**New Smart Multi-Ended Differential Solution for Power Networks.**

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**Abstract**

Line current differential protection is based on Kirchhoff's current law calculating the vector sum of the currents from each line end to detect faults in the protected zone. For synchronisation of the current vectors time compensation with a ping-pong measurement of the propagation time delay is used.

A new smart multi-ended differential protection is presented in this paper which includes a new capacitive current compensation technique. The protection relay is scalable for any transmission system topology including hybrid lines. The protection is based on RMS values calculated from samples making it immune to frequency variations and the protection operating time is sub-cycle.

The protection uses an accurate algorithm for capacitance current compensation with a distributed line parameter model, where only the impedance and admittance per unit are required. This technique has an error less than 1% even considering transients in the algorithm.

The need to provide connections to new renewable generation has increased the need for a multi-ended line differential protection. This new smart protection concept is a step forward in providing reliable, cost effective and integrated protection for these new network topologies.

## 1. Introduction

Current differential protection is based on Kirchoff's law. It uses the Merz-Price principle in which the sum of the currents entering the protected zone should equal the sum of the currents leaving the protected zone, see Figure 1. The difference between these currents is known as differential current. If the differential current exceeds a threshold, then the protection relay may be required to trip. If the differential current is below the threshold then the relay is expected to restrain. The differential principle is summarised below:

$$I_1 + I_2 + I_3 + I_4 + I_5 + I_6 = 0 \text{ Healthy}$$
$$I_1 + I_2 + I_3 + I_4 + I_5 + I_6 \neq 0 \ (= I_F \text{ faulty})$$

At each terminal in the protection scheme the power system current input quantities are acquired, converted into numerical values, filtered, and compared with current input values from the other terminals in the scheme. For each phase, and at each terminal, the vector sum of the currents entering the protected zone is calculated. This is known as the differential current and provides the operating quantity. Also calculated is the scalar sum of the same currents, a proportion of which is used as a restraining quantity. This is known as the bias current. To determine whether tripping should occur, the differential current is compared with a percentage of the bias current. If it is exceeded then a trip can be initiated.
The differential and bias currents are calculated on a per phase basis, and the tripping decision is made on a per phase basis. However, the bias current used in the calculation is the same for all three phases and is based on the highest of the bias currents calculated for each phase. This is called the maximum bias and improves stability for through faults.

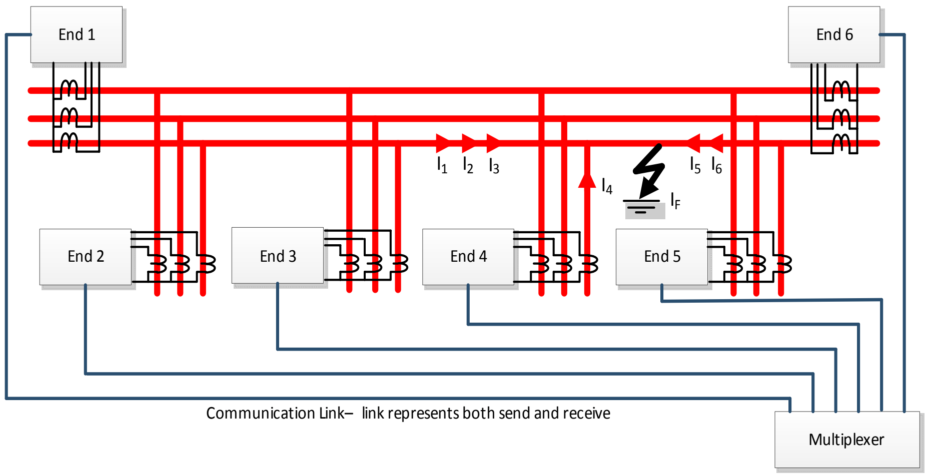


**Figure 1 - Multi-ended line differential protection principle**

Line differential protection requires the comparison of currents measured at the different line terminals. To ensure accuracy of the calculation of the differential current, the locally derived current values and the values derived from inputs at remote terminals must be aligned to a common time reference before the differential calculations are made. This process is called 'Time Alignment' or 'Synchronisation'. Synchronisation can be achieved by using accurate time signals from sources such as atomic clocks or the Global Positioning Satellite (GPS) system. Synchronising the sampling using a GPS input is recommended for schemes using communications that may be subject to switching. For many applications, however, asynchronous sampling can be used and the relays can self-synchronise the current vectors using the "ping-pong" technique.

