Application of the Line Differential Protection Scheme For Radial Transmission Lines

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Abstract — Modern communication networks have dramatically increased the implementation of the line differential scheme (87L) as one or both primary protection for transmission lines. The transmission network is usually meshed which also provides fault current contribution from both ends of the line. When supplying electricity to specific loads, for instance mining in rural zones, the transmission network could be expanded radially with single or double circuit applications. In a radial system, in the event of fault, fault current contribution is drawn mainly from the source side. Very weak or absent current contribution from the remote end of the line presents a menace to the traditional current supervisory elements of the 87L, such in the cases of low load and a three phase fault or where the power transformers at the remote end do not provide a zero sequence path.

This paper reviews this specific application with particular attention to solutions which balance the need for security, speed and dependability of the line differential protection scheme. First, some practices of 87L and supervisory elements used in today's relays are investigated. The complications and challenges for the application of 87L on radial lines are then examined. Two genuine phase-to-ground fault events on the same 132 kV line in Australia have been reviewed to analyze the performance of the 87L supervision. Most important, several practical solutions are proposed and compared to enhance the functionality of the 87L supervision and meet the need of increasing the dependability of the 87L without affecting security, simplicity and speed of operation.

Index Terms — Line Current Differential Relay, Radial Transmission Lines

I. Introduction

The transmission network has the crucial role to transport the bulk of the electrical energy from the generators to the loads. The system is meshed as center of loads and generators are geographically dispersed. As a result, the transmission network is well interconnected and provides an inherent redundancy of supply to each node of the network. Although the cost and engineering effort to establish, operate and maintain such complex system, a meshed network is fundamental for the operation of a reliable power system.

In Australia the majority of the transmission network and substations has been built decades ago. If possible, new substations are usually located adjacent to existing transmission lines to avoid the construction of new ones. Transmission lines are very expensive. For instance, for a single 220 kV line on lattice towers, the average capital expenditure (CAPEX) cost in Australia is above AUS$ 900k per kilometer. In addition, the construction of new lines has become rather problematic due to the difficulties to obtain public opinion support, permits and land easement.

It is noted that there is an increasing demand to reduce the energy cost for customers and, subsequently, to control investments in the electricity sector. As a result, it is likely that more radial line will be considered and implemented in the near future to connect new large industrial or mining customers, existing sites which require a higher capacity and radial transmission backbone in rural areas currently fed by the subtransmission network.

Radial application in transmission network tends to be a solution mainly used in large countries like Australia where relevant loads are sometimes located in remote areas. According to the latest planning reports, there are several existing applications in South Australia, Queensland and Western Australia. New radial lines are currently considered for future new connections. For the scope of this exercise radial double circuit application are included in the analysis as are still dependent on the same source. In practice even a small ring network could become a radial line if one of the lines is open for maintenance or outage. Last , we should consider also radial lines from this study point of view even a line that connects a small generator or inconsistent source of load, like a wind farm, ,which does not generate or generate at small capacity during the line fault.

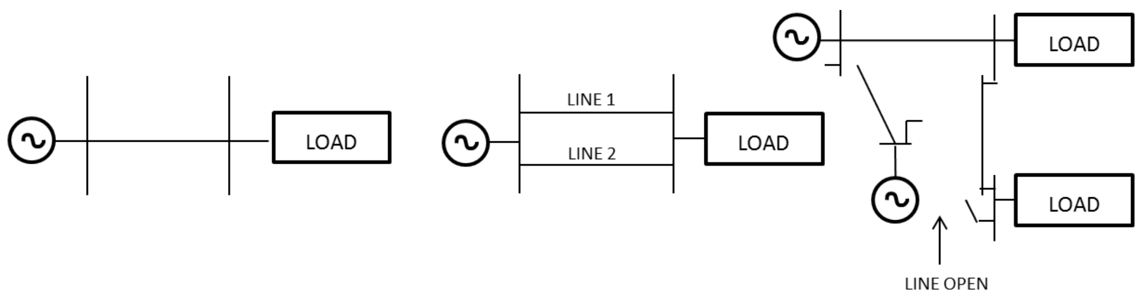

Figure 1. Examples of radial transmission lines

Transmission lines are usually protected by the line differential scheme and/or distance protection. Benefits of the line differential scheme versus the distance scheme are widely documented in the existing literature. In the last decades, with the advent of modern and more affordable communication between substations, the line differential scheme has become more popular and is now used as one or both primary protection.

Table 1. Primary protection schemes used by Australian transmission utilities where modern communication is available

Relay	Utility 1	Utility 2	Utility 3	Utility 4	Utility 5	Utility 6	Utility 7
X Protection	87 and 21	87 and 21	87	87 and 21	87 and 21	87 and 21	87 and 21
Y Protection	87 and 21	21T	21T	87 and 21	21T	87 and 21	87 and 21

Note: 21 refers to time stepped distance and 21T refers to distance with teleprotection.

It is noted that in in the event of fault on a radial line, fault current contribution is drawn mainly from the source side. Although the 87L scheme works satisfactory in this scenario, the supervisory element at the remote end of the line could potentially no operate, hence inhibit or delay the 87L operation.

This paper reviews the 87L scheme applied on radial line with particular attention to solutions for the supervisory element. The paper investigates answers which balance the need for security, speed and dependability of the line differential protection scheme in this challenging application. The study targets transmission network and its peculiar needs of high reliability. However, the findings and suggestions are also applicable at subtransmission level.

II. OVERVIEW OF EXISTING 87L AND SUPERVISORY ELEMENTS PRACTICE

The principle of the line differential is an extension of the First Kirchhoff's Law applied to the full length of the line as elaborated in 1845 by the young German physicist during its early studies. The sum of the current entering the line must be equal to the current leaving the line. As a result, the 87L scheme is a quite unique protection scheme as joins sophisticated electrical and communication techniques to provide a highly reliable line protection.

Modern 87L relays work on a peer to peer architecture. Each relay is a master and processes the 87L algorithm as well as sending the required data to the remote end of the line. Although the capability and high bandwidth of modern communications, line differential algorithm is still dictated by the bandwidth of the communication channel of 64kbps. This limitation requires some specific design in relation of the structure and contents of the data to be transmitted to the remote end. Another major element in the design of the scheme is sampling synchronization which enables to compare information at the ends of the line at the same time.

The implementation of the scheme as applied among modern relays has some obvious similarities and some important differences. In the electrical part of the design, the key element is the restrain current which then dictates the required operating current for the 87L trip. Restrain current can be derived by the maximum current at each end of the line or from symmetrical components values. Some 87L schemes also apply a restraining adaptive component which caters for power system errors such as noise, transients, harmonics, and inaccuracy in the DSP measurements, clock and asynchronous sampling. This adaptive stabilization of the scheme is based on the principle that the sum of all the currents entering the protected line is zero and, as result, the errors should be compensated by applying some additional and dynamic restrain quantity.

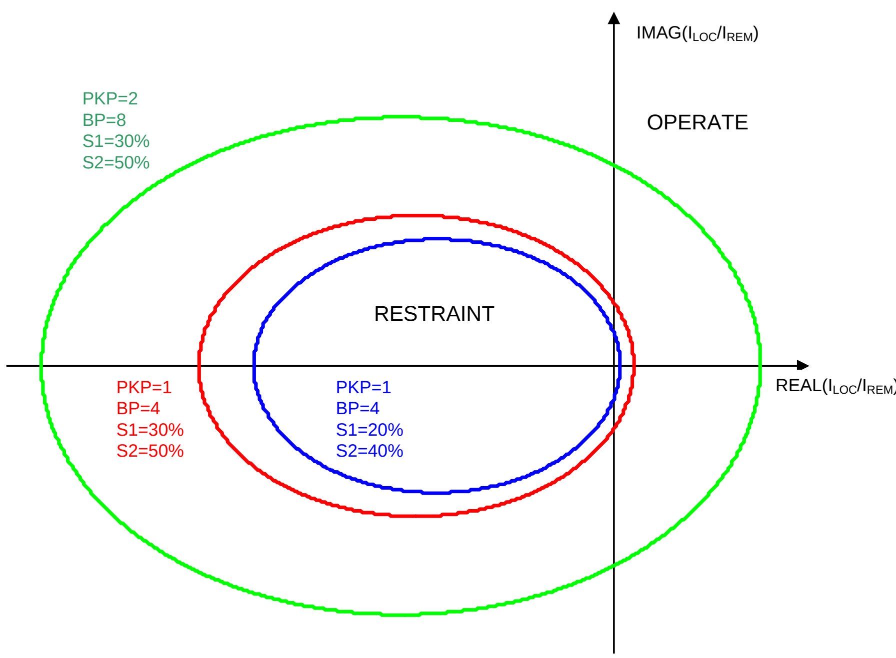

Figure 2. Setting impact on restrain characteristic of one 87L relay

A. 87L supervisory function

Protection philosophy is a continuous research of finding the appropriate balance between dependability, the capacity to operate when it is required, and security, the capacity to no operate when does not have to do so. This equilibrium continuously changes as per available technology, overarching philosophy and the specific application. In transmission lines, protection schemes are traditionally biased for security. This is particularly true when we analyze the 87L in stressed conditions for the protection relay.

