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# Next generation of Line and Cable fault Locator for HVDC transmissions

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**SUMMARY**

HVDC is often used for long transmission lines or long submarine cables creating a need for some kind of line fault locator for HVDC lines. The commonly used method in AC lines, to measure the impedance during the fault, does not work for HVDC lines. Therefore, ever since the mid 1970's, arrangements using the travelling wave principle with time tagging of the incoming waves has been employed. This requires accurately synchronized clocks in the two stations and up till the late 1980's this was accomplished by using dedicated high speed communication channels for clock synchronization. In 1990 the first line fault locator based on local clock synchronization using time synchronization from GPS satellites was introduced in the Quebec-New England multiterminal HVDC link.

For cable transmissions the need for on-line fault location has been considered less important, as there are no temporary cable faults, so off-line methods have in many cases been considered sufficient. When using the travelling wave principle on cables there is also the problem that the wave front arriving at the far end can be highly attenuated, which has so far made it difficult, or even impossible, to detect incoming waves with the high accuracy needed to apply the travelling wave type of fault locators.

Now with the availability of high speed analog to digital converters, fast Digital Signal Processors (DSP) and large Field Programmable Gate Arrays (FPGA) it has been possible to introduce what can be referred to as the third generation on-line fault locators. Here the incoming wave is not just detected and time tagged, but also digitally recorded with very high sample rate and with each sample accurately time tagged. This makes it feasible to apply the two sided travelling wave fault locators also to long HVDC cable installations.

This new type of line fault locator has been installed and tested in the Pacific Intertie HVDC link, in two sections of the Quebec-New England Multiterminal HVDC system and in the Baltic Cable, which is a 250 km submarine cable combined with a 12 km overhead line.

This report presents the main characteristics of this new on-line fault locator system and some staged fault measurement results.

**KEYWORDS**
HVDC, Line Fault Locator, Cable Fault Locator, On-line Fault Locator

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## AC compared to DC on-line fault locators

High Voltage Direct Current (HVDC) is the preferred technology for really long overhead transmission lines (OHL) as well as long submarine cables. Therefore there has, from the beginning, been a need for accurate line fault locators (LFL) for HVDC lines.

However, the traditional method used for AC lines, namely measuring the impedance during the fault, which is an algorithm often integrated in modern AC line protections [1], does not work for HVDC lines. Therefore, ever since the mid 1970's, arrangements using the travelling wave principle with time tagging of the incoming waves has been employed for HVDC lines. By recording the accurate arrival time for the incoming wave to each station it is possible to calculate the fault location based only on the time difference of the arrival of the travelling waves in the two stations.

## The early years

The first experiments with on-line fault locators based on the arrival time of the travelling waves were performed in the 1970's on the Pacific DC Intertie, a 1360 km long overhead line from The Dalles in Oregon to Sylmar in Los Angeles California. The accuracy of this type of double ended fault calculation algorithm is highly dependent on the accuracy of the clocks used to time stamp the incoming wave-front in the two stations.

From this first installation up until the late 1980's the synchronisation of the local clocks were accomplished by sending synchronization messages between the two stations using dedicated high speed communication channels. We can refer to this as the first generation Line Fault Locators and that method was after the Pacific DC Intertie employed in the CU, Itaipu, and IPP projects. These fault locators could all be set up to work, but the limitation of available high speed telecommunication channels, as well as the requirement to have identical delays in both communication directions were the main limiting factors both for the accuracy that could be achieved and for the reliability of the fault locators.

## Single ended fault locators

A very compelling solution to be able to avoid the clock synchronization problem is to be able to determine the location of a line fault based only on measurement from one end of the line or cable. Also here the Pacific DC Intertie was used as a testbed and in the mid 1980's a single ended line fault locator was installed [2] [3]. A similar device was also put in operation in the Gezhouba–Shanghai HVDC line (1048 km) in 1990. Even if good results could be shown from staged faults, this type of single ended LFL proved unreliable for HVDC lines in the long run and both these installation have subsequently been replaced by double ended solutions.