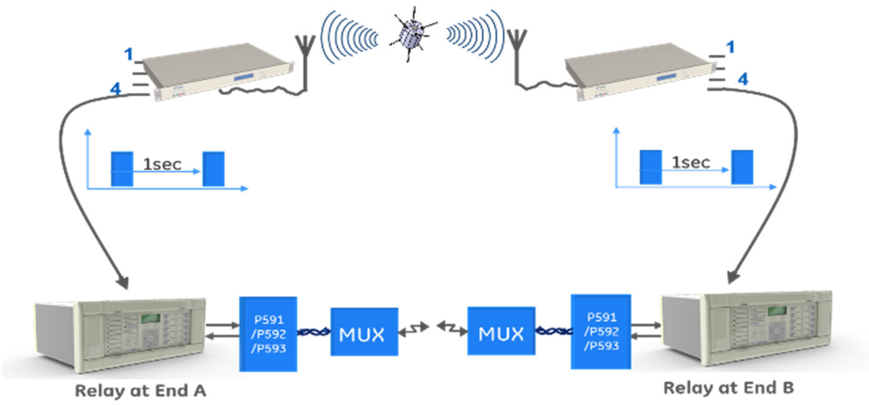


**Figure 2 - GPS-synchronized scheme**

There are certain requirements for the communications network to achieve stable operation. Line differential protection using asynchronous sampling requires the communications system to have low latency, latency symmetry, and low jitter. However, most line differential protection schemes deployed using GPS to synchronise the sampling are configured to fall back to asynchronous sampling to protect against a GPS signal failure so these requirements may also be applicable to these schemes.

Communications channel latency impacts the time it takes for current samples to travel to the remote end for comparison, thereby impacting the time it takes the relay to detect the presence of a differential fault condition. Asynchronous sampling is based on a continuous propagation time measurement and vector transformation performed by the differential function to align current samples. Propagation time measurement is performed based on the ping-pong technique, which averages the delay between send and receive times, assuming symmetrical latency in transmit and receive directions between the two relays.

The presence of an asymmetrical delay in the received and transmitted data results in incorrect vector alignment, which can produce a false differential current and may result in a false tripping of the protection.

Similarly, the presence of jitter in the communications channel leads to a constant change in the average propagation delay calculation. The time difference between two consecutive messages must be as constant as possible to avoid an incorrect sample alignment and hence incorrect differential current.

## 2. New Multi-Ended Line Differential Protection

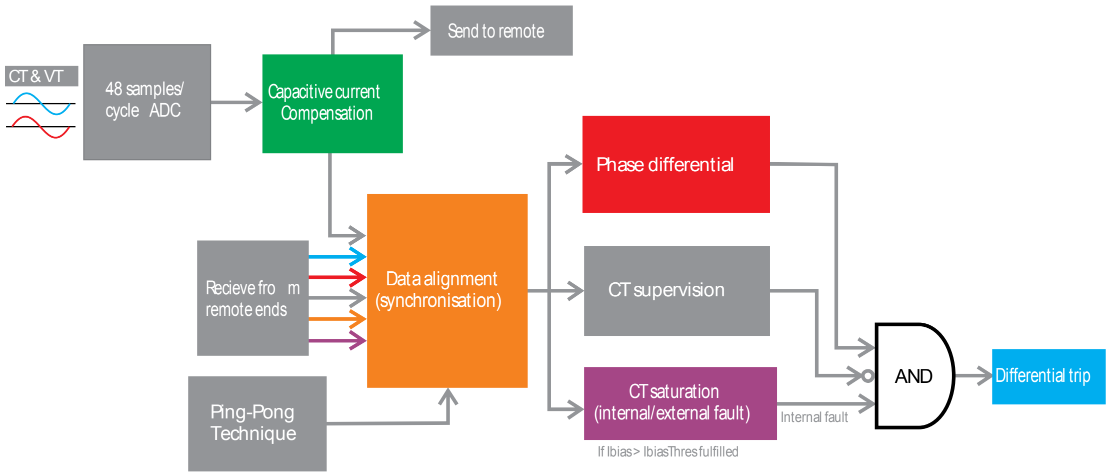


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**Figure 3 – New multi-ended line differential overall scheme design**