Although the line differential scheme is intrinsically secure, there is a consensus between relay vendors to improve its security by addressing its main challenging conditions: data corruption, data misalignment, CT saturation, specific application requirements and incorrect settings.

Transmitted 87L packets implement BCH algorithm, checksum or CRC-32 bit data integrity check to detect any corruption or missing data. Digital relays do not provide any data replacement or data repair in order to preserve the security of the scheme. Corrupted packets are discarded and protection relays hold the operation waiting for the next available and correct received packet. Data corruption can arise due to communications noise, interference in the channel bearer, failure of devices involved in the data transmission and conversion within the multiplexer, channel switching, or within the relay itself when data is transmitted from communications port to CPU. These algorithms have a very low probability of undetected data error even below one every 10 billion a data. In a relay that generates and sends at 50 Hz two packets at every cycle, the total number of packets in one second would be 100 or 3.15 billion every year with still clear risks for the security of the 87L. It is important to bear in mind that even the most sophisticated data error algorithm cannot eliminate the risk of an undetected error being accepted by the 87L and generating a relay maloperation.

Large progresses have been done in the synchronization area to align the current data at the local and remote end of the line by using the well-known ping pong technique. GPS functionality is provided for communication network prone to asymmetry in the relay data propagation. Data synchronization is closely monitored to detect any misalignment and this information can be used to improve 87L security.

CT saturation is addressed by specific saturation algorithms either:

- Adding a portion of the signal distortion to increase the restraining current
- Switching the differential settings to more secure settings
- Use the transient bias as the additional restraining signal

There is also a consensus among relay manufacturers to provide extended 87L capacity to include ground differential, multi CT input, Direct Transfer Trip to the remote ends of the line, line charging compensation, stub bus protection, in zone transformer capability, hence, enhancing its inherent security for specific and challenging application.

Human error is also a predominant cause of maloperation in secondary engineering. Incorrect operation of personnel could happen during the design phase of the project or oversight during commissioning. The multiplication of IEDs within the substation has also made more difficult the integration of new protection and control scheme especially for a brown field substation. Incorrect manipulation of the protection setting could appear during a routine maintenance or remote or local engineering access to the relay to monitor online metering or the existing settings. These concerns have led manufacturers to work extensively on the security of the relay in different forms not excluding the specific algorithm of each protection element.

At the beginning of the modern 87L digital relays period, 1995-2000, the work to enhance the 87L security brought relay manufacturers to also add an independent protection element to supervise the operation of the scheme. One of the solutions to achieve this goal is by confirming that the fault is taking place by implementing a disturbance detector (DD) element at each end of the line. If there is not a disturbance in the network, it is very likely that there is not a fault. This section outlines the approaches and functionalities of the supervisory element of the line differential scheme as applied by different relays.

One approach uses a current sensitive algorithm that compares actual symmetrical component values to the values of four cycles before. The threshold is set at 0.04 pu. If detected, the supervisory element also resizes the operating window of the 87L packet to remove the pre-fault current, thus reducing the operating time of the 87L. The supervisory element also provides an adaptive level detector operating on zero and negative sequence absolute values. The scheme was designed to be flexible to accommodate different application and provides seal in and no current supervision detection functions.

Another approach provides a flexible supervisory functionality based on current and voltage which is articulated in four subsections operating with a parallel logic. Thresholds as well as timers are user definable and provide the start for the protection element. Each subsection is independent and can be disabled if required. Phase to phase current variation is the main element and provide sensitive detection for the majority of the type of faults. The zero sequence current is monitored to target high impedance fault scenarios. Instead, low current criterion is suited for switch onto fault scenarios where the pre-fault current is below a settable threshold. The undervoltage element is tailored for weak infeed scenarios with pre fault no load conditions. Phases to phase as well as phase to ground voltages are monitored to supervise the differential element under any type of weak infeed fault.

One more method has been tailored to provide additional security for internal and external faults. The scheme is fully integrated within the 87L. The external fault detection is designed to tackle fault scenarios followed by high AC components or a long lasting DC component. The scheme is also used by the 87L element to switch the scheme to the extended security settings logic. The disturbance detection logic is based on current and voltage and also integrates the detection logic from the remote end. The detector is adaptive and based on full cycle filtered current phasors to adjust its threshold to avoid asserting under normal load variations. Once asserted, the detector signal is maintained for 10 cycles.

Some relays do not have a specific 87L supervisory element, but ensure additional stability upon communication propagation changes which can be encountered in a SDH system or monitor the stationary or slow building unbalance in the time propagation between transmit and receive packets if GPS synchronization is available.

All the methods have programmable logic capability to allow the implementation of specific supervisory logics and are able to send this status to the remote end of the line. Current detectors are not usually phase segregated. Hence, at current change detection on a phase could be used to assert the 87L operation on a different phase.

III. COMPLICATIONS FOR THE APPLICATION OF 87L ON RADIAL LINES

Upon a fault on the protected radial transmission line, the remote line end has either no infeed or weak infeed current contribution. At the source end phase and symmetrical current phasors depends on the fault level, fault type, fault resistance, and location of the fault. In the event of an external fault on the remote end side, current seen by both ends of the line will have similar phasors as in a meshed network.

For an internal fault, voltage level at the source end will be reduced but still relevant in comparison to the remote end where the voltage will collapse. The voltage at the source end depends to the source impedance and the fault impedance. At both ends voltage level will increase in the event of a resistance fault. For an external fault the voltage phasors at the two ends are more similar except for long lines due to the voltage drop created by the fault current.

Typically, radial transmission lines are located in remote areas where the fault level is average to low. In rural Australia it is not rare that the maximum fault level at 220 or 132 kV can be as low as 2.5 kA. Assuming I fault minimum/I fault maximum ratio of 70%, the fault level could decrease to 1.75 kA during minimum fault level scenario. Other weak infeed scenarios include high resistance faults, simultaneous faults, line or transformers out of service in the same network area.

Radial lines are often located in areas prone to bushfires. According to field experience, arc resistance through smoke and fire dust can potentially reach 30-40 Ohms. These elements suggest that this analysis should also include weak infeed scenario at the source end.

Voltage at any point of the line can also be calculated easily by using the Source Impedance Ratio, SIR:

$$Vpu = \frac{1}{(SIR + 1)} \tag{1}$$

Where,

$$SIR = \frac{Zsource}{Zline} \tag{2}$$

A high level representation is provided in Figure 3 to Figure 6 for a three phase fault at the end of the line with different fault levels, fault resistance values and line length. It should be noted that any current contribution coming from the remote end will increase the voltage level at the remote substation. Usually this increase is not relevant due to the minor current contribution.