## GPS makes an entry

In 1990 the deployment of GPS satellites allowed a more reliable and accurate solution to be employed. GPS (Global Positioning System) is a system of satellites, each with a very accurate clock, the system was developed primarily for localization, but because of the accurate clocks used it can also synchronize local clocks on the ground with a difference well below one microsecond. This provided a much better opportunity to synchronize clocks located at a long distance from each other and the first line fault locator based on GPS clock synchronization in the two ends of an HVDC line was introduced in the northern section of the Quebec-New England multiterminal HVDC (MTDC) link in 1990. This was very early in the GPS deployment and at the latitude of 53° for the Radisson station there were still long periods (up to 6 hours) when no satellite was visible above the horizon because of the limited number of low orbiting GPS satellites available at that time. This meant that the local clock in Radisson had to be equipped with a disciplined rubidium oscillator to keep the time reasonable accurate also during the time periods when no satellite synchronization could be obtained. After this first installation in the Quebec-New England MTDC had been put in operation the success story spread and most long HVDC lines were equipped with GPS synchronized on-line fault locators.

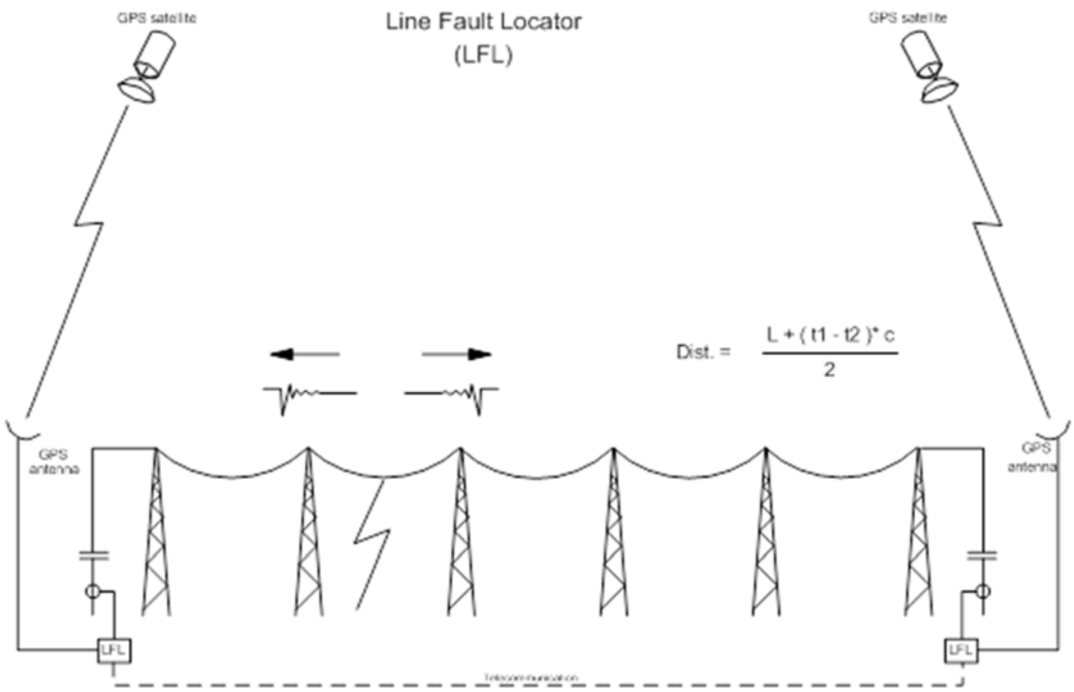


**Figure 1 Principle of the two sided Line Fault Locator with GPS clock synchronization**

These worked in such a way that a small capacitor was connected to the high voltage line. As the capacitance value is usually not critical, the capacitor could often be a part of a filter to attenuate harmonics in the PLC[1] or radio frequency ranges. In the grounding point of this capacitor a wideband current monitor was placed (often referred to as a pulse transformer), and the output from this current monitor would then represent the derivative of the direct voltage on the HVDC line. This output was connected to a comparator and when $\frac{dU}{dt}$ exceeded a pre-set threshold, a pulse would be generated and sent to a GPS clock with the option to time stamp a binary input. A computer could then read out the time value from the clock and communicate this to the other end of the HVDC link after which it is easy to calculate the fault location.

