ADVANCES IN PILOT-WIRE DIFFERENTIAL PROTECTION

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ABSTRACT

A new numerical current differential relay that operates by digital communication over metallic pilot circuits has been developed, allowing utilities to re-use their existing pilot-wire protection signalling infrastructure while benefiting from the advantages of numerical relay technology. Sophisticated techniques were applied to achieve digital communication over metallic pilots without the use of modems. The new relay has been successfully applied in site trials and commercial installations in a number of countries, from which experience is reported in this paper.

INTRODUCTION

Many power utilities have applied pilot-wire differential relays to the protection of overhead lines and underground cables since the 1930s, and there exists a substantial installed base of direct metallic pilot-wire signalling channels for use by protection relays. Conventional pilot-wire differential relays, based on electromechanical and analogue technologies, remain popular and, although their replacement with numerical technology could be expected to realise a range of benefits, in terms of performance and cost, this replacement process has been slow, particularly at distribution voltage levels. This has been partly due to the technical problems associated with achieving digital communication over the existing copper wires, and also because the provision of alternative communication channels more suited to use by numerical relays, for example fibre optic links or digital communication networks, is often difficult for practical and economic reasons [1]. Some alternative solutions for re-use of the existing pilot circuits by more modern relays have been proposed, but these have relied on the use of external equipment such as summation transformers and modems, inevitably leading to higher costs and complexity for the user while also introducing significant technical drawbacks.

This paper describes a digital current differential feeder protection relay that has been developed for use with conventional copper pilot-wire links. The application of digital communications to pilot-wire relaying will enable utilities to re-use their existing protection signalling infrastructure and at the same time provide the utility with the option of a future upgrade path to direct fibre optic links. This paper describes how the problems presented by bandwidth limitations and interference which are imposed by metallic circuits have been overcome. It presents details of the communication method employed by the relay and explains how a high degree of immunity against communication failure has been achieved.

The relay described in this paper has now been installed for a number of years in field trials and full commercial installations around the world, and experience from these installations is reported in this paper. A number of the installed relays have experienced primary network fault conditions, and have been demonstrated to have responded correctly.

DEVELOPMENT OF NUMERICAL PILOT-WIRE PROTECTION RELAY

The use of metallic transmission media presents a number of problems for digital communication, notably in the form of limited bandwidth and signal attenuation. One approach that has been proposed for communication between numerical relays over pilot wires, is to convert the digital communication signal into an analogue signal in the voice frequency band by the use of a modem [2][3]. However, not only does this method entail a cost increase due to the use of the modem but also a performance penalty in terms of a delay in the operating time of the relay, because the modem needs time for modulation and demodulation of the data. The relay described in this paper, on the other hand, incorporates a baseband transmission system that performs digital communication directly without using a modem.

The characteristics of metallic pilot-wire circuits present a number of significant difficulties for a protection relay using digital communication, and these had to be resolved during the development through application of the design techniques described in Table 1. A commercial current differential protection relay has been developed using these techniques [4], providing phase-segregated current differential protection and, in addition, integrating a range of other functions, including magnetising inrush restraint, overcurrent guard function, transfer trip, back-up phase overcurrent and earth fault protection, and pilot supervision. Synchronised simultaneous sampling is performed at both line terminals through timing synchronisation control, with no external timing reference being required. Instantaneous current values are sampled every 30 electrical degrees and are sent from one terminal to the other in pairs, every 60 electrical degrees. The current differential relay has a typical operating time of 25ms following the occurrence of a fault. The distance over which the relay can operate varies with the type of pilot cable used, but for example, communication can be achieved for distances up to 8km using typical 0.9mm diameter pilot cable. Isolation to 5kV is provided by the pilot-wire interfaces internal to the relay.