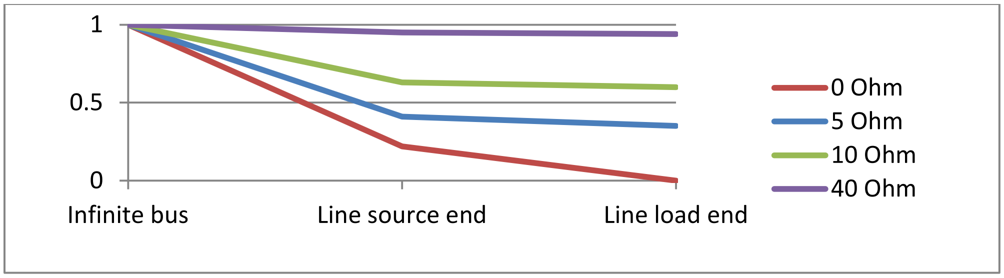

Figure 3. Fault voltage profile – 220 kV, 10 km, 10 Ω Z1 source, three phase fault

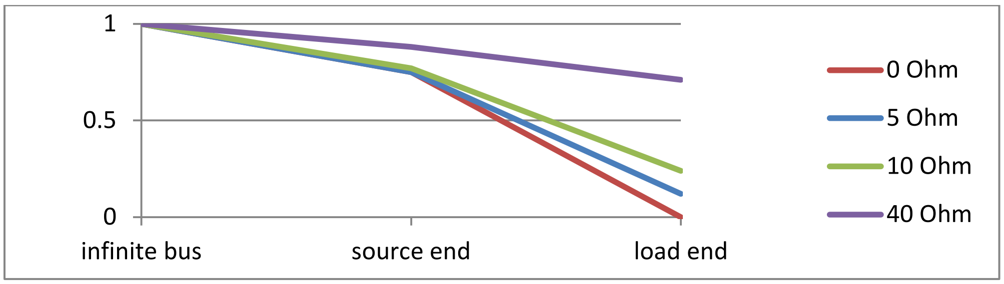

Figure 4. Fault voltage profile – 220 kV, 100 km, 10 Ω Z1 source, three phase fault

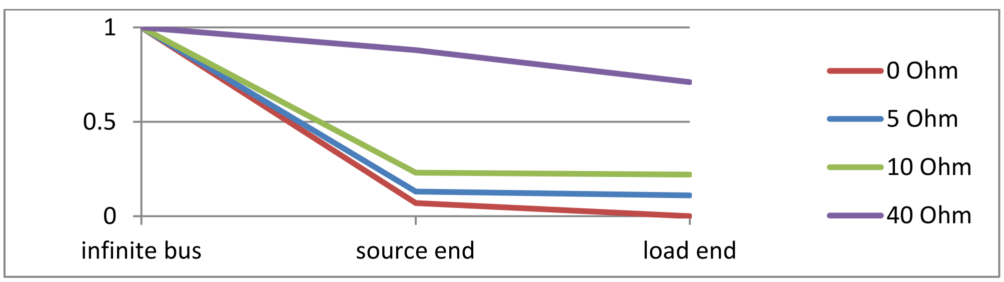

Figure 5. Fault voltage profile – 220 kV, 10 km, 40 Ω Z1 source, three phase fault

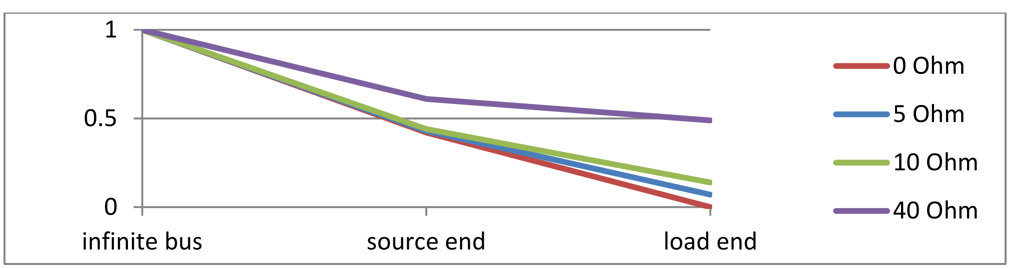

Figure 6. Fault voltage profile – 220 kV, 100 km, 40 Ω Z1 source, three phase fault

One of the key advantages of 87L protection is being able to detect and operate for a very large range of fault currents. The scheme is generally insensitive to how the current contribution is derived from the two ends. Despite the specificities of each relay, the 87L should be treated as one scheme which transfers current information between locations via communication. A zero current contribution from the remote end is still a valid and meaningful data for the operation of the 87L algorithm.

For a transmission line located in a weak network area, the impact of the radial line on the restraining current is minor and mainly depends on the 87L algorithm design, the specific protection settings and the CT ratio selected. Referring to the fault scenario and results shown on Table 2, the operating current of the 87L scheme is still well above the restraining current with a high level of dependability.

Figure 7. Dependability of 87L for high resistance fault – software simulation with 87L relay

Table 2. Dependability of 87L for high resistance fault – 220 kV radial line, CT 500/1, PKP 0.2 pu, slope 1 20 %, slope 2 40%, Breakpoint 4 pu

Fault current (A)	Operate current (A)	Restrain current with fault current from one end only (A)	Restrain current with fault current from both ends. 50-50 % contribution share (A)	Dependability
250	250	158	150	Yes
500	500	200	173	Yes
1000	1000	316	245	Yes
2000	2000	583	425	Yes
4000	4000	2045	812	Yes

A. CT saturation

During an internal fault, if the fault level and the total CT burden are very high, there is a higher risk of CT saturation at the source end as the full fault current is seeing by one end only. However, with correct selection of the 87L high end differential slope setting, it is very likely that the 87L will operate, hence confirming a general tolerance of modern 87L relays towards CT saturation for dependable operation.

The saturation caused by an external fault is more a concern for the 87L scheme, especially in breaker and half application or where the CT performances between the two ends are rather different. For an external fault on the remote end side, for instance on the HV side of the transformer, a high fault level could develop CT saturation at one end and challenging the security of the 87L. The relay maloperation will completely disconnect the load. This risk is minor for a fault on the LV side of the transformer due to the reduced fault current drawn from the network.

In a double circuit, sharing the fault current contribution with the adjacent line will sensibly decrease the risk of CT saturation. Similarly, for an external fault at the source end side, the two CTs on the breaker and half will always see the same current on the diameter and, likely, will have similar performance even during high through fault currents and reduced CT performance. We should reiterate that CT performance is still one of the key points for the stability of any type of differential scheme which affect in the same way meshed and radial applications.

In order to analyze the 87L reliability during CT saturation generated by an external fault, relay manufacturers are developing specific tools tailored for the specific relay. The software tools are used for CT selection and to check if it is possible to reduce the CT requirement. It could also support the designer to determine the impact of changing the 87L settings. One of this tool implements the CT model and saturation algorithm proposed by IEEE PSRC and simulates the signal processing and data calculations as applied the 87L relay. As a result, the tool incorporates in one application the analysis of the CT and the performance of the 87L algorithm.

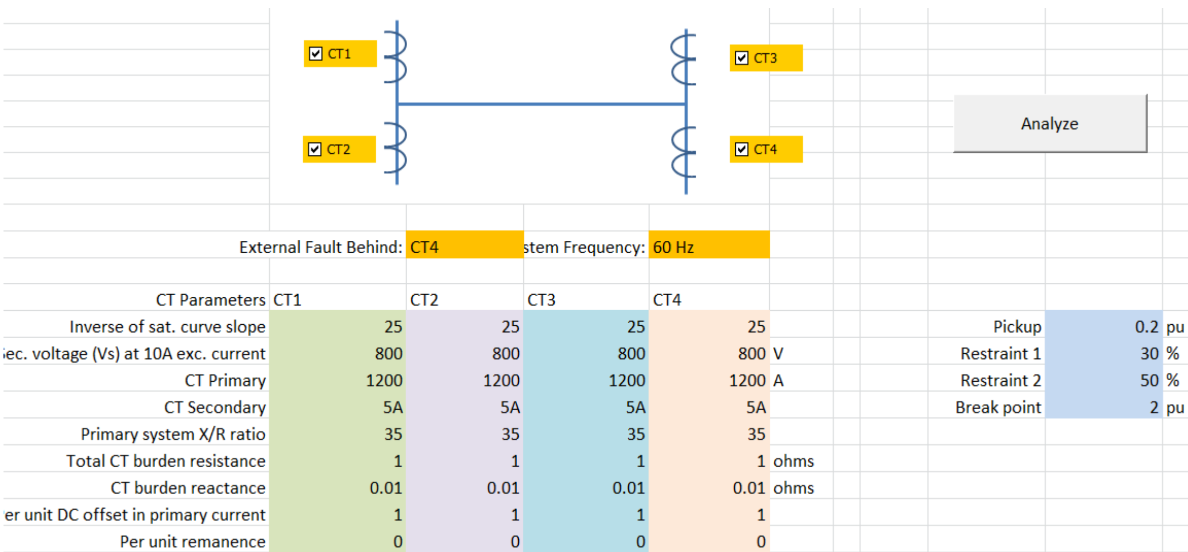

Figure 8. CT saturation analysis tool

B. Radial line and 87L sensitivity

Apparently in radial double circuit application, upon an internal fault, the remote end will see some fault current contribution coming from the healthy adjacent line. Assuming that the two circuits have the same line impedance, the highest current is for a fault near the remote end with 50% of the total fault current seen by the relay. Vice versa, the lowest weak infeed scenario is during faults towards the source end of the line. For instance, for a phase fault located at 95% of the line, the remote end will see 2.5% of the total fault current. Assuming, a minimum fault current of 1.5kA, the remote end contribution will be as low as 24A or 0.04 pu for a 600/5 CT ratio. However, upon a fault on one of the two lines, an 87L incorrect operation on the healthy line will completely disconnect the supply to the load, hence a blackout to the remote substation.

