INTEROPERABILITY BETWEEN NEW AND LEGACY PRODUCTS IN DISTRIBUTION SYSTEM PROTECTION

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INTRODUCTION

An Electrical Distribution Power System, in contrast to an Industrial Plant, develops continuously over a long period of time and uses the differing current generation of technologies available at the time. Its expansion progress measured over the past decades is a mirror reflection of the economic growth of its country.

Similarly the growth of the citizen population corresponds to generational profile of the protection relays with its differing products and technologies. Especially numerous are the product types and technologies of major power system expansion phases. There were high growth rates particularly in the 60’s and 70’s in most industrialised countries. However, the installed assets of these years are now nearing the end of their economic useful life.

The exchange of line differential protection relays becomes complicated due to the geographic coverage of the protection systems over medium and long distances. At the minimum, two substations find themselves using relays of the same system that exchange data over a R2R communication channel.

The advances in telecommunications frequently make a change of the complete protection system concept necessary. The majority of today’s telephone networks have now been upgraded from analogue to digital, with the result that there are hardly any rentable wire pilot wires available anymore for analogue differential relays.

There are two possible strategies for operating differential relays over digital communication channels. Either the analogue measured values of the existing differential relay are digitised first and then sent over the digital channel, or the analogue relay is replaced by a numerical relay. In any case the numerical relay should be able to operate over a traditional pilot cable.

The exchange of a single relay function is in many cases just not possible because the technological surroundings themselves have changed and the demands expected from the relay have increased. More and more automation systems are installed today in distribution power systems and these require more and better quality data from the substations. Such comprehensive data can hardly be provided by traditional analogue protection relays.

Frequently the exchange of technically obsolete equipment is carried out because of the data acquisition requirements of automation systems.

Modern Intelligent Electronic Devices (IEDs) are the best suited to meet the extended tasks of protection and substation automation [1]. As well taking care of their own specific power system tasks they can also control and monitor the circuit breakers and isolators of the associated feeders as well as record the current feeder data. Each IED is also a comprehensive feeder database for distribution automation schemes (Fig. 1). All static and dynamic feeder data can be downloaded via the informative port over a R2S communication link to the subscriber.

It is hardly to be expected that a refurbishment can simultaneously realise all the new strategic goals of the protection, substation and power system automation in both stations as well as provide the associated communication link. The upgrade of these substations confronts the planner with challenges that do not occur with new plants.

Indispensable for investment security is however a stepwise concept that leads to the final planned performance scale of all the stakeholders. For that purpose, products are necessary that on the one side can be simply connected to the existing traditional pilot cables while on the other side have all the necessary facilities readily available for a later protection and automation upgrade.

CONVERTERS TO INTERFACE TRADITIONAL AND MODERN COMMUNICATIONS MEDIA

R2R Communication technology from the last 20 –30 years can be found in today’s typical distribution substations. Analogue as well as digital systems operate over a range of
media from conventional pilot cable, or over ISDN and
even up to sophisticated digital communication networks.
These side-by-side technologies frequently cause
difficulties at the interfaces of the relays with the
interoperability between the products. If a pilot wire relay
applies instead of analogue measuring quantities digital
ones, modern digital communication media such as fibre-
optic cables and digital communication networks as well as
traditional pilot wires can be used for the transmission of
measuring quantities. For the actual adaptation to the
different types of communication media it is practical to
separate out the actual communication part of the relay.
The
relay remains basically unaltered and can always be reused
later even after an exchange of the communication media.
External communication converters, that adapt the interface
of the relay to the communication media to be used, offer
the planner the best economic option.
The regulations for protection and telecommunications
follow completely different philosophies. All protection
relays as well as the communication converter must
conform to IEC 255. This is not always so for the
commercially available communication devices. The
simultaneous voltage stress on devices and multi-core
cabling during system faults demands preventative
measures and secure measurement approaches. It is directly
under these conditions, which are not usually normal for
communication equipment that the protection relays must
reliably operate. The converter must also be suitable for
operation in an electronically hostile substation
environment. Moreover, this is also applicable for the fibre-
optic systems. The cables themselves are indeed free from
electromagnetic interference but their Digital
Communication Equipment (DCE) and the auxiliary power
supplies are not. These can be inductively influenced via
the substation multi-core cabling or directly influenced
from the common station batteries.

**TRADITIONAL PILOT CABLES**

The overwhelming majority of the more than 200,000
differential relays that are in worldwide operation today use
pilot cables as their communication media. The useful
working life of the cable is about double that of the relay.
Their exchange is extremely expensive and in many cases
not practically possible.