Phase differential protection has been used for many years to protect transmission lines and distribution feeders. A new smart multi-ended differential protection is presented in this paper which includes a new capacitive current compensation technique. The protection relay is scalable for any transmission system topology including hybrid lines.
The new multi-ended differential protection is applicable for systems up to 6 ends with a sub-cycle operating time of <20ms (50Hz) for 2 to 4 ended schemes and a 25ms operating time for 5 and 6 ended schemes.
The multi-ended differential protection scheme has been designed with the following new features/requirements:

- Sample based differential algorithm
- Sub-cycle tripping for communication time delays up to 7ms
- The algorithm for multi-ended differential is scalable for many different topologies up to 6 terminals and 4 junctions
- New algorithm for capacitive current compensation

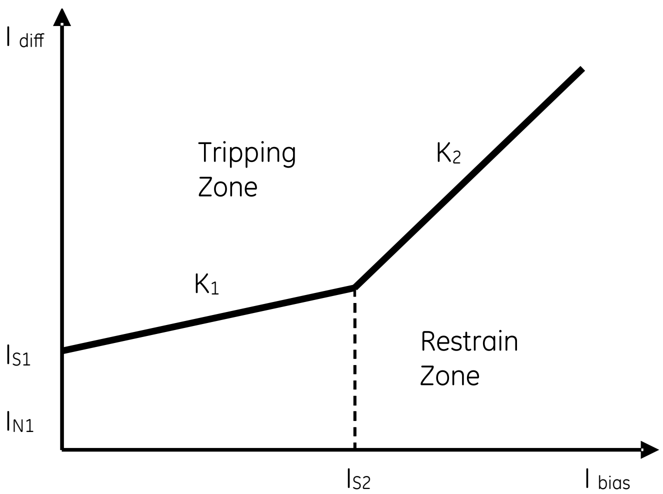


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**Figure 4 – Bias differential characteristic**

The criteria for internal and external faults can be seen from the differential characteristic and is described below in equation1:

$$I_{diff} \geq \begin{cases} I_{S1} + K_1 I_{bias} & when\ I_{bias} < I_{S2} \\ I_{S1} + (K_1 - K_2) I_{S2} + K_2 I_{bias} & \text{when}\ I_{bias} \geq I_{S2} \end{cases} \qquad \text{Eq.1}$$

The **Is1**, **Is2**, **k1** and **k2** settings are described below:

- **Is1**: The basic differential current setting which determines the minimum pick-up level of the protection
- **k1**: The lower percentage bias setting used when the bias current is below the Is2 setting. This provides stability for small CT mismatches, while ensuring good sensitivity to resistive faults under heavy load conditions.
- **Is2**: A bias current threshold setting, above which the higher percentage bias setting k2 is
- used.
- **k2**: The higher percentage bias setting used to improve protection stability under heavy through fault current conditions.

Is1 is required to be set higher than the maximum unbalanced current due to measurement and calculation errors. Typically, Is1 is set to 0.2~0.5In to avoid unbalanced currents. When the fault is small, the bias current will be smaller and sensitivity is more important than security as the CTs should not be saturated for lower bias currents, so the slope setting is smaller, a typical setting of k1 = 30~50%, the default setting is 30%.
When the fault current is high, the bias current will be higher and security will become more important than sensitivity as the CTs could be saturated, which can result in a much higher Idiff. So the protection uses the steeper K2 slope, a typical setting of k2 =100~150%, the default setting is 150% for 2 ended schemes and 100% for 3-6 ended schemes and the Is2 default setting is 2In.

### 2.1. Multi-Terminal Time Alignment

In a system with multiple terminals, in order to align all the data to the same reference time, it is crucial to select a reference time for which data of all the terminals are available. Therefore, the terminal with maximum time delay is identified and the rest of the terminals are aligned with the time delay difference between them and the terminal with maximum time delay. For example, the following figure explains how the time alignment is carried out where there are 3 remote terminals.