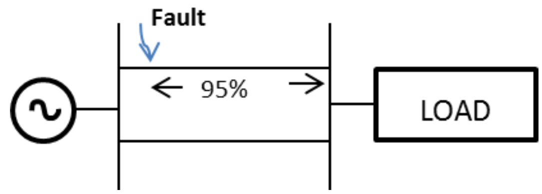

Figure 9. Double circuit with fault at 95% from remote end

These considerations for single and double circuit application are generally valid for three ended line application with only one end acting as the source.

In relation to a long radial line and the line charging current compensation function, the radial line itself does not add any additional challenge to the 87L scheme. For a long line charging current should be always considered as a standing differential current which impacts on the performance of the scheme. If the compensation is not applied the security could be affected. If the designer prefers to modify the protection settings with a more secure approach, for very long line say above 200 km, the sensitivity for very high impedance fault could be marginally reduced. It is worth to note that the line charging current compensation might be required at the source end and could be ignored at the remote end of the line if there is not earthing reference to close the loop of the line charging current.

At this stage we have based the analysis considering that the remote end does not contribute to the fault. In real application, however, the remote end of the line can supply some fault current contribution due to the transformer windings, embedded generators and large motors.

For an internal phase to ground fault, the zero sequence path of the transformer with HV star earthed and a tertiary winding will act as a fault current source. Even if the HV side is unearthed zero sequence path can be created by the core and tank of the transformer. As a result, the magnitude of the current contribution from the remote end depends on the transformer winding connection, impedance and the network impedance connected behind the remote substation. Instead, the transformer itself is not capable to supply current contribution for three phase or phase to phase line faults but is still capable to contribute for phase to ground faults even if the CB on the LV side of the transformer is open.

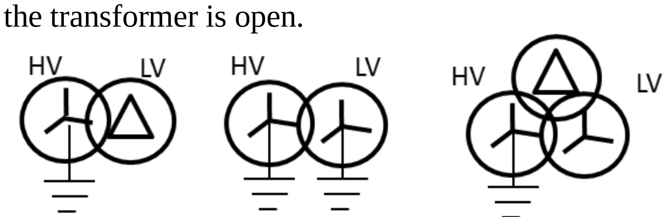

Figure 10. Examples of transformers that provide zero sequence current path or shunt

Embedded generators are often located in large industrial or mining plant for emergency supply and, in some cases, to offset the energy production cost. In this event, it is likely that the generator will be connected during a fault on the line.

Synchronous machines contribute between 6-10 times the nominal current to the steady state fault current, about 2-3 times in few cycles. For 87L protection consideration and protection coordination, it is usually recommended to use either the subtransient or transient reactance according to the related time constant.

Large motors could also generate large fault current contribution. Direct On Line induction motors contribution is typically 5-6 times the nominal current. Initially, the contribution contains both AC and DC components. Due to the voltage collapse the current quickly decays. For VSD and soft starter motors the fault current contribution is lower and limited to 2-3 times the nominal current.

It is worth to note that if generators and large motors are connected at a lower voltage, the power transformer impedances will considerably limit the three phase fault current contribution. For ground faults instead, the various parallel zero sequence paths will still reduce the overall impedance of the remote network. Fault current contribution from these sources can be determined by applying IEC or IEEE standards. However, it is common that Utilities tailored the study to suit the specific application.

IV. Complications for the Application of 87L on Radial Lines

As reviewed in Section II-A, 87L supervision operates mainly on current detectors or current change. Upon a fault, the impact of the radial application to the 87L supervisory element has a dramatic performance difference between the source and remote end of the line. If at the source end the application does not create any specific difficulties compared to a traditional meshed network, the remote end current detector is at risk of not operating, hence, preventing the fault clearing of the remote circuit breaker.

Do we really need to trip the remote end for a line fault? Complete isolation of a faulty part of the network is a cardinal rule of power system operation. Although the opening of the source side only prevents damage to equipment and is common practice in radial feeder at distribution level, this should be avoided at transmission level. Transmission substations contain duplicated, overlapping, redundant protection and control schemes. The complexity of the system suggests that fault outcomes should be unique and in line with standard practice in other substations. Double contingencies will also add more difficulties to the operators. It is foreseen that at both substations fault finding and fault investigation will be more complicated.

These substations are often located in remote areas which makes site visit from personnel more onerous. Site inspection upon a fault is usually a stressful event which could take place at the most unexpected time of the year with challenging weather conditions like bushfire or cyclonic conditions. Remote end substations could be shared owned by the Utility and the mining owner which usually adds more complexity to site operation and maintenance. Potentially, the level of knowledge and experience on secondary engineering in the privately owned part of the substation could be lower. Providing the least ambiguous design and event outcomes will decrease the likelihood of any safety issue.

Technically, the absence of circuit breaker trip at the remote end allows current contribution from motor to the fault during the dead time of the Autoreclose function. This decaying current could potentially maintain the arc fault till AR recloses. The result is defeating the AR purpose of self-healing transient faults.

A list of some existing and potential solutions for the 87L current detector for the remote end is below provided.

A. Do nothing

This “solution” implies no modification to the standard 87L supervisory current detector. It relies on the deep knowledge of the remote substation load such as plant operation details, and subsequent expected minimum and maximum fault current contribution. Motor data and duty cycle are also required. Often this information is not available during feasibility study which forces utilities to base the design on typical figures and other assumptions. The decision of how many transformer and motors should be included in the system model is critical as reducing the impedance will increase the expected fault current contribution.

Maintaining the same current detector design for all applications also embraces the need of standardization of protection schemes, simplification of design and cost reduction. A specific solution for the current detector on transmission line could potentially be seen by some utilities as an unwelcomed concession no in line with a modern and efficient approach to substation design.

Design changes following commissioning are expensive and, wherever is possible, should be avoided. For mining plants, due to the market volatility and fluctuation of commodities price, it is not uncommon to see plant operations and loads changes over time. Therefore, utilities tend to be very cautious in using plant information too closely as these conditions might not be valid any more even in the short/medium period.

Typically, selection of the CT ratio is based on the line rating and the CT performance during an external fault. It is also noted that utilities usually select the same CT ratios to avoid using 87L CT ratio compensation function. Sometime these factors lead utilities to select a higher CT ratio of what it is really required. On radial line it is suggested to consider a CT ratio above maximum load plus a safety margin for future use. At the remote end, the CT ratio could be further reduced for additional disturbance detector sensitivity based on avoiding onerous CT saturation and significant CT performance differences between the two ends of the line. This solution is often feasible in remote areas with a low fault level or in an application with a new CT with satisfactory specifications. This approach will improve the sensitivity of the current detector as shown on Table 3.

Table 3. Examples of CT ratio selection and current detector sensitivity

Fault level at remote end (kA)	Line Rating (A)	Remote end max load (A)	Source and remote end CT ratio (A)	87L current detector with typical CT ratio (0.04py) (A)	Suggested CT ratio (A)	87L current detector with new CT ratio (0.04py) (A)
6	550	130	600/1	24	400/1	16
6	550	260	600/1	24	400/1	16
3	550	130	600/1	24	400/1	12
3	550	260	600/1	24	400/1	12

For double circuit radial line there is also the consideration of the current contribution from the healthy line: Should it be considered? For the dependability of the 87L supervisory element, it would be prudent to keep in mind that the adjacent line could be out of service, hence, the consideration for a single radial line still persists. This approach is in line with the distance scheme where several line scenarios including adjacent circuit out of service and earthed at both ends are considered for distance zone reach design.

The support of this solution also considers that the current change on the healthy phases during a fault is often sufficient to enable the current detector. This is particularly true for 24/7 operation plant. Further details are elaborated in Section 6. However, power system protection is for its nature conservative and requires a high level of reliability, especially at transmission level. If a credible current change or contribution from the remote end is not foreseen for likely fault scenarios, other means to satisfy the 87L supervisory operation should be investigated.

B. Sequential trip

This is a natural progression of the solution detailed above. The fault will be cleared by the source end anyway which eventually drops on all the phases the current to zero.