Communication Issue	Countermeasure
Data must be transmitted and received over a single pair of wires to enable drop-in replacement of conventional pilot-wire relays.	A half-duplex communication system was developed, in which the relay transmits and receives data on a single pair of wires in alternate time slots, thus enabling it to use a conventional two-wire pilot circuit for communication.
Improvement of signal to noise ratio (S/N) is necessary for digital communication.	The effects of the limited bandwidth and signal attenuation associated with metallic communication media increase with signal frequency, so lowering the frequency of the transmitted data brings advantages by improving the S/N ratio that can be attained. This was achieved in the new relay by careful selection of the method of digital encoding, and by optimisation of the quantity of data transmitted in each frame, as well as the interval between frames, while considering the trade-off against ensuring satisfactory performance of the protection.
Signal attenuation along the length of the metallic pilot wires results in reduction in amplitude of the received signal and distortion of its waveform.	An automatic gain control (AGC) function in the signal receiving circuit automatically adjusts its amplification in order to obtain a constant output, thereby counteracting the effect of signal attenuation.
Severe voltage surges are commonly experienced on pilot wires during system earth fault conditions, either in the form of induced voltage from the primary power conductors or earth shift voltage caused by the impedance of the earth fault return path.	An integrated 5kV isolation transformer provides protection against voltage surges. Isolation to 5kV is sufficient for the majority of applications [5], but to provide additional isolation in the most severe cases, an external 20kV isolation transformer can also be applied as an option.
Despite the measures described above, periodic communication errors are inevitable due to induced noise from external sources. Dependability of tripping must be assured despite potentially high bit error rates.	Each transmitted data frame contains sufficient information for the protection algorithm to make its trip decision, based only on the data in that frame, thus ensuring that single-frame errors do not result in unacceptable delays in tripping.
Security against incorrect tripping due to communication errors must be assured.	Corrupted frames are detected by a 16-bit cyclic redundancy check (CRC) error detection code, but there remains a very slight possibility of a corrupted frame going undetected. Therefore, although the relay algorithm makes its decision based on a single frame of data, in order to ensure security of the protection, the new relay gives a trip output only when it receives two healthy frames, each of which give the same result. Tripping is allowed if two healthy frames give a trip result even when corrupted frames occur between the healthy ones, thus preserving the relay's dependability.

Table 1: Challenges and countermeasures for digital communication over metallic pilot wires

FIELD EXPERIENCES

Since the completion of its development, the new relay has undergone extensive field trials and commercial installations in a number of countries in Europe and Asia.

UK Trial and Applications

In order to demonstrate the capability of the new relay, and as part of its assessment by the UK Energy Networks Association (ENA), a site trial installation was established on the UK distribution network in December 2006, as reported in detail in [6]. The trial relays were installed on a 33kV cable feeder circuit of approximately 4km in length, communicating over an existing pair of 2.5 sq. mm plain copper pilot cables, and connected to the existing protection current transformers. The untwisted pilot cables were part of an existing multi-core cable, two cores of which were used for the existing conventional pilot-wire protection, and were laid in close proximity to the primary power cables as shown in Figure 1, thus presenting extremely severe conditions in terms of induced noise. The trial relays were connected directly to the pilot cables through their own internal 5kV isolation transformers.

Since the successful completion of the initial 1 year trial period, the trial relays have remained installed on the network and have, during the ensuing 3 years, experienced a large number of external primary faults causing through-fault current to flow in the trial circuit, the circuit being part of an extensively interconnected network. In the case of each of these external faults, the trial relays remained stable and no communication failures occurred. On one occasion, when the pilot-channel was disconnected for operational reasons, the integral pilot supervision function within the trial relays correctly detected the communication failure condition and issued an alarm.

One incidence of a power system fault on the trial cable circuit itself was also experienced. The trial relays operated correctly for this internal B-phase to earth fault, both terminals issuing a trip signal in approximately 25ms, suggesting an improvement in operating time of more than 30ms when compared to a conventional pilot-wire differential relay.

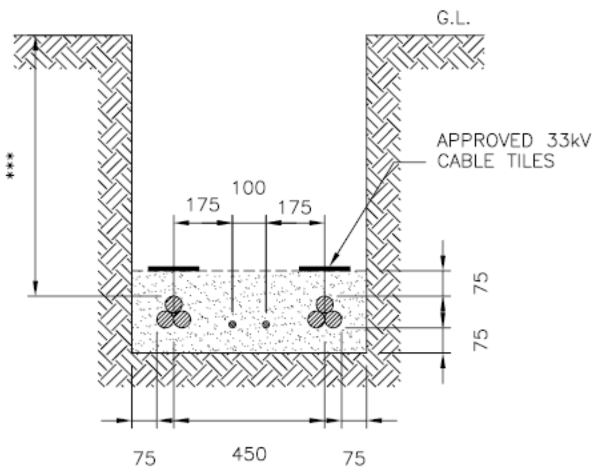

Figure 1: Installation of pilots in trench with primary power cables

Following this trial experience, there are now a number of commercial projects involving the new relay at various stages of completion around the UK. These are utilising the additional integrated functions within the numerical pilot-wire relay in order to reduce the cost to the user. For example the integrated transfer trip function is replacing the requirement for external intertripping equipment, while magnetising inrush restraint enables the protection of feeders with in-zone "teed" transformers, as illustrated in Figure 2.