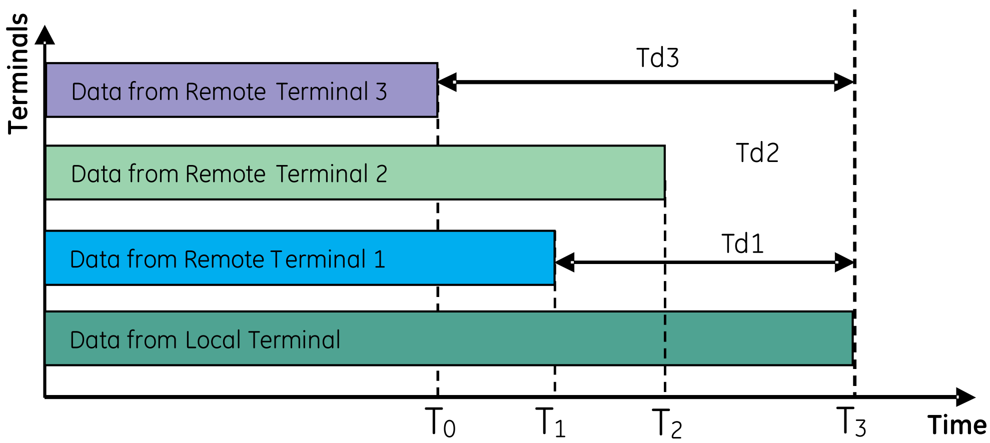


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**Figure 5 - Snapshot of available data for processing at each terminal**

From the above figure, it is clear that if we take a snapshot of available data for processing from all the terminals, the local terminal has the most recent data. Remote terminal 3 has the least amount of data to be processed due to having the biggest time delay Td3.

To calculate the differential or bias current using the data from all the terminals, it is important to select a time point where all data is available for all the terminals. In this case, T0 can be selected as the reference time to align all the data as the remote terminal 3 has the largest time delay from local end. Therefore, the currents and voltages for each terminal will be time aligned according to below:

For local terminal, the delay time is Tdmax = Td3;

For remote terminal 1, the delay time is (Tdmax - Td1);

For remote terminal 2, the delay time is (Tdmax – Td2);

For remote terminal 3, the delay time is (Tdmax – Td3 = 0);

Therefore, the mechanism of time alignment for the multi-ended system is presented as follows:

1. Input all the communication time delay Tp1~Tp5 of all remote ends.

2. Obtain the maximum communication time delay Tpmax = max(Tp1~Tp5).

3. Make the delay time of local data to TdL=Tpmax

4. Make the delay time of data of each remote end to Tdk = Tpmax – Tpk, where, k = 1~5

Because the time delay is not always an integer of time of the sample interval, an interpolation of the sample and time delay is required. The relay can calculate the interpolation based on a mathematical model derived from the Laplace transform. After this time-alignment process, the respective differential and bias currents can be calculated.

### 2.2. Current Differential Algorithm

The current differential algorithm is sample based to provide fast sub-cycle tripping. For a Fourier based algorithm, the Fourier window always contains both pre-fault data and post fault data during the fault time. For the sample based algorithm, the instantaneous differential current is ideally zero during the pre-fault stage so it is inherently faster. The sample based algorithm is not affected by any frequency variations, which means frequency tracking is not necessary.

A digital low pass filters is used for data re-sampling. The primary sampling rate of the platform is 48 samples per cycle, whereas the secondary sampling rate is 8 samples per cycle.