The first installations used a coaxial cable to communicate the output from the wideband current monitor to the control room and the comparator device. This worked very well in several projects also at long distances of several hundred meters between the current monitor and the detector and after the multiterminal Quebec-New England installation this solution was used for the LFLs in the HVDC projects in Rihand Delhi, Leyte Luzon, and ChaPad.

In the late 1990's a new type of requirements on how to implement line fault locators started to appear in HVDC specifications. These specifications mandated the use of a passive detector (powered from the measured signal) in the field with an optical output. To fulfil this

[1] Power Line Carrier

detailed requirement special detector cards had to be developed (Figure 2). This solution also worked, but as this detailed requirement kept reappearing in most HVDC specifications this also stalled the development of more advanced LFL algorithms for more than a decade.

On-line fault locators with this type of passive detectors were installed in, for example, the HVDC line projects in Gezhouba - Shanghai (replacing the single ended devices), Three Gorges – Changzhou, Three Gorges – Guangdong, CU Control Upgrade, Square Butte Control Upgrade, Three Gorges – Shanghai, IPP Upgrade, Xiangjiaba – Shanghai, Caprivi Link, Rio Madeira bipole 1, Rio Madeira bipole 2, and North East Agra.

**Figure 2 Passive detector unit with optical output**

## The third generation

Even though this requirement for a specific design in the procurement specifications prohibited the use of more advanced algorithms the electronic development didn't stand still. Instead new faster and low power digital signal processors (DSP), large Field Programmable Gate Arrays (FPGA) and new possibilities to accurately synchronize many devices over Ethernet using the Precision Time Protocol (PTP) as specified by IEEE1588 [5] became available.

Therefore a new active pulse detector was developed as an alternative to the passive devices, and by using modern electronic components an only slightly larger circuit board could house a fast (20 ns) A/D converter, a DSP and a wave shape memory as shown in Figure 3. With this unit it is possible to do more than just send a trigger pulse to a GPS clock, instead the wave shape of the incoming surge can be recorded as a transient record with each sample time tagged with 20 ns resolution all referenced to a GPS clock using IEEE1588 and the distributed clocks of the EtherCAT[2] fieldbus.

To "close the circle", line fault locators using this new active detectors were installed in the original testbed for different LFL solutions, the Pacific DC Intertie, in 2015. Several staged faults and a few real line faults have demonstrated the capability of the LFL to calculate the fault location with an accuracy better than 0.1% for this 1360 km overhead line [6].

[2] Ethernet for Control Automation Technology (IEC 61158-x-12)

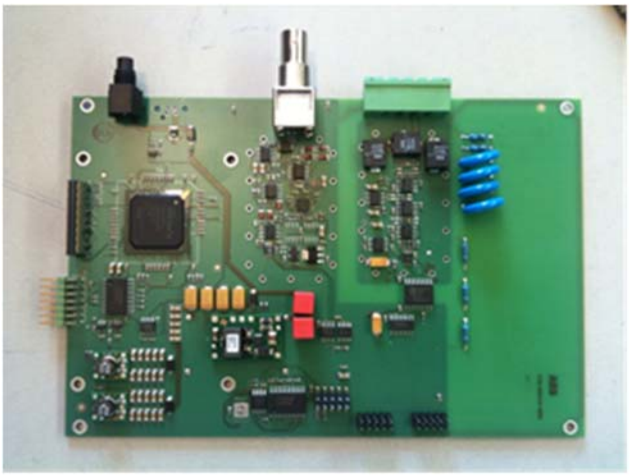

**Figure 3 Active detector unit with high speed A/D conversion and wave shape memory**

This active detector unit is thus offered as a better alternative for new HVDC projects even if many project specifications still require the passive detector units. So far it has been installed in the HVDC projects: Pacific DC Intertie, Quebec-New England MTDC after the control upgrade (both northern and southern sections), Cahora Bassa, Inga Kolwezi (1700 km OHL). It has also been installed in the HVDC cable projects Baltic Cable, DolWin 2, Maritime Link and Caithness Moray Link.

