlaub, USA, proposed in 1948 a busbar protection based on a high-impedance current differential principle. In 1951 this was already used in 600 substations. High-impedance protection, especially restricted earth fault protection, is quite common in English speaking countries. In German speaking countries low impedance protection is the typical one. Maret,A. proposed in 1938 to use electron tubes instead of electro-mechanical relays for line differential applications (Fig. 12).

In 1940 a line with a length of 130 km in Germany was protected by a directional power comparison protection. A high-frequency connection along the line combined with a distance protection was used. One year later Fröhlich,F. proposed a fast directional comparison protection to be used for short parallel cables (DRP 646 348 and 653 787). The use of 5 A secondary current limited the possibilities for line

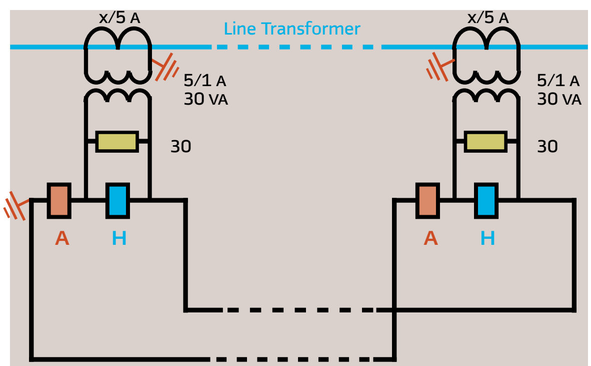
> The need of busbar protection was not recognized in the first years.

12 Electron tubes differential protection 1938



D circuit brk | F filter | L electron tube | R maximum current relays

13 Voltage differential protection RQU2, EAW, 1959



differential due to the burden of the cable ($S = I^2 R$). Especially distant transformers shall be protected as well. That's why voltage differential protection was developed in the 1950s. This protection compares voltages (proportional to currents), sometimes only with thin communication cables. The principle of the RQU2 of the East-German EAW is shown in Fig. 13.

"Pilot-Wire-Protection" was introduced at Commonwealth Edison Company, Chicago (US) in 1954. The CFD-Relays (product characteristic-differential-relays) were used in a 138 kV system. It was solidly earthed with mixed cables and lines. The length of the lines was between 3 and 25 kilometers. Several problems occurred: no startup with fault currents of up to 20 kA, no startup when energizing the line, startup on both ends of the line even with single side short circuit currents of 2 kA and more, proper working of pilot wire on lengths up to 25 km only (impedance of 125 Ω and capacitance of 4 μF). Voltages up to 19 kV have been induced.

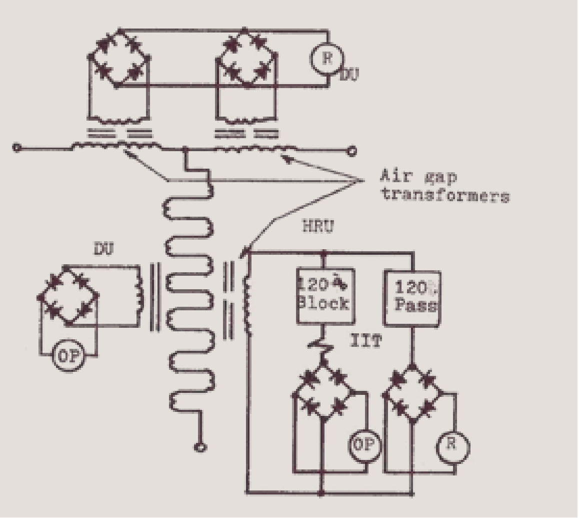
In a paper published in 1960 a phase comparison relay working with transistors was described by Marchal (Belgium). It worked without any problems for more than 3 months. It was obvious that the use of electronics in relays was met with skepticism. The idea of this system was developed with tubes.

Phase comparison systems have been used in the US, the Soviet Union and some English speaking countries. Especially for long lines with high-frequency communications, this protection system was a possibility. The phase comparison protection compares the direction of the single phases of the current. Another possibility was power direction comparison.

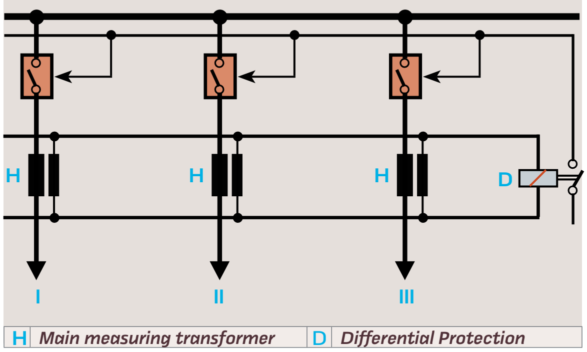
Longitudinal differential protection with inherent pilot-wire supervision Gutmann, AEG, was proposed with his Cross conductor differential protection RQL (Fig. 18). The values to be compared were measured with mixed transformers (Fig. 16). The setup of the relay was possible with a knob between 0.7 up to 2,5 In (3-pole-failure). A short circuit in phase A starts up the relay at a value of 0,5 $\sqrt{3}$ of the scale value, while a fault B-C and C-A the $\sqrt{3}$-times value. This behavior occurs with the common ratio of windings 2:1:1 of the three primary windings on the left and on the right, supplied with phase A; phase C and the sum current.