The sample based algorithm uses the RMS value, in which the instantaneous differential current is the sum of instantaneous current of all terminals.

$$i_{diff}(n) = \sum_{m=1}^{M} i_{Tm}(n) \qquad \text{Eq. 2}$$

Where, iTm is the current of mth terminal; M is the number of terminals; idiff is instantaneous differential current; n is present sample number. The RMS value of the differential current is used in the differential bias characteristic;

$$I_{diff}(n) = \sqrt{\frac{1}{N}\sum_{k=n-N+1}^{n} \left| i_{diff}(k) \right|^2} \qquad \text{Eq. 3}$$

Where, Idiff is the RMS value of idiff; N is the window length in samples for the RMS calculation, which is selected as a cycle of the fundamental frequency; n is the present sample; k is the history sample number within the window length N. Similarly, the Ibias, is the sum of the RMS currents of all terminals:

$$I_{Tm}(n) = \sqrt{\frac{1}{N}\sum_{k=n-N+1}^{n} \left| i_{Tm}(k) \right|^2} \qquad \text{Eq. 4}$$

$$I_{bias}(n) = \frac{1}{2}[\sum_{m=1}^{M} I_{Tm}(n)] \qquad \text{Eq. 5}$$

Where, Ibias is RMS value of bias current; ITm is RMS value of iTm; M is the number of terminals; N is the window length in samples for RMS calculation, which is selected as a cycle of the fundamental frequency; n is the present sample number; k is the history sample number within the window length N.

### 2.3. New Capacitive Current Compensation

For both overhead transmission lines and underground cables, there can be significant capacitive charging currents between the conductor and ground due to the line to ground shunt admittance. The charging current of a line or cable is seen as differential current so if this current is not compensated, the differential protection could maloperate. Two issues are apparent with charging current: the inrush during line energisation and the steady state charging current. Inrush charging current is predominately high order harmonics (9th and 11th for example). The filtering used by the relay removes these frequency components and hence provides stability. Steady state charging current is nominally at fundamental frequency and may cause protection maloperation.

Therefore, to increase the reliability, sensitivity and security of the differential protection, the capacitive current of the transmission lines should be eliminated, especially for the lines that are longer than 50km, or for cables longer than 10km.

A new sample based algorithm has been developed for the capacitive current compensation. It uses a distributed parameter line model, where only the impedance and admittance per unit are required. From the testing, the distributed parameter line model was proven to be more accurate than the lumped model. The distributed parameter transmission line function has been transposed from the frequency domain to the time domain so that it can be applied to a sample based input. The algorithm is much more accurate especially for topologies with long lines with errors <1% even considering transient conditions.

## 3. Protection Communications

Each relay has up to 2 fibre-optic communications channels for the current differential protection schemes as well as intertripping command signalling which can be freely allocated to realise protection schemes such as permissive and blocking schemes. The communications can be via direct fibre connections or indirect connections via telecommunications equipment using the industry standard IEEE C37.94 protocol.

The packets (sometimes called telegrams) communicated between relays include addressing, timing, and error checking information as well as teleprotection commands and current vector data. These packets are transmitted between terminals at regular intervals. Upon receipt they are checked for integrity before the contents are used. The assignment of teleprotection commands is realised with mappings between the InterMiCOM 64 signals and internal logic signals using the relay's Programmable Scheme Logic (PSL).

The multi-ended line differential communications uses a ring structure using the IEEE C37.94 protocol for the protection communications. The 2Mbps E1 communication protocol is also available via a conversion box which uses a C37.94 fibre optic input and E1 at 2Mbps over copper as an output.