Differential relays for refurbishment projects must therefore
be also able to exchange digital data over traditional pilot
cables. At this point the traditional and the new operating
conditions meet each other.

Because according to the rules, the pilot cable and the high
voltage cable are laid parallel to each other, usually in the
same trench, earth fault current induced voltage along the
pilot wires up to a few kV are induced into the pilot cable
[2]. One portion of the earth fault current flows back
through the ground and the resulting magnetic field along
the pilot cable becomes unequal to zero. These currents can
be extremely high especially in power systems with low
resistance star point earthing or during double earth faults
in isolated power systems. The phase true added sum of
the current is now no longer zero, but has the size of the fault
current. The current flows via a multitude of paths over the
ground back to the voltage source. Every one of these
paths, according to its length, induces a voltage in the pilot
cable. The potential level on the pilot cable rises with the
distance and the fault level. This causes a high voltage
stress between the pilot wires and earth. This is at the end
equal to the full amount of the induced voltage V (Fig. 3).

If the cable screen is earthed at both ends of the pilot cable
then there is a reduction in the influence. In this case,
during an earth fault there now only flows a part of the
earth fault current back through the ground. The remaining
part flows over the metal shield or in a parallel earth cable
with no influence on the pilot cable. This percentage
reduction of the influence of the disturbance current is
called the reduction factor r of the cable.

When L is the length of the parallel cable, then the induced
voltage along this length is equal to:

\[ V = I \cdot r1 \cdot r2 \cdot 2\pi f \cdot M \cdot L \]
where:
f  frequency, e.g. \( f = 50 \text{ Hz} \)
M  inductivity between power and pilot cable per km, for a distance of 80 cm between power cable and pilot wires, and for an earth conductivity of 0.02 S/m, e.g. \( M = 1.347 \text{ mH/km} \)
I  earth-fault current, e.g. \( I = 15 \text{ kA} \)
L  length of parallel running cables, e.g. \( L = 8.4 \text{ km} \)
r1  reduction factor of power cable, \( r_1 = 0.2 - 0.4 \) for single conductor cables, e.g. \( r_1 = 0.3 \)
r2  reduction factor of pilot cable
  - for unscreened cables \( r_2 = 0.4 \)
  - for best screening, e.g. \( r_2 = 0.4 \)

Example: \( V = 15 \text{kA} \cdot 0.3 \cdot 0.4 \cdot \frac{2\pi}{50} \cdot \frac{1}{1.347 \text{m}\Omega/k} \cdot 8.4 \text{km} \)
\[ V = 6.4 \text{kV} \]

These voltages must not rise above the insulation level limits of the cable and relay.

Voltage differentials also exist for cables that have non-symmetrical, untwisted pairs. If the induced voltages of the two pilots is unequal, a resulting voltage is generated across the pilots, that can have an impact on the traditional relay’s performance.

Fig. 4 Galvanic separation of ‘dirty’ pilot potential

This over-voltage is simply shorted out by surge diverters on plain old telephone lines. However, this method cannot be used for differential protection systems, because at precisely this very moment, the relay must acquire measured values through the pilots for its fault calculation. Pilot cables and differential relays must therefore be rated for these high voltage stresses. According to VDE standard 0228/4.65 the maximum induced voltage must not exceed 1.2 times the normal 2kv relay insulation level. This value is hardly sufficient according to the rules for differential protection relays. For midlength lines, up to 5kv over voltages can occur and for longer lines, 20kv can be expected. For such stresses, the relays must be outfitted accordingly or separated from the dangerous pilot potentials with barrier transformer protection.

For the protection of personnel, it is recommended to block off the dangerous over voltages directly at the door of the substation with barrier transformers mounted on the pilot cable sealing ends.

The relay panels and the pilot cable within the substation up to the cable ends are then insulated from the over voltages induced into the pilot cable between the stations.

INTEGRATED SERVICES DIGITAL NETWORK ISDN

A digital standard was established a number of years ago called ISDN that replaced the plain old analogue telephone network. This old system has now been widely replaced by the digital ISDN. Today most telephone networks are digital. Only the last mile to the individual subscribers are frequently still to be found using the conventional pilot cable. Thus the network provider can hardly offer analogue pilot wires anymore. Many differential protection schemes must therefore be reengineered from analogue measuring method to digital technique and matched to suit ISDN.

If ISDN devices establish links between each other then as well as the call number the required service can be transmitted. Thus various services such as telephone, data transmission over one call number can be carried out in a substation. The switched link remains exclusively dedicated for the subscribers for the full time of the session. This scheme also permits a much higher data transfer rate than analogue lines. In addition, the latency, or the amount of time it takes for a communication to begin, on an ISDN link is typically about half that of an analogue link. This improves response for numerical relay applications.

