



by Phil Beaumont, and Gareth Baber, Toshiba International (Europe) Ltd, UK, Ian Hall, Cable & Wireless, UK  
Masamichi Saga and Hachidai Ito, Toshiba Corporation, Japan

## Line Current Differential Relays Operating over SDH/SONET Networks

The “numerical line current differential relay” has proven to be one of the most successful types of transmission line protective relay system, and advances in communication technology have facilitated its ever wider application. The adoption of SDH and SONET as standards for high speed data communication over optical fibre and microwave has further encouraged the use of this type of protection. However, the impact of these standards has given rise to the possibility of communication links with characteristics unsuitable for conventional line current differential relays. Even where utility communication networks are mostly dedicated, public telephone operator provided links may be used at the periphery and these are likely to be the weak link in the chain.

CONVENTIONAL LINE DIFFERENTIAL RELAYS utilise methods of synchronisation to ensure that samples compared by relays at all terminals of a power transmission line are taken at the same time instant. The techniques employed are generally based on the premise that propagation delays in the communication link are equal for both send and receive paths. However, this premise is not necessarily valid for SDH/SONET, (Synchronous Digital Hierarchy/Synchronous Optical Network) communication networks which can exhibit different propagation delays for the send and receive paths. The consequence is that conventional methods of achieving sampling timing synchronisation cannot be applied. Line current differential relays that utilise GPS

time information can accomplish sampling timing synchronisation independent of the characteristics of the communication medium.

For line current differential relays using GPS synchronisation the need for the relay to have a comprehensive GPS back-up system is an indispensable requirement from utilities. The back-up system must be able to maintain the performance of the protection in the unlikely event of a failure within the GPS system which may occur over a protracted period. It must also maintain sampling synchronisation during periods of GPS signal interruption and accommodate path switching within the SDH/SONET network. The back-up mode function is also required to cover problems that may occur with integral components of the protection system such as the GPS receiver or antenna.

Current sampling timing synchronisation lies at the heart of the security of current differential protection. Synchronisation design needs to be rigorously proven in conjunction with the telecommunication network. It is of vital importance that any new product undergoes extensive type testing and with such a novel

technique it is imperative to undergo field testing and trials. The first commercial products of this type were installed in 2001 and the article includes some observations on the service experience to date.

### Impact of SDH/SONET Communication Networks on Line Current Differential Relays

The rapid growth of digital networks and the convergence of telephone and high-speed data networks have enforced the development of new standards. Proposals in ITU-T, (formerly CCITT) for a Broadband Integrated Services Digital Network (B-ISDN) were an enabler for a new synchronous multiplexing standard that would better support switched broadband services. The new standard first appeared as SONET in the United States.

Initially, the objective of the SONET standard was to establish a North American standard that would permit inter-working of equipment from multiple vendors. Also at that time, a different standard for digital hierarchies was in use in Japan. Subsequently, the ITU-T was approached with the objective of developing a world-wide standard.

Phil Beaumont read Electrical Engineering at Leeds in the UK and graduated with a BSc(Honors) degree. He is Engineering Director with Toshiba International (Europe) Ltd. Phil is a Fellow of the Institution of Engineering and Technology (IET) and a Senior Member of the IEEE.

Ian Hall was educated at Imperial College and graduated with a BSc (Honors) degree. He is currently Service Delivery Manager for Cable & Wireless. Ian is also a Member of the IET and ACGI.



Despite the historical differences between the North American, European and Japanese digital hierarchies, this goal was achieved with the adoption of the SDH standard (1988), the international equivalent of SONET. Figure 1 shows these different standards in Europe, North America & Japan and SDH hierarchies.

In synchronous networks, all multiplexing functions operate synchronously using clocks derived from a common source. SDH/SONET are expected to be in common use for the foreseeable future as the multiplexing structure has been designed to carry not only current services but also emerging ones using ATM (Asynchronous Transfer Mode) and/or IP framing structures for example.

SDH/SONET allows the development of network topologies that are able to achieve 'network protection', that is, they are able to survive failures in the network by reconfiguring and maintaining services by alternate means. One of the methods that can be employed to provide network protection is by the use of self-healing ring architectures. Protection switching in a ring topology can be either

'unidirectional' or 'bi-directional'. The description unidirectional means that only the faulted path is switched whilst the non-faulted path follows the original route.