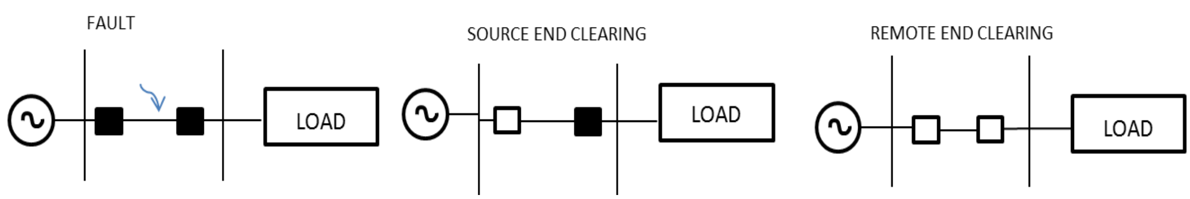

Figure 11. Sequential trip example – the three typical phases

If the load was connected at that time, the current change even on the healthy phases is likely to enable the current detector and, then clearing the fault with some delay. However, it is required to latch the 87L operation to prevent the element dropout upon source end clearing, hence inhibit of the sequential trip. In addition to relying on a minimum connected load, the other drawback of this approach is delaying the fault clearing time of 80-100 ms at the remote end. Considering the small current contribution from the remote end this issue appears to be acceptable. However, this delay might not be tolerable from a National Electricity Rule point of view as, in the end, the radial line is still part of the transmission network.

C. Disable 87L supervision

In this option the 87L remote end will trip without supervision which raises the key question about the need of the 87L supervisory element for a radial line.

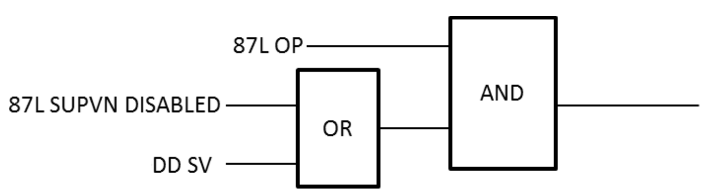

Figure 12. Disabling the 87L supervision logic

In fact, it is likely that X and Y protection will have dedicated redundant communication bearers with often no practicable SDH rerouting. Hence, channel asymmetry is less likely or not possible in comparison to a typical meshed network. However, extreme noise and data corruption are related to the communication performance and are still possible as in a meshed application.

Further review of the 87L philosophy of the balance between security and dependability in a radial line is also warranted. **Is this balance for a radial line different from a meshed application?** It is noted that there are two schools of thought. The first approach leans towards dependability of the scheme. The second one is biased for security.

Radial lines are often dedicated to one customer or to a rural area with less customers connected. As a result, a lower degree of supply security might be acceptable. Besides, power supply will not be interrupted to other substations and no thermal overload on adjacent line will be generated. Even in a double circuit application, the rating of one line is capable to cater the full load of the remote substation.

The concern is rather related to a load rejection which triggers dynamic changes on voltage and frequency in the network. The opening of a transmission line, even in a radial application, always creates transient overvoltages and surges which propagate to the adjacent lines with consequent stress on the insulation of the system. Presence and performance of shunt capacitors, reactors or other specific equipment at the source end should be also considered. In general, a maloperation on a radial line has a low impact to the stability and supply to the overall transmission network and is contained within the system specifications.

In terms of protection, 87L and 87T applied to adjacent lines and transformers are generally immune from dynamic oscillations as the Kirchhoff's first rule always applied even during transient conditions. Modern distance relays also have satisfactory performance during these stressed conditions.

The other approach considers the importance of supply customers fed from one source only. For a large industrial plant financial impact of an incorrect line trip including interruption (loss production, restart operation, risk of damages on connected drives) to large motors, conveyor belts, crush rocks drives and large mining machines is also taken into consideration.

The importance and need to maintain the supply during transient faults has also lead some Australian utilities to implement single pole tripping on some specific applications. These projects remark the need of the continuity of supply and the security of the protection scheme applied to a radial line.

Although disabling the 87L supervisory element completely resolves the issue of the current detection, the authors suggest that, in general, the importance of continuity of supply and security for the 87L scheme still applies to radial line as for meshed application. This is particularly true where MUXes are implemented in the communication between the two ends of line. Considering that this is becoming common practice for transmission utilities, the use of the 87L supervisory element is obviously encouraged.

D. Decrease the threshold of the current detector

Current supervision threshold depends on the minimum pick up, the conversion range of the relay and the accuracy of the current detector. It is common to add a safety margin which is usually equal or above 100% of the minimum conversion range. Although an increase sensitivity of the scheme will improve the dependability of the 87L detector, this will not fully resolve the risk of no operation for extremely weak infeed or no current change. It should be also noted that relay manufacturers do not allow the setting of the current detector, hence, this option is not always possible. Moreover, it would be not advisable to have a major sensitivity increase, let’s say from 0.04 pu to 0.01pu with the risk of an unwelcomed disturbance detector pick up during normal load current fluctuation. For instance, considering an hypothetical threshold of 0.01 pu with a CT ratio of 300/1 A on a 220 kV line, the current detector would continuously pick up for load change above 2.25MVA which is rather common in a large industrial plant.

E. Undervoltage detection

The use of undervoltage supervision appears to be a solution that could work correctly for a large variety of fault scenarios. This element is already implemented for some off the shelf 87L relays. Where the undervoltage supervision is not readily available, the undervoltage check could be implemented and AND gated with the 87L element in the protection logic.

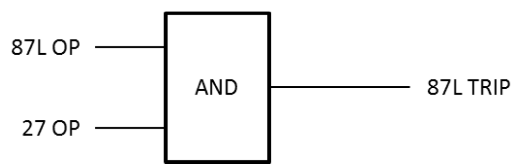

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Figure 13. Use of the undervoltage element for the 87L supervision logic

The undervoltage element could be implemented either using a pick up threshold or monitoring the change compared to the voltage of four cycle before fault inception. Design of the undervoltage pick up should consider the maximum expected fault resistance on the line and voltage dip during the worst credible motor starting scenario. Voltage depression during simultaneous faults on adjacent line should be disregarded in this instance. Usually, an undervoltage pick up setting between 0.6 to 0.8 works correctly but needs to be confirmed during the power system study for the maximum expected high resistance fault. Voltage elements are fast and will no delay the 87L operation.

It is noted that the use of voltage element does not utterly convince the protection engineering audience for historical and technical reasons. One of the key points of the line differential over the distance protection is being independent from the voltage input and overcome VT fuse failure issues. Therefore, this solution has still a minor impact on the dependability of the 87L element.

F. 87L supervision signal from the source end

The remote 87L supervision is here paralleled, OR gate, with the identical signal from the source end which is deemed to detect the fault.

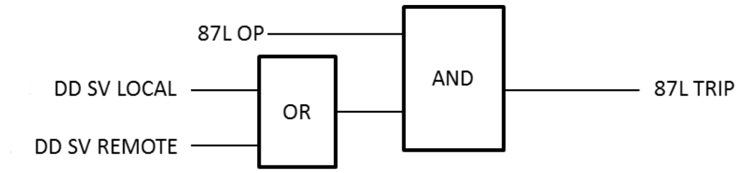

Figure 14. Use of the DD supervision from the source end for the 87L supervision logic

This signal will be contained in the first 87L packets with no risk of delay the 87L operation. This solution appears to be in line with the nature of the 87L scheme which is, in the end, one scheme only. As current and other data is used from the source end, there is not a strong reason not to use the 87L supervisory signal. In theory, this solution does not perfectly align with the peer to peer 87L architecture and independency of the operation of the relay upon fault detection. However, the likelihood of simultaneous and undetected corruption of the differential data and the 87L current detector supervision from the source end is extremely remote and, hence, should be disregarded.

G. Direct transfer trip

Modern 87L relays are provided with Direct Transfer Trip function, DTT. DTT signal is generated by the other end 87L trip operation. In theory, the DTT signal could be also used to map other protection elements operation. If the signal is enabled, the 87L trip at the source end will trip the remote end.

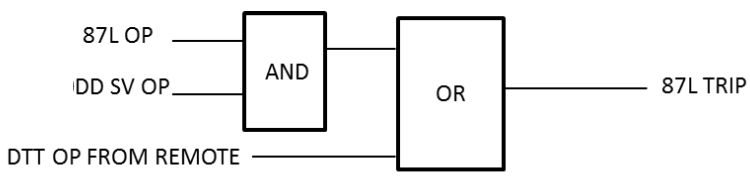

Figure 15. Use of DTT from local (source) end for the 87L supervision logic

In a typical application, this is a redundant tripping signal as the 87L at the remote end should clear the fault anyway. We note that some utilities always enable this function all the time for redundancy and simplicity purposes.