The switched link operation can tolerate transmission times up to 30ms so that sufficient safety margin is given.

FIBRE-OPTIC CABLES

The direct link with remote relays operates interference free using mono-mode optical fibres. The fast data exchange at 512kBits/sec reduces the operating time of the protection system to 15ms. For reasons of cost, modules of differing performance ratings are selected that are suitable for distances between 10km up to 35km.

DIGITAL COMMUNICATION NETWORKS

X.21 interfaces, 64, 128 or 512kBit or G703.1 64kBits/s interfaces are selected according to the available bandwidth of the communication network. A IEC 255-proof converter changes the optical signal into an electrical one for the DCE that accesses the communication network. The converter is mounted close to DCE of the communication network. The short distance to the DCE provides the noise-free electrical connection. The link from the converter to the harsh relay environment uses a cost effective 820-nm multimode fibre. The particular use of teleprotection over digital communications network are described in [3].

THE R2R LINK FOR MULTIPLE DATA TRANSPORT
The powerful digital communication connection is only partly loaded by the protection relay tasks. It can in fact be used to transmit in parallel other useful data and commands to the remote end.

**Intertripping Channels and Remote Monitoring**

By using telegrams, additional remote commands and distance indications can be safely and quickly sent using the digital channel capabilities. Possible applications include, phase segregated intertripping at the remote end, distance teleprotection signals and remote messages. The intertripping can also be initiated through an external relay (e.g. distance protection) via binary inputs in the differential relay. The status of the circuit breaker then becomes known and can be displayed and evaluated at the other end as soon as the circuit breaker auxiliary contact is cabled to the relay’s binary input. If the status position of the breaker is not wired, the relay assumes from the load current the breaker’s Open and Close position.

**All Data Available at Both Ends**

The measurements of the current and voltage can be transmitted in each direction over the R2R communication link according to the values and phases.

**Relay and Channel Supervision**

Modern differential protection relays continuously monitor all components in the complete system chain. This includes from the current transformers at the local end via the relay and the communication link up to the remote end. The communication link is because of its length and the resulting failure probability the weakest component in the protection system. Thus the channel supervision is of special importance.

With analogue systems, this was solved only with great difficulty.

A supervision of the link is automatically available because digital relays continuously exchange information. Any transmission disturbance is immediately detected causing a back-up over-current time protection to be activated. Thus some selectivity is maintained even during a channel failure.

The data integrity is tested for plausibility using checksums in the telegrams. This guarantees security against any false tripping caused by disturbances or damage to the pilot wires. On top of this, the quality of the transmission is measured and logged. The failure tolerant protection algorithm adapts and takes into account the data transmission quality. Thus the measurements are additionally stabilised during long signal transmission times on the channel.

An alarm is given whenever there is a break in the communication link together with immediate attempts to re-establish the link. No tripping occurs due to faults in a pilot cable, neither from broken nor from short-circuited wires.

Even the voltage across the two pilot wires do not rise in the fault case as they do for analogue relays and therefore do not endanger the insulation between the pilot wires.

**EXCHANGE OF DEVICES**

The exchange of traditional relays is quite straightforward in practice. In order to keep the relay variations to a small number, always the same relay version is installed regardless of the type of communications. The external communications converter itself carries out the adaptation onto the respective medium. Fibre-optic cables however can be directly connected onto the relay. Should pilot wire links be used then the converter changes the light signal into an electric one. Distances of up to 10 km can be bridged using this discipline. The pilot wires are connected to the communications converter directly at the pilot cable-sealing end. The converter complies fully with IEC255 and provides an insulation level of 5 kV at the pilot cable input. Should the induced voltages exceed this value then 20kV barrier transformers can be added. Thus the complete substation can be secured against any dangerous potentials on the pilot wires. A 820nm graded fibre leads from the converter to the input/output fibre-optic connectors of the protection relay.

The current transformer circuits are wired up in the usual traditional method. Voltage transformers can also be connected if they are available. This then allows voltage measurements to be taken and displayed.

**COMMISSIONING AND FUNCTION TESTING**

The set up of the relay is simple. After the input of the current transformer data and the required sensitivity, the relay calculates the best characteristics that meets the...
Browser supported service tools simplify the commissioning and testing of the relays. No special application software is required for the PC. The relay may be either accessed directly by a laptop computer or via the enterprise intranet (Fig. 5).

The differential protection topology can be displayed as well as the local and remote measured values according to magnitude and phase (Fig. 6). The commissioning can therefore be carried out from one of the cable ends. It is also not necessary to have a second person at the other end at the same time.