With bi-directional switching both the go and return path are switched to follow the opposite direction along the ring. The important point to note is that bi-directional switching will maintain equal signal propagation delays for the go and return path (any differences will be transient), whilst unidirectional switching may introduce permanent, unequal propagation delays that can cause severe difficulties for current differential relays. The creation of unequal delays is illustrated in Figure 2, Figure 3, and Figure 4.

Comparison of measured quantities from differential protection relays must be based on pairs of samples that were taken at the same sampling instant. As samples are transferred to the remote end of the protected circuit for comparison, the delay that is introduced by the telecommunications link has to be compensated by the protection relay that performs the comparison. However, if the sampling clocks are synchronised at each terminal

## SDH/SONET networks can exhibit different propagation delays between the send and receive paths.

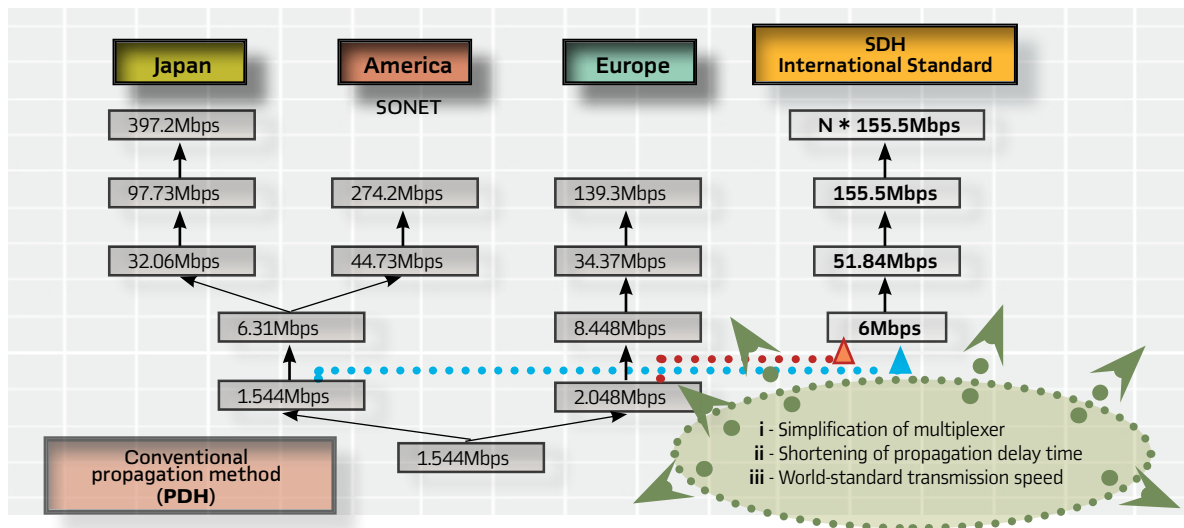
(see later), the process is simplified to one of comparing referenced current samples which are derived from synchronous clocks. With the introduction of SDH/SONET communication systems it is essential that the comparison of the respective samples does not depend on equal signal propagation delay times for the send and receive paths nor on stringent limitations for signal propagation time variations.

Figure 5 shows that the occurrence of a different propagation delay time between the send and receive paths in the communication network will result in a sampling synchronization error for a

**System Tests** should be undertaken both in the laboratory and in a practical installation.

The purpose of these tests are twofold: To confirm that sampling synchronization is maintained despite interruption of the GPS standard time signal and also to confirm the stability of the system in the event of a communication path being switched or becoming defective.

### 1 Conventional propagation method & SDH in respective countries



conventional current differential relay.

**Current Differential Relaying Scheme**

Current differential protection exhibits some very desirable features:

- it can provide high selectivity for all fault types even on complex power systems with multi-terminal lines and series compensation

- it benefits from both high speed operation combined with high sensitivity even for transmission lines having terminals with weak or no-infeed

- it remains stable in the presence of high frequency ac and dc components generated during power system faults and is not reliant on complex starting arrangements to negate the effect of capacitance at low loads.

Let us consider the case of a two terminal line.