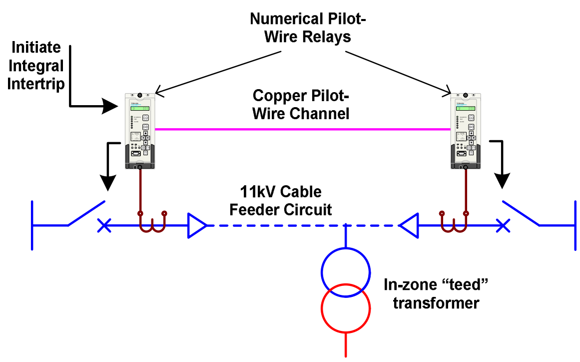

Figure 2: Application including in-zone "teed" transformer and integral transfer trip

Field Experience in Asia

The new relay has been applied by a number of power utilities in Asia, a region in which pilot-wire differential protection has been widely used for many years.

In July 2006, one of the major utilities in the South-East Asia region installed the new relay on 3 field trial circuits, followed in the December of 2006 by a further 63 circuits which were commissioned during the subsequent 18 months. Detailed records were kept for each circuit, including characteristics of the pilot cables and faults on the 11kV network, as part of a major approval exercise for the new relay.

Pilot cables in this particular network take the form of 19 twisted pairs of 0.9mm copper conductor. These are installed in the ground either by direct burial or in cable ducts, and are laid in close proximity to the power cables, such that they may be subject to induced voltages up to 15kV, although 5kV is a practical limit in most cases. At time of installation, the cables are specified to exhibit the characteristics shown in Table 2.

Max. resistance	30 ohm / km
Min. insulation resistance between conductors	500 M ohm
Max. mutual capacitance	60 nF / km
Max. pair-to-pair capacitance unbalance	300 pF / 100m

Table 2: Installed pilot characteristics

The lengths of the pilot circuits on which the relays were applied varied from as little as 50m up to 9.1km, while pilot insulation resistances varied from 3MΩ to effectively infinite levels. A total of 34 through-faults were recorded on the 11kV network, as well as one internal fault on one of the protected circuits, which was cleared correctly by the new relay. As a result of the performance demonstrated by the new relay in this extensive trial, it was approved for general use on the utility network in 2009.

Re-use of Installed Pilot Cables and Upgrade to Fibre Optic

One of the key advantages of a numerical pilot-wire relay is that it provides the utility with the option of re-using installed pilot channels, while benefiting from the improved performance and enhanced functions available with numerical technology. Much of the existing copper pilot infrastructure is now quite old, and is exhibiting the effects of age-related deterioration of its insulation resistance. In some cases the pilot insulation resistance has been reported to have fallen to such low levels that the installed conventional pilot-wire relays are no longer able to operate. The effect that age-related deterioration of the insulation resistance would have on the performance of the new relay is therefore of interest, and tests have been carried out in the field to examine this effect.

Direct measurements were made of the transmitted signals on the pilot channel, by connection of a digital oscilloscope.

A recording of one of the measurements taken on a healthy pilot channel is shown in Figure 3, in which the operation of the half-duplex communication system can clearly be seen from the alternate bursts of data. The higher magnitude burst represents transmitted data, while the lower magnitude burst is data received from the remote terminal having been attenuated and distorted somewhat by the pilot cable.