### Special challenges to apply an on-line fault locator (OFL) to cables

The normal application for on-line fault locators in HVDC has been for long overhead lines, where it is the only way to detect the location of a fault, as off-line methods can not apply high enough voltage to recreate for example a flash-over across a damaged insulator string.

For HVDC cables, on the other hand, on-line fault locators have been considered unnecessary up till now, as a fault in an HVDC cable is almost always permanent and can thus be detected with off-line methods. However, as more HVDC cables are being installed and also more land-cables, which have a large number of underground cable joints, the need to have a fast detection of the fault location is becoming more and more requested.

The travelling wave propagation in a cable is similar as in an overhead line, but the wave propagation speed is determined by the insulation material of the cable $v_{cable} = \frac{1}{\sqrt{\varepsilon_r}} c$, where c represent the speed of light in vacuum. The surge speed in a cable is thus 0.5 – 0.7 times the speed of the surge in an OHL.

Electrically the most significant difference is that the capacitance is much higher in a cable than in an OHL, this do not affect the arrival of the initial wave front, but will greatly influence the shape of the wave that arrives at the ends of the cable.

Applying the two sided fault detection is still possible, but the determination of the arrival time of the first incoming wave is crucial for the accuracy of the fault location calculation. This kind of detection of the first incoming wave front requires a recording of the wave shape and an algorithm to determine the time for the arrival of the initial wave.

### Sources of inaccuracy in the fault location calculation

There are several different sources of inaccuracy in the fault location calculation.

The first is the uncertainty in the values for cable or overhead line length. For cables it is also important to know the wave propagation velocity, which is often available from the factory testing of the cable sections. If the cable length is uncertain it is sometimes possible to measure the total travelling time through the cable during the commissioning tests and adjust the length used in the calculation algorithm.

The next source of inaccuracy is the uncertainty in determining the arrival time of the first incoming wave, especially when long cables are involved, but also this error can to some degree be compensated using the results from staged fault testing.

The final source of inaccuracy is the difference in time between the two satellite synchronized clocks and the synchronization of the detection units. This difference varies over time in a non-predictive manner and cannot be compensated. The worst case time error for the equipment used in Baltic Cable is estimated to be below 1.5 µs.

### Installation of an OFL and field tests in Baltic Cable

The Baltic cable was built in 1994 as a connection between the Swedish 400 kV grid in Kruseberg outside Malmö and the German grid in Herrenwyk outside Lübeck [4]. For many years this was the longest submarine cable installation in the world (250 km). It has suffered some cable faults mostly caused by external damages to the cable, and there was an expressed interest from the owner, Baltic Cable AB, to have a faster and reasonable precise determination of the fault location, and a development work was initiated to adapt a modern double sided line fault locator to the specific situation with the combination of a 250 km long submarine cable and a 12 km overhead line.

The first task was to find a suitable point to detect the incoming waves. In many OHL installations there are filters installed for the PLC or radio frequency range and these filters usually contain a capacitor connected between the high voltage line and ground, which provides an ideal location to install a pulse transformer.

In the case of a submarine cable installation that type of PLC frequency filters are not used, and thus that option was not available in Baltic Cable.

However it turned out that zero-flux type current measurement devices (also referred to as DC Current Transformer or DCCT) were available in both converter stations and these devices were of the oil filled type with a capacitive tap connection. It was therefore possible to place a suitably sized current monitor (pulse transformer) in the ground connection of the capacitor tap and connect this to the new time synchronized active pulse detector device, see Figure 4.

**Figure 4  Junction box with current monitor and detector unit installed in Baltic Cable**

### Field testing of cable fault locators

For OHL the common practice is to always perform a few staged faults along the line to test and calibrate both the DC line protections and the on-line fault locators. Such faults are reasonable easy to arrange and for Line Commutated Converters (LCC) the disturbances to the AC networks are minimal. The most used methods for fault generation has been to use a pendulum with a thin copper wire or a remotely operated cross-bow with a copper wire as a tail. Nowadays, when remotely operated aerial vehicles has become widely available the opportunities to safely arrange faults in different locations have become even easier [8].