Sampled instantaneous current values are transmitted from one terminal to the other every 30 electrical degrees as shown in Figure 6. Relays 'A' and 'B' installed at respective ends of the protected circuit sample the power system current data simultaneously using the sampling synchronisation method described below. Relay 'B' transmits the current data sample, (ib) complete with reference number

to relay 'A'. Relay 'A' then performs a current differential calculation using the referenced current data samples, (ia) from its own terminal and (ib) from the remote terminal. Samples (ia) and (ib) have the same sample reference number. The propagation delay time incurred in receiving the transmitted data frame from the remote terminal does not affect the current differential calculation because it is performed using synchronized samples having the same sampling reference number.

**Sampling timing synchronization**

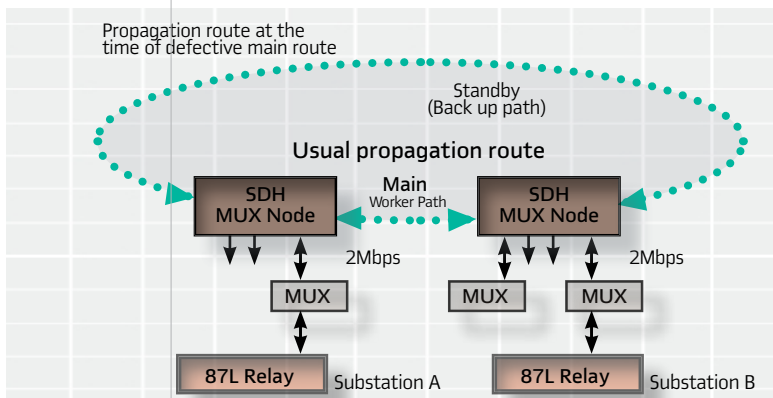
In order to carry out the current differential calculation, it is necessary to synchronize the sampling at all terminals. One method of achieving this is for the current differential relays to perform sampling timing synchronization according to the 'ping-pong' method. This method assumes that the propagation delay time, (td) of the send and receive communication paths between the two terminals are equal. Figure 7 shows the method used to achieve sampling timing synchronization. In case (a) No sampling timing error,  $t_1=t_2=td$ ; and in case (b) Sampling timing error of  $\Delta t$ ,  $t_1-t_2=2\Delta t$ . The values of  $t_1$  and  $t_2$  are used to calculate the sampling timing error and hence execute sampling timing control.

**Sampling timing synchronisation, must be maintained even during GPS interruption and repeated switching**

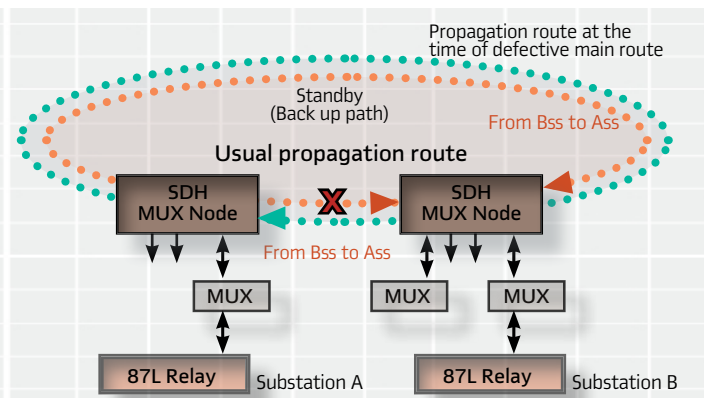
**Sampling synchronization - SDH/SONET communication**

In the case of an SDH or SONET communication network, where path switching may result in propagation delays of the send and receive transmission paths (*tdu* and *tdr*) being different, the conventional method of sampling timing synchronization cannot be employed, for the reasons illustrated in Figure 8-(b). This is because the conventional method will adjust the clock relationships to cause  $t_1$  and  $t_2$  (as seen by the relay) to be equal, when in reality they are not. A sampling timing error of  $t = (t_{du} - t_{dr})/2$  is thereby generated. Consequently, an erroneous differential current,  $I_d$  is measured by the relay which will cause the relay to operate incorrectly if the  $I_d$  setting value is exceeded.