Although this solution includes advantages and disadvantages that appear to be similar to the 87L supervision sent from the remote end, this option is not biased for security as the corruption of the single DTT bit, the remote end will trip with no any other safeguard.

H. Use of current angle change detector

For the 87L supervision in very weak infeed application other studies have investigated the use of angle change of the symmetrical components in parallel with the traditional current magnitude change detector as an alternative method to overcome challenging scenarios. Although the principle is correct and feasible, there is still a limitation in the event that the current is still lower than the relay current threshold.

I. Use redundant protection element

Microprocessor based protection relays are provided with multiple protection functions. Even where the 87L is the primary protection, it is common that the distance or directional elements are enabled to provide either redundant protection or back protection in the event of 87L unavailability. This “off the shelf” protection element should operate continuously to provide dependable redundant supervisory function.

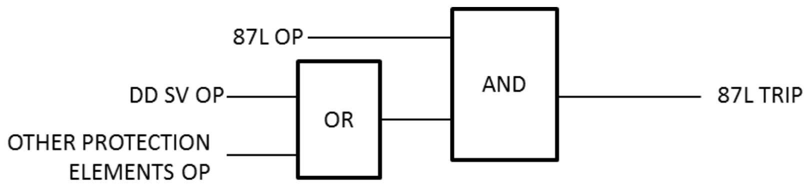

Figure 16. Use of redundant protection element for the 87L supervision logic

Unfortunately, due to the weak infeed at the remote end, distance protection and directional overcurrent do not have better dependability of the dedicated 87L current detector. Therefore, this option is unconvincing.

J. Combination of two or more options

Multiple solution approach is already implemented by several relay vendors or could be implemented by the user via relay logic. Where three options are considered, decision should be made regards of any of the elements enable the 87L supervision or rather a 2 out of 3 logic biased for security approach which is not recommended for a supervisory scheme. It appears that a simple multiple approach suits the 87L supervision as provides enough flexibility to cover different scenarios. However, there is a potential risk to overly complicate the design, commissioning and maintenance of the scheme with subsequent impact on dependability.

V. PERFORMANCE ISSUES OF 87L

There is a general understanding that if a minor load is connected at the time of the fault the current detector will operate even for a three phase fault due to load drop current changes, hence, disregarding the fault current contribution. Although this statement is statistically correct, there are some scenarios where the load connected is low or below the current detector threshold, such as:

- Following a fault which has disconnected a large part of the remote substation load
- At a rural zone substation, for some very short period at night, in particular during mild weather conditions, where air conditioning or electrical heating loads are at minimum
- At an industrial substation, during routine plant shutdown period, which usually takes place every six months or one year
- At an industrial substation, where a major production reduction has been implemented

In any case, the extreme scenario of no load connected is during line energization or during the transitory phases between line energization and load connection. The latter phase can take several minutes or hours. In these scenarios and an internal fault, the source end will see enough fault current to enable the 87L current detector and the remote end none which is not different from a typical two source two ended line.

How does the 87L perform during simultaneous faults? For a radial line simultaneous faults are not usually thoroughly investigated. Utilities are concerned whether the line shares the same towers with another circuit. In this scenario, a simultaneous fault could take place for a broken conductor, a dramatic pole or lattice tower collapse or a lightning event which hits or transfers the fault to the adjacent line. We have reviewed the 87L performance upon a first fault on four different locations of the network as shown on Figure 17. The 220 kV radial line supplies an industrial plant which provides a small but still reasonable fault current contribution.

The first fault is on the following location:

1. Adjacent 220 kV transmission line
2. HV side of the 220/22 kV power transformer
3. LV side of the 220/222 kV power transformer
4. 22 kV switchboard within the plant

The second fault is obviously on the radial line under review. In particular, the focus is on the undervoltage and current disturbance detector considering an internal three phase fault.

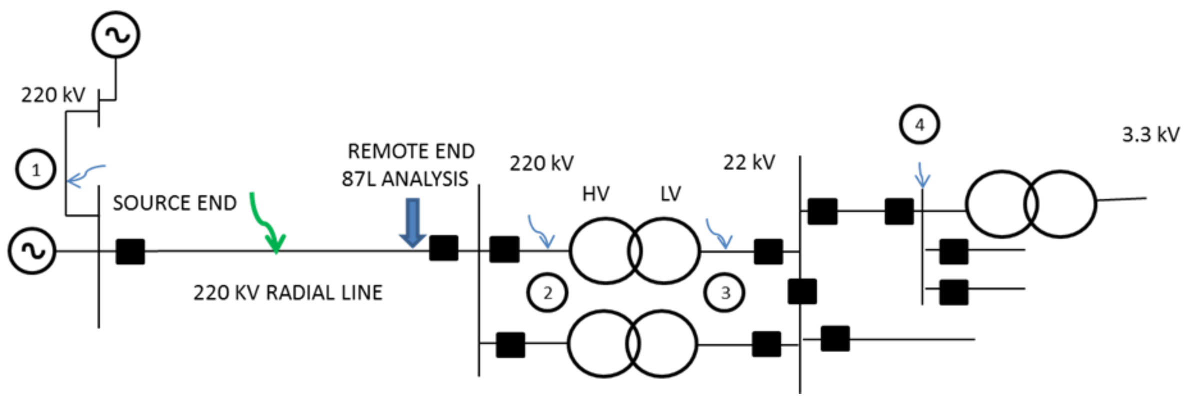

Figure 17. Simultaneous fault analysis and impact on 87L (Location of first fault is 1 to 4)

In any scenario the reduced fault current is sufficient to operate the 87L and the current detector at the source end. At the remote end, fault current contribution the substation will be reduced until the first fault is cleared. This could affect the disturbance detector supervision (DD SV).

- For Scenario 1, it is expected that a reasonable fault current will be provided from the plant anyway, with a reasonable chance to have the disturbance detector enabled well before the fault on the radial line
- The impact on the disturbance detector is minor for Scenario 2, as the two fault locations are not electrically very far away. In theory, if the faults are just before and after the 220 kV bus at the remote substation with no fault resistance in both incidents, the fault current seen by the disturbance detector is 50% of the total current contribution from the plant

- For Scenario 3 and especially Scenario 4, the increased impedance between the two fault locations, will limit the fault current drawn from the plant. It is likely that the disturbance detector will not operate
- The use of the undervoltage element as 87L supervision will instead operate correctly for Scenario 1 and 2 and partially for Scenario 3. For Scenario 4, there is a high risk that the voltage collapse on the 220 kV line is minor, hence disabling the capacity of the 27 element to operate

Faults in a distribution network are not always cleared instantaneously due to protection coordination requirement. As a conservative approach we should consider that for Scenario 3 and 4, the scheme supervision and the 87L operation at the remote end of the radial line could be delayed up to 0.5-1 second.

Academically, we should also mention that for Scenario 1, there is a minor risk for the fast 87L operation upon a high resistance fault on the radial line connected to a breaker and half configuration at the source end during high current transfer on the diameter. In the event that the other diameters are interrupted, it is possible that a high current flowing on the affected diameter will restrain the 87L until the first fault has been cleared. This scenario is unlikely and the drawback or delaying the fault clearing of say 100 ms, is considered acceptable.

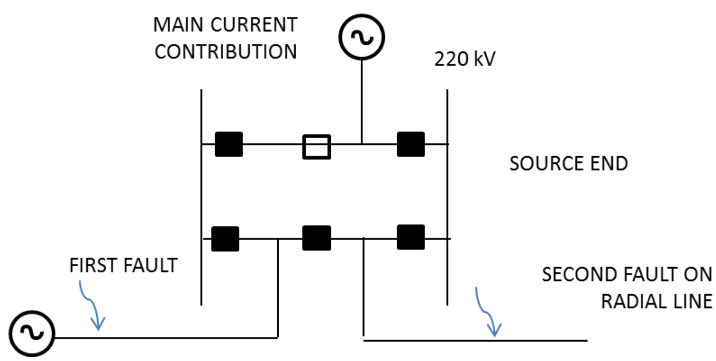

Figure 18. Simultaneous fault – Scenario 1 with high fault transfer on the diameter feeding the radial line

Last, let's now try to invert the scenarios by applying the fault on the 220 kV radial line first. In this event and Scenario 1, we can safely state that the fault on the 220 kV radial line will not worsen the operation of the disturbance detector on both ends of the other 220 kV line.