For cables, and especially for submarine cables, it is usually not possible to arrange staged faults at all. In those cases the only option is to perform staged faults in the end points of the cable if there are transitions to overhead lines or busses available there. In the above mentioned HVDC project, Baltic Cable, the cable end in the Swedish side is connected to a short (12 km) overhead line and in the German side the cable is terminated in a small DC switchyard before entering the valve hall. This provided the opportunity to perform staged faults in 3 interesting locations, namely the DC switchyard in Germany (Herrenwyk), the DC switchyard in Sweden (Kruseberg) and finally in the cable termination location in Sweden, 12 km from the converter station as illustrated in Figure 5. As these locations include a number of high voltage apparatus in a quite crowded area the method to apply the fault was to pre-install a weight with a thin cable connected to the high voltage bus fastened with a release mechanism that could be remotely operated by pulling a long nylon cord with an insulated stick, Figure 6. The weight would then fall and hit an aluminium plate connected to the ground grid and thus generate a restricted and predictable arc.

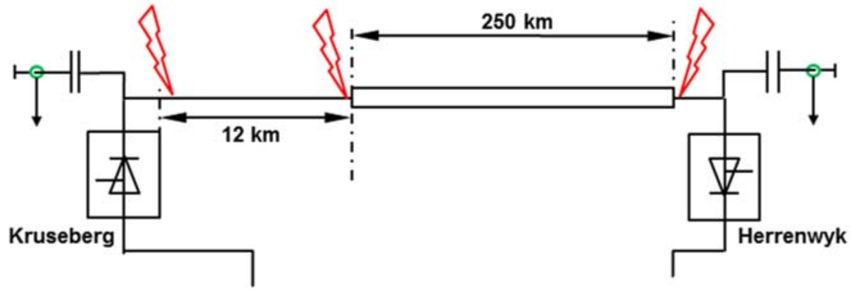


**Figure 5** **Simplified view of Baltic Cable to indicate staged fault locations for Cable Fault Locator testing**

For a Line Commutated Converter it is possible to perform the staged faults in Open Line Test mode and then it is also possible to select a lower voltage to perform the faults to limit the discharge currents from the cable. Therefore the staged fault tests in Baltic Cable was performed at 100 and 150 kV (operating voltage is 450 kV).

**Figure 6 Staged fault device used for OFL tests in Baltic Cable**

This was the first time that staged faults was performed on a long submarine cable and before the general opinion was that the signal in the far end of the cable would be too attenuated and distorted to allow the normal double sided on-line fault locator to calculate correctly. Figure 7 show the high speed recording (50 MHz sample rate) of the signal as detected in Kruseberg for a staged fault in Herrenwyk and we can see that the amplitude is quite adequate and well above the noise level. However due to the large capacitance of the cable the rise time (10-90%) is 37μs, which means that some form of signal analyzing is needed to determine the correct arrival time for the incoming wave necessary for a correct fault location calculation.

The initial results obtained for the fault location was not very accurate, but as faults were staged in both ends of the cable the total wave travel time through the cable could be measured and it was thus possible to conclude that the cable length initially used for the algorithm had not considered the extra sections installed after several cable faults since 1994. With a corrected cable length and compensation for the rise-time, the location of the staged fault was calculated with an accuracy better than 0.5%.