Signal transmission times, measured values and the circuit breaker positions at each end are also displayed. It is also possible to test the complete configuration and the current transformer polarities under load conditions, whereby a load current of 10% is sufficient. In contrast to traditional protection relays, no summation transformer is required since the measurement is phase-segregated. Thus the earth fault polarity of the summation transformers need not to be checked anymore, since there are no windings in the residual path.

The next step measures and records the availability of the communication link. Selectable procedures such as Logout Mode or Commissioning Mode and Test Mode support the commissioning and servicing of the relays. The complete configuration can be set up in Test Mode for testing purposes. The local end is set up in a mode of operation that, for example, allows the testing of the relay sensitivity. The received currents from the other end are set to zero so that defined test conditions are established. The other end ignores the differential currents that arise from the testing program and blocks the circuit breaker trip. If it is so set up, then it functions as a back-up over-current protection.

Injected test currents at one line end that produce a differential current do not cause a circuit breaker trip. All alarms are logged in exactly the same way and displayed as for a real system fault.

**FURTHER ENHANCEMENTS**

The user can now take advantage of a series of further advantages.

**Expanded Functionality**

As well as their basic capability as a differential protection relay, the modern relay provides a full range of functions for protection, control and monitoring of distribution system feeders (Fig.7).

**Improved Relay Algorithms**

Modern relays work with adaptive algorithms, that means with two different parallel running measurements that adaptively match themselves to particular fault conditions. For fault currents above the rated current in the protection zone a charge loading comparison algorithm is employed with tripping times less than one cycle.

High resistance faults from 10% full load up to full load current and evolving faults from outside the protection zone inwards are determined through sensitive current vector procedures [5]. An in-rush stabiliser can be activated for transformers or reactors in the protection zone. It evaluates the same as with the transformer differential protection, the second harmonics of the differential currents with respect to the fundamental frequency. Should the result exceed a set point then the differential protection relay is temporarily blocked.

Analogue systems work mainly with summation transformers because of the limited number of pilot cable cores. These transform the 3 phase currents into 1 phase. Digital relays work on the other hand, phase segregated. The fault sensitivity is however equal for all types of faults.
The transformer burden is reduced from a few VA to less than 0.1VA through the deletion of the summation transformer.

**FURTHER APPLICATION AREAS**

Lengthy cables often connect power transformers to a distant distribution system substation. There are no circuit breakers or current transformers on the transformer itself.

Legend:
- 87L Differential relay
- B Buchholz relay
- 49 Thermal overload

Fig. 8 Power transformer within the protected zone

In the past the protection zone of the transformer differential protection was usually expanded to include the cable. This resulted in a high burden for the current transformer at the far end of the cable, which endangered the stability of the differential protection relay due to the large through-fault currents. The trip command must be transmitted to the far end over not supervised links. Here the new concept provides considerable advantages. The line differential protection relay accommodates also the power transformer in the protection zone. The transformer vector group and the in-rush stabilisation can be set in the relay. Because in this configuration a relay is available at each line end and the tripping command is given at both ends. For the opening of the remote circuit breaker through the sensitive Buchholz relay B a parallel inter-tripping channel can be used.

Differential protection relays are strictly selective but offer no remote back-up protection. An over-current back-up protection is integrated into the relay that works independently from the differential relay. In addition an emergency over-current time protection is activated upon the failure of the information channel.

In case the relay protects overhead lines then 1 and 3 pole auto-reclosure may be applied.

**DATA LOGGING WITH REAL-TIME STAMPS AND TIME SYNCHRONISATION**

The internal battery-buffered clock in each relay can be synchronised via an interface (DCF77, IRIG-B over a satellite receiver) or via a binary input (1-minute pulse) or via the system interface.

The time synchronisation can also be transmitted to the other end via the communication link. Therefore it is sufficient to synchronise only one relay externally. The clock control of the other relay is carried out automatically over the R2R communication link. Every fault- and status report as well as fault record receives a real-time stamp with date at 1ms resolution. This eases the fault analysis at either line end.

**SUMMARY**

It can be seen from the age curve of the protection relay population of many distribution power system that there is an extreme need for exchange. The resulting refurbishing projects require adaptive products that let themselves be matched to the different technologies existing throughout the power system. Therefore the replacement relays must meet the requirements of the technology variations and satisfy substation and distribution system automation needs even when the implementation of some functions will be needed and executed later. This is particularly for differential relays that are distributed over two or more substations and must also still be matched to different communication systems.

Indispensable for investment security is a stepwise concept that leads to the final planned performance scale of all the stakeholders.

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