**2 SDH network 'Normal'**



**3 SDH network With defective propagation route**



### SDH/SONET Communication System

The majority of communication networks use SDH/SONET as a transmission platform. These networks often deploy some form of communication link protection mechanism to improve availability. Several methods can be employed, but they can expose power system protection systems to differences in go and return delay. This difference can be permanent or transient and can be of a significant value. Traditional current differential protection systems rely on equality of go and return times to provide a sound reference for sample synchronisation between the line ends. Simply disabling the protection mechanism may not be possible and would also cause a significant reduction in communication availability. High communication path availability is important for protection systems otherwise fault clearance dependability may be reduced. Also the procedures involved in the manual switching of protection paths after failure require significant real time coordination as well as the implementation of special provisioning processes. The type of communication protection mechanism with the potentially smallest affect on unit protection systems is where

the receive path is switched at both ends of the communication channel (bi-directional switching). Bi-directional switching is not the normal mode of protection switching for commercial networks as it involves the switching of the received information to the alternative path at both ends of the protected zone. This results in two disruptions to the traffic instead of the single traffic hit which results when unidirectional switching is applied. Therefore, bi-directional switching can be implemented on a dedicated network; however, any interconnectivity with public networks will inevitably result in an inability to coordinate the type of protection switching applied. It is therefore very important that a utility takes this into consideration and ensures that GPS protection is applied in this situation. It is not possible for a utility to replace its legacy protection in a short timescale because of power system outage constraints etc. However it is important that the utilities' power system protection systems' refurbishment program gives priority to the replacement of conventional unit protection by GPS based unit protection where SDH/SONET links cannot be guaranteed to utilise bi-directional switching. Even when bi-directional switching

The protection must perform correctly for uni and bi-directional, auto reversion and 'split-path' conditions.

is used, conventional unit protection may not be secure and a significant amount of testing is required to establish whether a particular protection system is stable under all switching conditions. To avoid the necessity to specify performance parameters for bi-directional switching in line with specific types of unit protection it is safer and more flexible to deploy unit protection utilising GPS synchronization.

### GPS Synchronisation System

In a GPS based unit protection, sampling timing synchronisation is accomplished by using GPS time information, and as such, synchronization is independent of the characteristics of the communication medium. Each relay measures the time difference between the output of its own sampling oscillator and the one pulse per second (1pps) GPS signal

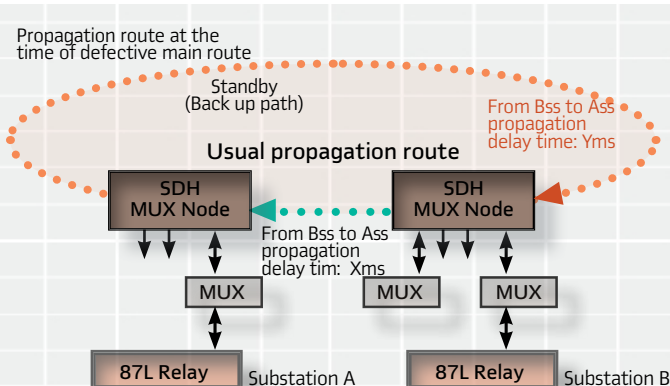
**Masamichi Saga** graduated from The University of Electro-Communications, Tokyo. He joined Toshiba in 1991. His special fields of interest include software development for numerical protection relays. He is currently manager of the Protection and Control Engineering Group of T&D Systems Division.

**Gareth Baber** graduated from the University of Salford in the UK in 1991. He is currently Marketing & Technical Development Manager at Toshiba International (Europe) Ltd and is a Member of the IET.

Hachidai Ito joined Toshiba in 1981 and is now a Chief Specialist in Power System Protection & Control. He is a senior member of IEEE, a member of CIGRE, IEEJ & IEICE, a secretary of Japanese National Committee of IEC/TC95, a convenor of its MT1 and a member of other working groups.