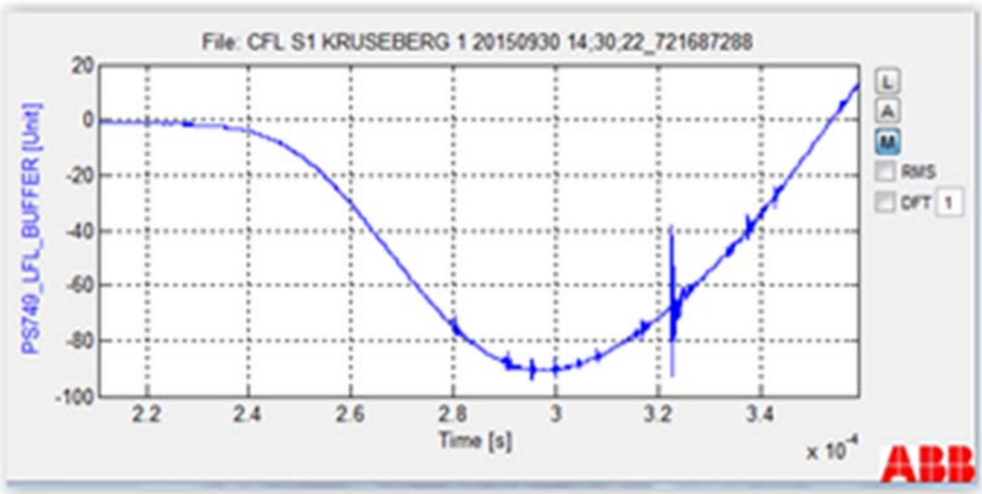

**Figure 7  Staged fault in Herrenwyk, transient recorded in Kruseberg**

## OFL solutions for networks and grids

A possible future development for HVDC can be the introduction of meshed DC grids. In such a network on-line fault locators can present new challenges, but the fundamentally simple double sided detection method would be quite easy to employ also to each section of a meshed grid. In that case each station would have detectors that time tags and records the first incoming wave after a fault and then communicates this to a central calculation unit. This type of fault location calculator would be very well suited for implementation as a cloud based algorithm. Each station would then communicate the time stamp and recordings from its own detection of the fault to a cloud based algorithm, which could then easily utilize information from all nodes in the grid to determine the exact fault location. For a complex DC grid it would also be possible to provide some degree of redundancy as there would be more measurements available than would be necessary for the calculation and this abundance of measurements could be used to check and validate measurement data to improve the certainty and accuracy of the fault calculation.

## The future

The double ended fault locators are to a large extent independent of discontinuities in the transmission system arrangement, such as cable joints and transitions between cable and overhead line sections. The signal will of course be damped in such discontinuities because some energy is reflected back in each junction, but the time of the first arriving wave is not influenced. Therefore the double ended on-line fault locator with high speed sampling and recording can be expected to remain the base solution for on-line fault locators.

With high sampling rate recordings of the incoming wave after a fault, it will be possible to complement the double sided fault locators with different types of fingerprint analysis of the wave shape with all its oscillations and reflections. Here different types of pattern recognition algorithms to determine the fault locations can be applied for example as suggested in [7], but the difficulty so far is to build the accurate models of complex cable OHL combinations to achieve the simulation results needed to provide reliable templates for this type of comparisons.

An important feature would be to record many real faults especially for line and cable combinations and to store these for future comparisons to allow better simulation models to be developed. In some cases such recordings could also serve as a base for self-learning algorithms that would gradually improve the accuracy of fault location algorithms.

**Conclusions**

This report has presented the next generation of on-line fault locators for HVDC which introduces high speed digital recordings of the transients at each converter. These recordings are synchronized by GPS or similar satellite systems and to synchronize the recording devices the standard IEEE1588 (Precision Time Protocol) can be used, which allows several detector units to be synchronized from a single satellite synchronized master clock. This is advantageous for example in bipole HVDC transmission lines or in VSC[3] stations built with symmetric monopoles.

With such high speed recordings available it is possible to detect incoming travelling waves also in cable and overhead line combinations and to provide accurate fault location estimates within a few seconds. This has been proven by field tests with staged faults in the Baltic Cable HVDC link between Sweden and Germany as presented in this report.

The same type of equipment has now also been installed and successfully tested in the Maritime VSC link from Newfoundland to Nova Scotia in eastern Canada, which is a cable (170 km) and overhead line (187 km) combination. It has also been installed in the pure cable project DolWin 2, but in that case no staged fault tests have been possible to perform.

With these successful reference installations we can expect that on-line cable fault locators will be installed in most future HVDC Cable projects, just like they have been a standard feature in long distance HVDC overhead line projects for the last 40 years.

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