VI. FAULT ANALYSIS ON A REAL RADIAL APPLICATION

To analyze the performance of the 87L supervision two genuine phase to ground fault events on the same 132 kV line have been reviewed. The line is in the Electranet transmission network and connects Hummocks Substation, source end, to Kadina East Substation, remote end. The line is situated in the northern Yorke Peninsula in South Australia.

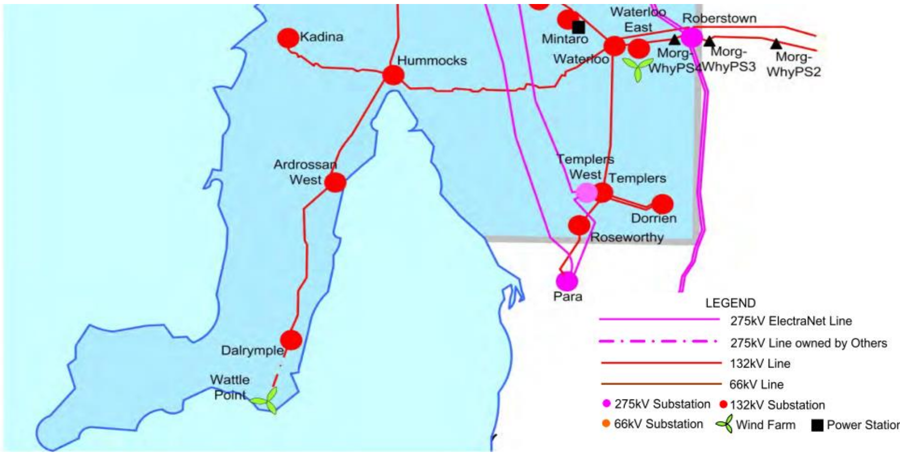

Figure 19. Yorke Peninsula transmission system diagram

At Kadina East there are two 60 MVA transformers, YNd11yn group. The delta tertiary side is used to supply the station service transformer. The LV side of the transformer is earthed via a Neutral Earth Reactor, NEX, of 2.5 Ohms. Both transformers were in service at the time of the events. At both substations there is a double circuit breaker or meshed configuration.

The fault level in the area is low. At Hummocks they are 4.2 kA and 4.1 kA for the three phase and phase to ground fault. At Kadina East the fault level decreases to 2.3 and 2.6 kA respectively. The 132 kV line is 40 km long. The faults occurred on 17th of December 2011 and 12th of October 2014. In both cases the current disturbance detector picked up correctly and, as expected, 10-20 ms before the operation of the 87L.

The disturbance detector of the protection relay under review compares the change in magnitude of the negative, zero and positive sequence current of the actual values to the values of four cycles before. The threshold is fixed and set at 0.04 pu.

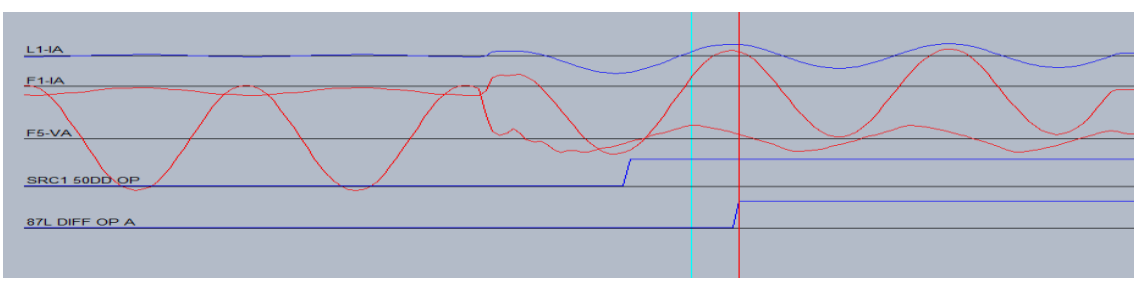

Figure 20. 2011 fault – Oscillography data

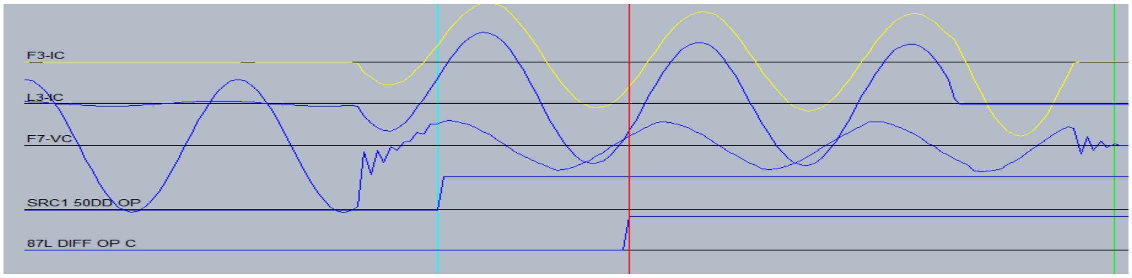

Figure 21. 2014 fault – Oscillography data

Table 4. 132 kV Hummocks Kadina East faults analysis - Results

Event	CT ratio at both ends	Pre-fault load current (A)	Fault current from Source end (A)	Fault current from remote Phase A (A)	Fault current from remote Phase B (A)	Fault current from remote Phase C (A)	Remote Io change (A)	Remote DD opera-tion	Vol at source (pu)	Vol at remote (pu)
2011 A-G fault	600/1	34	2950	480	410	480	455	Yes	0.31	0.25
2014 C-G fault	600/1	31	2260	330	390	390	368	Yes	0.4	0.25

From the two events we can derive the following:

- At the source end the disturbance detector will definitely operate for any type of fault
- At the remote end the disturbance detector dependability is also very high due to the significant zero sequence current provided by the tertiary winding of the two transformers
- The remote current contribution is above 400 A which is 0.6 pu. The disturbance detector would have operated even with only one power transformer connected
- Total fault current and fault voltage shows that there was some minor resistance involved. Considering the high current contribution, it is suggested that the disturbance detector would have operated even with a higher fault resistance
- The fault current contribution ratio between the source and remote end is about 6 in both events which suggest that the faults were located in approximately the same section of the line. Besides, the ratio confirms the impact and importance of the transformer tertiary winding zero sequence shunt for line internal fault
- For the purpose of dependability, it would be prudent to analyze the disturbance detector operation for the worst case scenario, which is a fault close to the source end, Hummocks substation, with a 40 Ohms fault resistance. Assuming typical transformer and 132 kV line impedances, it is possible to determine that the current contribution ratios between the two ends could be in the range of 7 to 13. Using a conservative ratio of 15 and

considering a high impedance fault of 1.3 kA close to Hummocks Substation, there is still a satisfactory 82 A of fault current drawn from Kadina East.

- It is noted that the current contribution from the remote end would have decreased in a strong network area or in a much longer line. Realistically, **it is believed that at Kadina East for a ground fault** the disturbance detector **will likely operate for any credible fault scenario**.
- The tertiary winding of the transformer generates current changes even on the healthy phases. As a result, even a current disturbance detector based on phase value magnitude change would have operated. Figure 22 shows the post fault phase current increase, phasor rotation and similar current contribution from the two power transformers as denoted by the CT source data

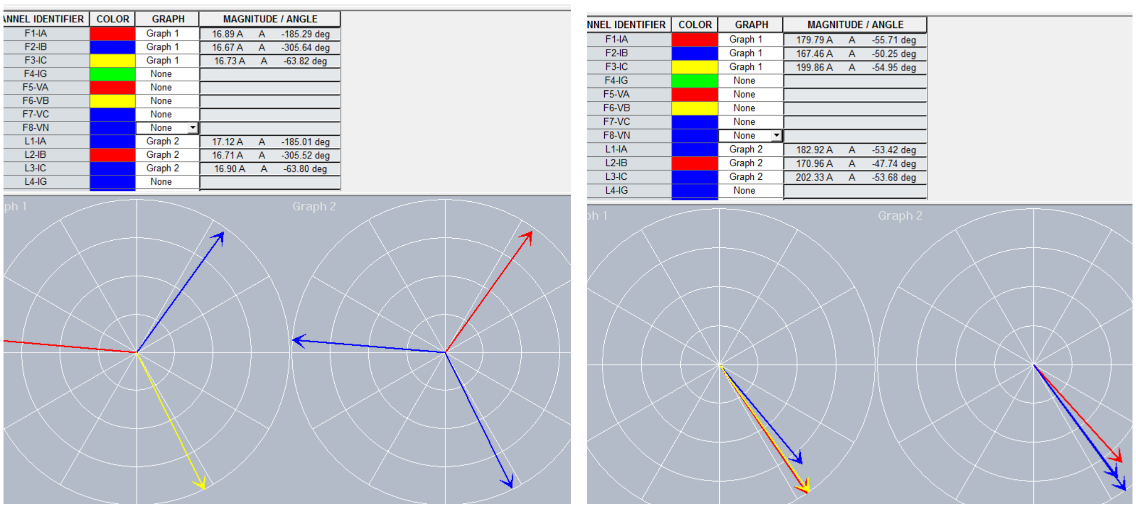

Figure 22. 2011 Fault – Pre and fault phasors of the remote end breaker and half CTs