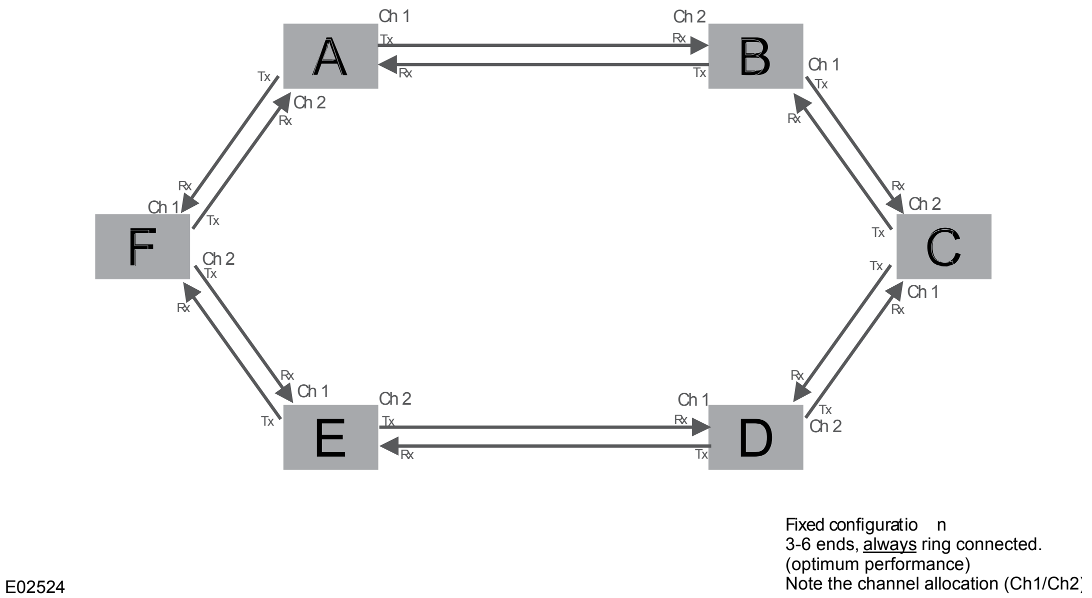


**Figure 6 – Teleprotection connections for a 6 terminal scheme**

For a 6 ended scheme, each terminal will need to communicate with 5 others and the protection message is transmitted at 8 times a cycle. The IEEE C37.94 standard defines an N*64 kbits/s selection, where N is the number of channel slots between 1 and 12. For multi-ended line differential, the communication is always using the 12 channels for 2 or 3 or 4 or 5 or 6 ended schemes to allow optimum protection performance.

The number of slots used by C37.94 is automatically selected by the relay. The slots in the C37.94 data frame are allocated using the relay terminal address order starting with the lowest. In most schemes data from each terminal will be available in each communication channel. The multi-end differential algorithm uses the first valid data received with the correct sequence number from either channel.

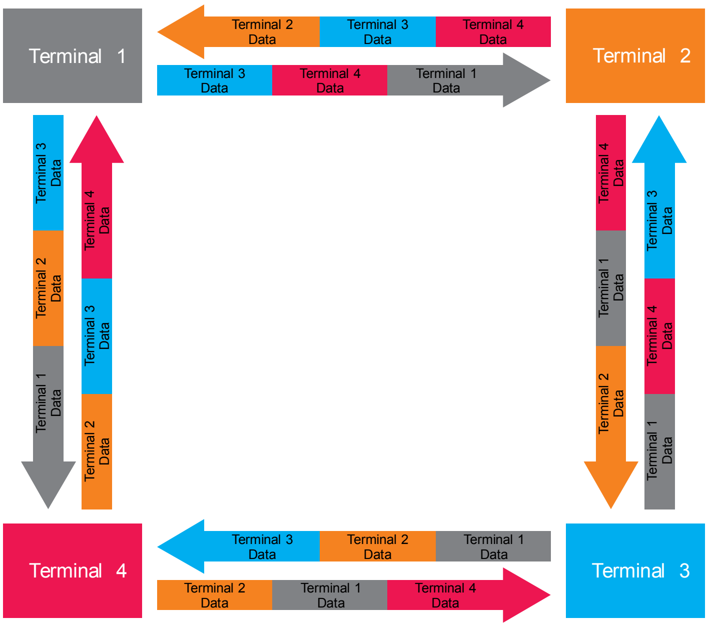


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**Figure 7 – Protection communications messages for a four terminal scheme**

The message framework is defined with two messages types, data and commands, in a message size of 34 bytes. The data message is transmitted regularly to each end and the command message is used for asking for and terminating the transmission of a data message on device power on. Information may be stored in any convenient form by the protection algorithm itself, but when transmitted it is formatted as frames. If the messages received by a connected device is not understood (such as an unimplemented feature, bad CRC, etc.) they are silently discarded.

For 2 ended schemes if there is a failure of one comms channel:

- If only one comms channel – No protection
- If using 2 comms channels – Protection is still available via the redundant channel

For 3 to 6 ended schemes if there is a failure of the comms channel

- If a single comms channel fails, or if a terminal is reconfigured out of service, comms can be re-routed the other way around the ring
- If 2 channels fails – No protection

### 3.1. Scheme Reconfiguration

Each relay in a multi-ended line differential scheme has a reconfiguration feature. This feature allows a relay to be put 'Out of Service' for maintenance or testing purposes. This can be achieved by toggling the Re-Configuration setting from Disabled to Terminal N, where N is the end to be taken out of service.