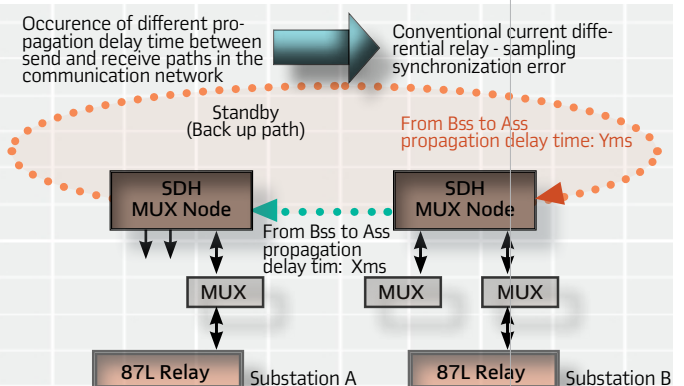
## 4 SDH network - split path

Different delay time between send and receive paths



## 5 SDH network

Influence on Line Current Differential Relay



providing a 1 us order of precision suitable for protection relay applications. Each relay then corrects the oscillation frequency of its sampling oscillator so that the time difference becomes zero. The relay continuously updates the correction factor and stores it as the absolute accuracy of the oscillator.

Standard time data is encoded from the GPS standard time signal that is provided to the relay from the GPS receiver so that any failure or corruption of the standard time signal can be detected by the relays, thus ensuring that sampling timing synchronization control is not adversely affected.

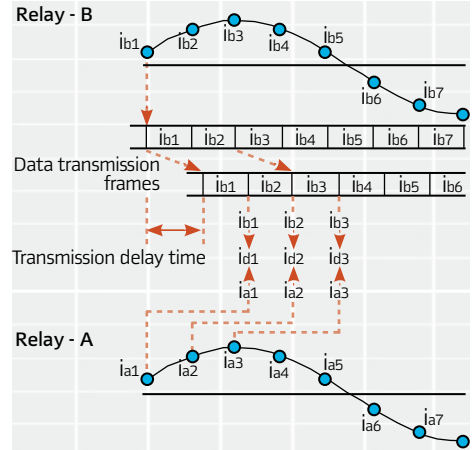
Thus GPS receiver design is critical and if general-purpose receivers are used the ability of the protection system to recognize and reject erroneous synchronization pulses is of paramount importance. If they are not properly detected and rejected by the protection system's algorithm, they can lead to an increase in relay differential current arising from synchronization errors and if the load current is sufficiently high false operation will occur.

**GPS backup system**

A robust back up mode which enables the protection system to operate reliably in the absence of the GPS system is very important. Since the alignment of GPS satellites

changes during the course of a day, the GPS antenna must be installed carefully with an unobstructed view of the sky, otherwise reception of the GPS time signal may be interrupted. Poor installation practice can result in the signal being unreliable. As well as representing a dependability risk, this has also manifested itself as a security risk where reports of poor front end receiver and algorithm design have resulted in the utilization of erroneous synchronization pulses by protection algorithms causing false tripping of the equipment. We are also aware of military GPS jamming exercises out to sea from various locations in the UK. There are no guarantees given that these will not affect devices on land! A significant satellite anomaly occurred on 1 January 2004 and an interruption to the 1pps signal occurred. It transpired that a failure had occurred in the atomic frequency standard on one of the GPS satellites and caused transmission of misleading information. This anomaly affected GPS receivers over a large geographical area. It is therefore very important that the performance of the protection system is unaffected by loss of GPS and certainly any back up mode should aim to enable the protection system to run as normal with high communication channel delay asymmetry as well as being