- Would the disturbance detector have operated for a three phase fault? The load at Kadina East is a combination of rural and residential customers with no large industrial loads, HV drives or co-generators. Considering the 132/33 kV transformers, other transformer impedances and feeder distribution impedances, it is estimated that the ratio between the positive sequence impedances of the source of the remote end is very high, hence reducing the fault contribution to a few amperes. For the sake of this analysis we have arbitrary used a load current drop to 10-15A at the time of the 87L pick up. Apparently, it is possible that the positive sequence current change would have been just below 0.04 pu, the disturbance detector pick up. Therefore, there are two possible scenarios:
    - If the source end clears the fault within 80 ms, the opening of the circuit breakers would drop the load to zero and enable the disturbance detector at the remote end. The fault clearing time would have a delay by 50-60 ms
    - If the source clears the fault after 80 ms from the fault inception, the dropping of the current to zero in two phases will not trigger the disturbance detector
- If this fault clearing time delay could appear acceptable, the sequence of events also highlight that with a lower load connected at the time of the events, the disturbance

detector would not have operated for a three phase fault. A similar conclusion can be draw for a phase to phase fault

- Considering that the maximum demand is about 30 MVA and the fault level is relatively low, a higher sensitivity for the current disturbance detector could be achieved by reducing the CT ratio to , for instance 300 or 400/1, based on CT ratio availability and no significant impact on the CT performance during an external fault
- The voltage collapse at the remote end also confirms that un undervoltage element could be used as an alternative method for the 87L supervision

VII. PRACTICAL SOLUTIONS

The use of the undervoltage element in a modern line differential relay appears to be a practical solution. As detailed earlier, there is a common concern that the VT fuse failure will block the 87L supervision. Considering that the substation could be situated in a remote location, fuse replacement and cable fault repair could require few hours or some days. There is a risk that the improvement provided by the undervoltage element is ineffective. A practical solution is to bypass the element in the event of VT fuse failure.

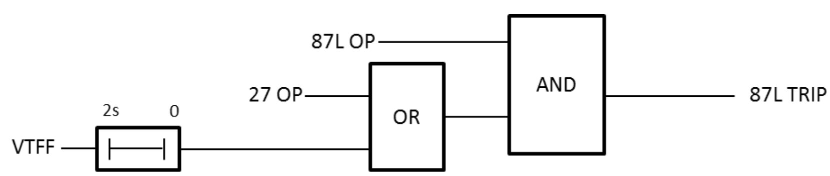

Figure 23. Bypass the undervoltage element if VTFF operates

A practical and simple fix to overcome very low load scenario would include the bypass of the 87L supervision and its benefit in the event of phase current being below a user definable threshold. For some radial line feeding large industrial customers, statistically, the impact on 87L security could be contained. For instance, in a 220 kV application where the typical load is 100 A and CT 400/5, a load current threshold of 0.04 pu to bypass the current detector would refer to 16 A equivalent to 6 MVA. If the remote end the plant was a 24/7 industrial plant like a smelter, LNG processing site or large mining, the percentage of time where the supervision is disabled could be low. This solution would require a detailed risk assessment but, as elaborated throughout this paper, the use of the 87L supervision is always recommended.

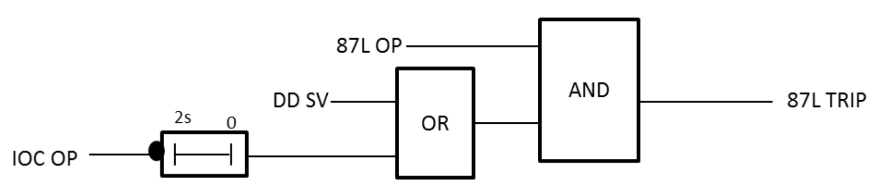

Figure 24. Bypass the disturbance detector if load below user defined OC

A practical extension of the option above would include the bypass of the 87L supervision in the event that the load current is below a certain threshold and the 87L DTT from the strong end has been received for more than two consecutive packets. In the event that 87L computation is completed every 10 ms, the tripping of the remote breaker would be potentially delayed by 10ms.

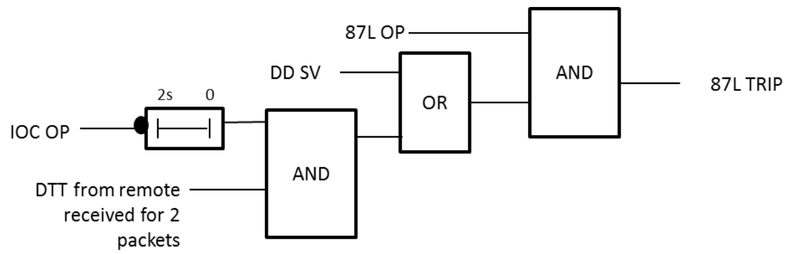

Figure 25. Bypass the disturbance detector if load below user defined OC and DTT received

It is obvious that these solutions aim to improve the dependability of the 87L scheme for a marginal impact on security or simplicity of the scheme.

Are these alternative methods fully convincing? **The use of the current detector from the source end to the remote end appears to be the most robust, simple, secure and dependable solution** to maintain security on the line differential element in radial application. Latching of this signal should be introduced to remove the risk of current detector signal resetting once the fault is cleared at the source end.

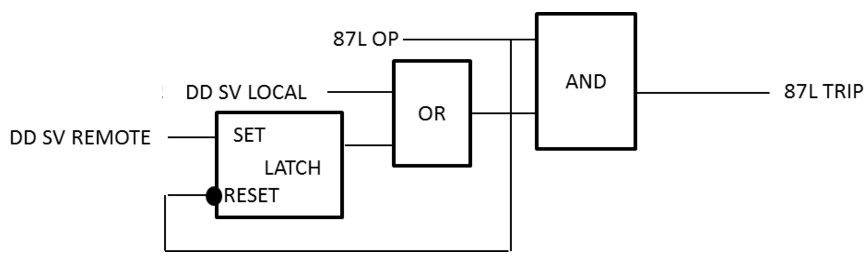

Figure 26. Disturbance detector supervision from remote latched for the 87L supervision logic

It can be argued that the need to confirm that the disturbance detector from the source end is received for two consecutive packets appears to be an over design measure which, in the end, could be disregarded.

For simplicity, the disturbance detector supervision "send and receive" could be implemented to any end of the line and applied as standard feature for any line differential protection application. In addition, the facility to use undervoltage detector as 87L supervision should still be maintained for product flexibility purposes and to allow designers to increase the dependability of the scheme as required.

VIII. CONCLUSIONS

Line differential schemes can be implemented in a dependable and secure manner to either transmission line in a meshed network as well as to radial application. It is obvious that the very weak or absent current contribution from the remote end of the line presents a menace to the traditional current detector supervision of the 87L. Especially in the event of low load and a three phase fault or where the power transformers at the remote end do not provide a zero sequence path.

This paper has investigated several options. Overall, the implementation of the other ends' current disturbance detector as part of the packet to be transmitted to the remote end meets the need of increasing the dependability of the 87L without affecting security, simplicity and speed of operation. Considering that double circuits, open ring network and radial line with no generation at the remote end could be exposed to the same issue, the results of this study envisages this option for any application and any end of the line.

IX. REFERENCES

[1] GE publication GEK-119623, *L90 Line Current Differential System - Instruction Manual,* 2015.

[2] *IEEE Draft Guide for Protective Relay Applications to Transmission Lines,* IEEE Standard Draft C37.113-2014, August 2014.

[3] Z. Xu, I. Voloh, M. Proctor, M. Lara, *CT Saturation Tolerance for 87L Applications*, in *Proc. the 68th Annual Conference for Protective Relay Engineers*, March 30-April 2, 2015.

X. BIOGRAPHIES

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