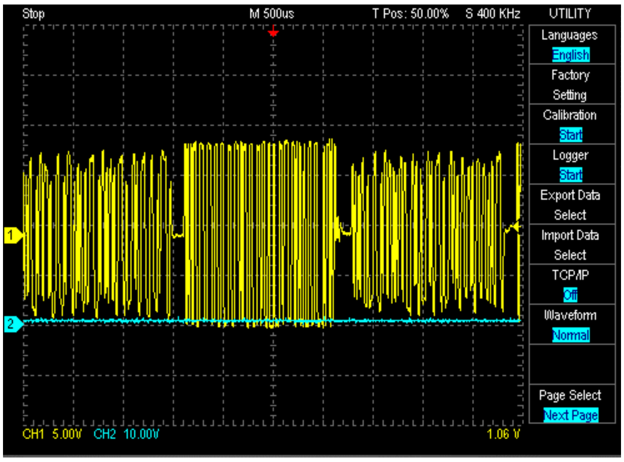

Figure 3: Data on the pilot channel

Deterioration of the inter-core and core-to-earth resistances of the pilots was simulated by connecting a resistance decade box in parallel with the pilot wires. The effective insulation resistance was gradually reduced from its measured value of more than 150M ohm to as low as 40 ohms. Increased attenuation of the received signal was observed, as can be seen in Figure 4, but the relays continued to operate correctly and no communication failures occurred. These tests indicated that the new relay should be suitable for use even where pilot cable resistances have deteriorated to a level at which conventional pilot wire relays have ceased to function correctly.

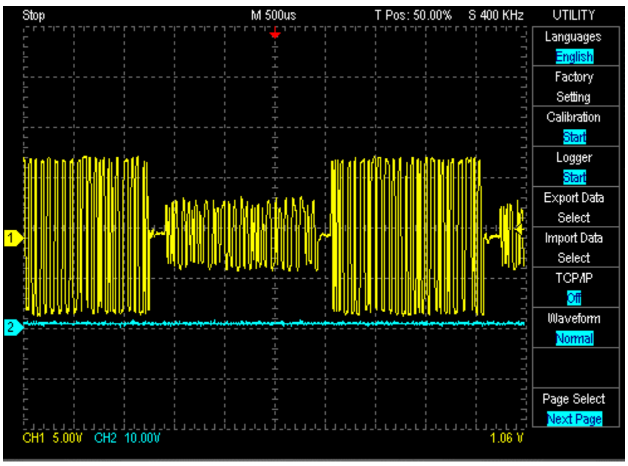

Figure 4: Increased signal attenuation due to reduced insulation resistance

In view of the age of installed pilots, some utilities have embarked on a programme of upgrading to direct fibre optic channels, and the capability of the new relay to support both pilot-wire and fibre interfaces within the same unit provides a solution for this upgrade path. The protection scheme is initially connected via the existing pilot wires and then, without any change to hardware or software, is re-configured to use the fibre optic link once it becomes available.

CONCLUSION

Many utilities worldwide have a large installed base of direct metallic pilot-wire signalling channels for use by protection relays. This paper has described a digital current differential feeder protection relay that has been developed for use with conventional copper pilot-wire links, thus enabling utilities to re-use their existing protection signalling infrastructure and at the same time benefit from the performance and cost advantages of numerical relay technology.

The relay described in this paper has now been installed for a number of years in field trials and full commercial installations around the world and experience from these installations is reported. A number of the installed relays have experienced primary network fault conditions and have been demonstrated to have responded correctly.

REFERENCES

[1] G. P. Baber, I. Shuto, H. Sugiura, H. Ito, 2006, "Numerical Line Differential Protection over Metallic Pilot Circuits", *15th International Conference on Power System Protection (Bled, Slovenia)*, 69-74

[2] I. Voloh, R. Johnson, 2005, "Applying Digital Line Current Differential Relays Over Pilot Wires ", *58th Annual Conference for Protective Relay Engineers*

[3] H. Y. Li, P. A. Crossley, 2002, "Optimum Message Transfer Rate for Distribution Feeder Protection Operating Over Switched Telephone Networks", *IEEE Trans. Power Delivery*. vol. 17, no. 2.

[4] Toshiba Corporation, *Instruction Manual for Line Differential Relay GRL150*, http://www.toshiba-relays.com/.

[5] G.E.C., 1987, *Protective Relays Application Guide*, UK, 165.

[6] G. P. Baber, I. Shuto, H. Sugiura, D. Griffin, 2008, "Development and Site Trial of a Numerical Pilot-Wire Differential Protection", *IET Developments in Power System Protection*, 74-79