**6 current differential calculation**

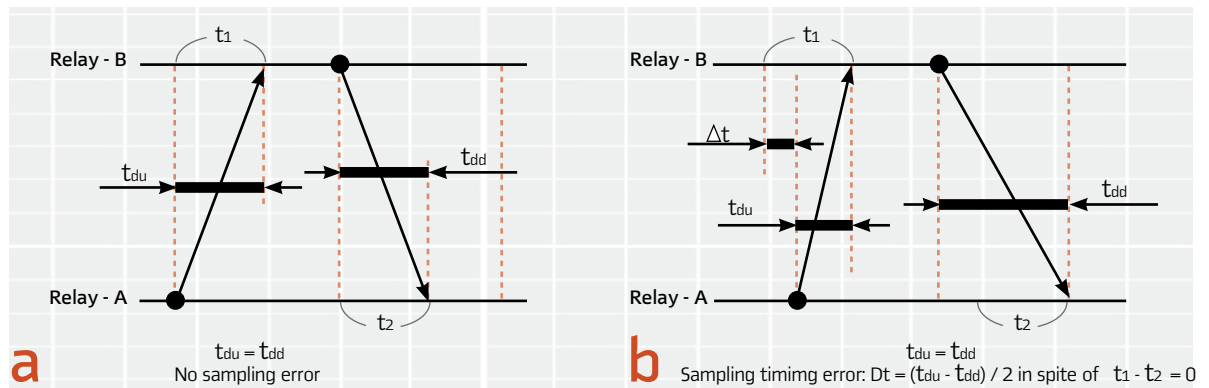


unaffected by any communication switching events. Although significant anomalies are believed to be a rare occurrence measures have to be taken within the design of the GPS receiver and relay to ensure that even under the most extreme conditions the integrity of the GPS based relay system is maintained. It is worth noting the point that the GPS antenna and GPS receiver must be treated as an integral part of the protection system.

In order to alleviate these problems and other potential causes of interruption of the GPS time signal, the back-up function

**7 Sampling timing synchronization**

With different propagation delays between send and receive paths



described below was developed that allows sampling synchronization control to continue during an interruption to the GPS time synchronization signal. Further, the back-up function can maintain sampling synchronization even in the event of the SDH/SONET communication path being switched during the period of interruption to the GPS time synchronization signal. In the event of the GPS signal being lost, the relay is able to control the oscillator's free-running frequency error to within 0.2ppm, by using the correction factor stored immediately prior to the loss of the GPS signal. By this method, the sampling synchronization error between two relays can be limited to within 1.5 $\mu$ s.

#### MODE 0: operation under normal conditions

During normal reception of the GPS standard time signal, relays A and B continuously record timing information  $t_1$  and  $t_2$  for the signal received from the other terminal.

Because the sampling time of relays A and B are synchronized by GPS,  $t_1$  and  $t_2$  are equal to the propagation delay time between relays A and B respectively. Changes in communication path propagation delay time caused by switching of the SDH network have no effect on the sampling timing of the relays.

#### MODE 1: operation following loss of GPS signal

Following loss of the GPS signal at terminal B, relay B becomes the 'slave' and controls the frequency of its internal oscillator so that the signal timing information for the signal received from the other end is maintained at a value of  $t_1$ , where  $t_1$  is the propagation delay recorded immediately prior to loss of the GPS signal.

In the event that the GPS time signal is lost at both terminals then the relay which lost its signal first becomes the slave, and synchronization is maintained at both ends by carrying out sampling synchronization control in the back-up mode.

In the event of the SDH communication path being switched during the period of interruption to the GPS time synchronization signal, relay B will detect the sudden change in the timing of the received signal since switching of a path in the SDH network takes a period of several milliseconds. Having detected a sudden change of propagation delay time, the relay records the new value of delay time  $t_1'$ , and continues to carry out sampling synchronization control according to the new delay time.

If relay B is unable to receive the signal sent from relay A due to a failure in the communication link, then it cannot continue to perform sampling synchronization control. Under these conditions the sampling oscillator is allowed to run free. After subsequent recovery of the communication link, the actual transmission time of signals received from relay A differs from the recorded time by an error which is proportional to the length of time for which the oscillator was in a free-running condition. Therefore, Mode 1 operation incorporates a limitation of allowable free-running time, after which the differential protection element is locked, since sampling synchronization can no longer be guaranteed.

#### MODE 2: operation without GPS time signal and following a prolonged period of communication failure

If, during MODE 1 operation, the allowable free-running time is exceeded, or if the dc power supply to the relays is removed causing loss of recorded propagation delay data, then back-up operation changes from MODE 1 to MODE 2. MODE 2 operation provides sampling synchronization control based on the assumption that the propagation delay times of the send and receive paths are approximately equal. This mode is used after having checked the difference in propagation delay times of the SDH communication link. However, the transition from

In the future, non-deterministic communication systems, such as Ethernet and IP will bring new challenges.

MODE 1 to MODE 2 may be made automatically by using a check of the phase difference of the current between the terminals at each line end (see below).

#### Current phase difference monitoring system

In order to continuously monitor the performance of the sampling synchronization control system, the relay is provided with a function for checking the phase difference between the currents at the relay terminals. The function operates when the measured current phase difference exceeds a specified threshold. The threshold can be adjusted since the measured current phase difference may be greatly influenced by the line charging current, particularly in cases of low load current.

## 8 Sampling timing synchronization