This affects the overall scheme in the following way:

- The communication channels of the ‘reconfigured’ relay remain in service. This means there is no interruption to the ring communication or loss of redundancy
- The current (load) values of the reconfigured terminal relay are not included in the idiff and ibias calculations by other relays in the scheme

The following should be taken into consideration during reconfiguration:

- Only one relay end can be reconfigured in a scheme at a given time
- A minimum of 3 terminals need to remain in service after reconfiguration
- The Reconfiguration Interlock signal must be asserted before the relay is reconfigured

Any terminal of the scheme can be used to send a reconfiguration command to another terminal that is required to be taken out of service. The relay will get ‘reconfiguration confirmation’ from all ends. Testing can then be carried out on the relay that is out of service.

## 4. Operating Time Test Results

The multi-ended differential function was validated for many different fault scenarios and network types using the RTDS: Energizing the local line end with different locations of the VTs; Frequency variation, Power swings; Harmonics; Switch on to fault; Series compensated lines (fixed/variable compensation); Evolving faults; Shunt-compensated lines; Switching on shunt-reactors; Ferro-resonance; Normalized CT ratios; Weak infeed; Single and multi-pole tripping and reclosing; High resistance faults up to 1000Ω (for 2-ended lines) & 300Ω for multi-ended lines; Isolated/impedance earthed system; Transient current response during parallel line breaker opening; Un-transposed lines; CT saturation from the inrush current of an in-zone transformer; Dual CT arrangement for 1½ breakers; Communications switching including split paths, Communication time delay more than 20ms; Communications failure/degradation and communications switching including split paths during a comms failure; Split path swapping to an alternative split path; Energizing a line with no load current (current based scheme); Internal and external faults on a two-ended system which has low load current.

The table below summarizes the results from the 1440 test cases:

| **Type Tests** | **Testing Case Topology** | **Max Tripping Time (ms)** | **Min Tripping Time (ms)** | **Average Tripping Time (ms)** |
|---|---|---|---|---|
| **1** | 6-ended system with 4 junctions | 24.90 | 12.40 | 15.13 |
| **2** | 6-ended system with 3 junctions | 22.40 | 11.15 | 13.60 |
| **3** | 6-ended system with 2 junctions | 22.40 | 11.15 | 13.43 |
| **4** | 6-ended system with 1 junction | 22.40 | 11.15 | 13.60 |
| **5** | 5-ended system with 3 junctions | 21.15 | 11.15 | 12.78 |
| **6** | 5-ended system with 2 junctions | 21.15 | 11.15 | 12.82 |
| **7** | 5-ended system with 1 junction | 21.15 | 11.15 | 12.97 |
| **8** | 4-ended system with 2 junctions | 21.15 | 11.15 | 12.82 |
| **9** | 4-ended system with 1 junctions | 21.15 | 11.15 | 13.26 |

| | | | | |
|---|---|---|---|---|
| **10** | 3-ended system | 21.15 | 11.15 | 12.89 |
| **11** | 2-ended system | 21.15 | 11.15 | 11.82 |
| | **Average:** | 21.83 | 11.26 | 13.19 |

## 5. Conclusion

Previously transmission and distribution circuits would have two or three ends only. However, five or more ends are becoming common because large distributed generation sites such as onshore or offshore windfarms and solar farms are being connected to the grid. As the power networks evolve to transport power in ever more complex ring and meshed networks, line/cable differential protection becomes increasingly attractive, with its inherent ability to address grading/selectivity challenges and is scalable for multi-terminal circuits able to accommodate many connections of distributed generation along the line. This paper describes a new multi-ended current differential protection that is now ready for any protection topology from two to six terminals, whether those multi-terminals exist now, or are provisioned for connection in the future.

As seen from the tests results presented in the paper, the new line differential relay is dependable and secure to protect the most stringent networks and is very fast operating; sub-cycle for 2-4 ended schemes and 1.25 cycles for 5 or 6 ended schemes.