In 1966 BBC commissioned the first electronic busbar protection in a 16-kV-substation. In the autumn of 1967 KEMA successfully tested in Arnheim (Netherlands) under extreme circumstances the electronic busbar protection. The tripping time measured was 13 ms. In 1972 more than 120 substations were already equipped with this protection. Fig. 20 shows a cubicle with the electronic busbar protection in a plant with double busbar, transfer bus, coupling and 25 feeders with a built in test set. In 1967 EAW launched the RQS4-family. It included RQS4T1 (3 pole differential); RQS4T3 (1 pole transformer differential); RQS4G (generator differential); RQS4Z (three windings) and RQV (inrush blocking for older relays). ASEA's busbar protection RADSS was put into operation in a 130-kV-plant in Västeras (Sweden) in 1969. Siemens developed an electronic busbar differential protection in the late 1960s. The tripping time was 7 ms

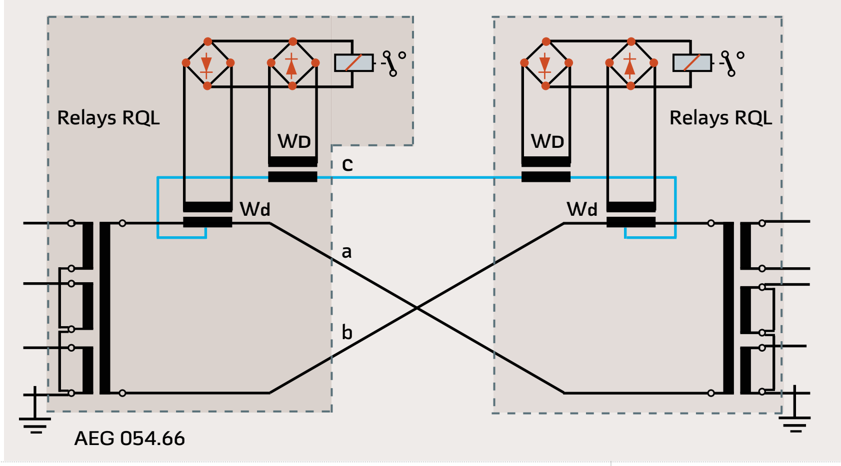
14 Filter, Westinghouse, 1976



15 Principle of a busbar-protection



16 Principle cross-conductor differential protection RQL, AEG, 1966



The first electronic busbar protection was commissioned in 1966.

17 Transformer-differential- relays DT92 modures©, BBC, 1982

Transformer-Differential-Relays DT92 modures©, BBC, 1982

(without saturation and with the time of a fast tripping relay) - as low as 25% of a period. In case of saturation, two following half-waves have to be observed ("2-of-2-circuit"), and the tripping criteria has to occur for a second time within 10 ms (at 50 Hz).

In 1976 Westinghouse improved their filters used since 1958 in order to address the use of new materials in transformers (Fig. 14). Further solutions of Larson,R.R.; Morrisson,I.F.; Schweitzer,E.O. and Skyes,J.A. published in 1977 should be mentioned. Strobl,J., ELIN, patented 1975 (AT328537) the adaptation of a vector group without interposing transformers with op-amps (Fig. 21).

The differential relays DT91(transformer) and DL92 became popular when BBC launched "modures" in 1978. DT92 (Fig. 17, 1982) works with 3 systems - so it is stable and independent from the type of fault. It operates in a 19"-rack with built-in interposing transformers. The line differential compares voltages. Due to that, an adaptation was not necessary for small lengths of lines, or only a raw adjustment was necessary for longer lines. The pilot wire was supervised. Static busbar protection UZ91 (single pole) and UZ92 (3-pole) were launched by BBC in 1983, both working with high-impedance-principle. Complicated busbar configurations, even with transfer busbars might require selective current direction comparison. If separate and sufficient cores of measuring transformers are available, single busbars, 1 ½ -schemes and ring busbar schemes are protected with high impedance protection.

The first phase comparison protection for high voltage substations was produced by BBC in 1985, Fromm,W. and Maier,H.A., (BBC) proposed a comparison protection for high voltage lines using a new approach two years later. The first digital busbar protection of Siemens was commissioned in 1988 in a 110-kV-substation. The digital differential relays 7UT51 (transformer) and 7SS50 (busbar) should be mentioned. ABB's RET316 (transformer) and AEG's PQ721 were launched in 1990, the busbar protection REB 500 of ABB in 1995. EAW's transformer differential DSQ2 has been available since 1995, ELIN/ VA TECH SAT launched the busbar protection DSR-BB in 2001, later DRS-C2BB. Decentralized DRS-BB operates for instance in Uttendorf (AT), Genf (CH) and Weimar (DE) in substations of the railway.

Final Remarks

Differential protection allows fast and selective 100% protection of lines, transformers, generators, motors or their combinations. Special use as multi-line protection and 4-windings-protection for transformers is possible as well. Improvements in the behavior of current transformers, discrimination of saturation and adaptation of characteristics improve stability. Sensitivity for single- and multi-phase faults could be improved. Interposing transformers are no longer necessary, which simplifies commissioning. Special applications and further protection devices for transformers shall be covered in a later issue.

This article does not cover all differential protection relays developed and used around the world. In order to provide a more complete coverage of the history of protection, please send us any information on products not covered in this, as well as any previous articles.

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18 Protection RQL, AEG, 1966

19 Relay LR91

Fast Direction Comparison Relay LR91, BBC, 1982

20 Cubicle with electronic busbar protection BBC, 1969

21 Op-Amps instead of interposing transformers, Strobl, ELIN, 1975