
Precise

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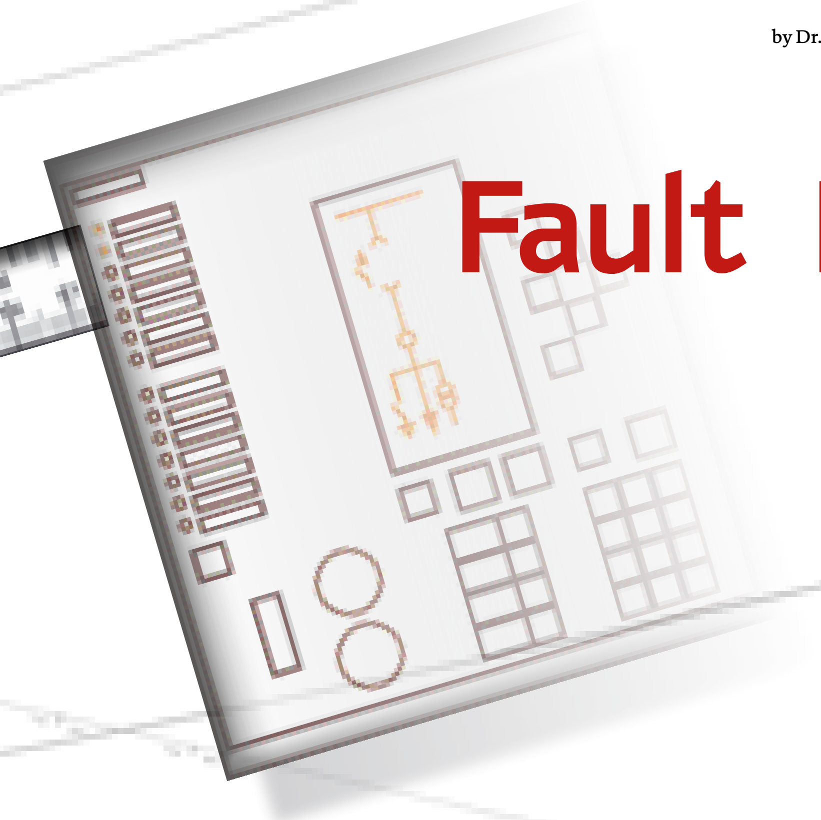

Fault Locator with two-end phasor measurements

● Fault locator functionality is a standard feature in modern numerical feeder protection devices for transmission systems. It is common practice to calculate the fault location via an impedance measurement separately at each line end. All calculation techniques used to date in this "single ended" fault location approach exhibit limited accuracy. ● Hereafter, the fundamental improvement provided by the "two ended" fault locator, which in addition uses the measured values from the opposite line end, are described.

Single-ended fault locators are normally based on an impedance measurement. Only the fault reactance is used to determine the distance to the fault. The distance protection is based on the same principle. All protection engineers know about the limitations of this measurement and use only 80-90% of the line impedance for a zone 1 setting. Even more difficult for the fault locator is, that an accurate measurement is expected along the whole line and not only on one

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setting point like on the distance protection function. This is especially a challenge for lines with a non linear impedance distribution along the line.

In the diagrams of figure 1 is an evolving fault shown on a 50 miles long line. The fault was at 5 miles from the shown location. The figure shows the signals of a C-G fault on the parallel line with a BC evolving fault on the actual line after approx 2.5 cycles.

The fault locator result from the single ended fault location from both ends (red) and the double ended fault locator (blue/green) are presented in Figure 2.

The common factors that influence the accuracy are described below. Hereafter, the fundamental improvement provided by the "two ended" fault locator, which in addition uses the measured values from the opposite line end, are described.

Factors that influence accuracy of "single-ended" fault locator

In the following the most important error sources for the result of a fault locators are listed.

1. Residual Compensation (ZG/ZL, k0)

The majority of the short circuits that occur in the transmission system are ground faults. The accuracy of the "single ended" fault location largely depends on the zero sequence compensation setting for the ground impedance when the short circuit involves ground. The exact value of this compensation factor is often not known. Even if the ground impedance of the line is determined by measuring the zero sequence impedance prior to commissioning – which is usually not done due to time and cost constraints – the actual effect of ground impedance during the short circuit may be severely dependent on the actual fault location. The effective ground impedance is often not proportionally distributed along the line length, as it may vary significantly depending on the consistency of the ground (sand, rocks, water, snow) and the type of grounding applied (tower grounding, parallel cable screens, metal pipes).

2. Parallel lines

In the case of parallel lines, inductive coupling of the current circuits is present. On transposed lines, only the zero sequence system is negatively influenced by this coupling. For load and faults that do not involve ground, the influence of the parallel line may be neglected. With ground faults in the other hand, this coupling may cause substantial errors in the measurement. On a 400 kV double circuit overhead line measuring errors at the end of the line may for example be as large as 35% /1/ Some devices with distance protection functionality have a measuring input that may be applied to measure the ground current of the parallel line. With this measured ground current of the parallel line the impedance calculation may be adapted such that the parallel line coupling is compensated. This parallel line compensation can however frequently not be implemented.

The reasons for this are that only a section of the line is in parallel to another line, two or more parallel lines exist or the connection of current transformer circuit between individual feeder bays is not desired by the user for operational reasons.

While the selective distance protection function can still be implemented by appropriate zone setting in combination with teleprotection systems, the results of the fault locator without parallel line compensation is often not satisfactory.

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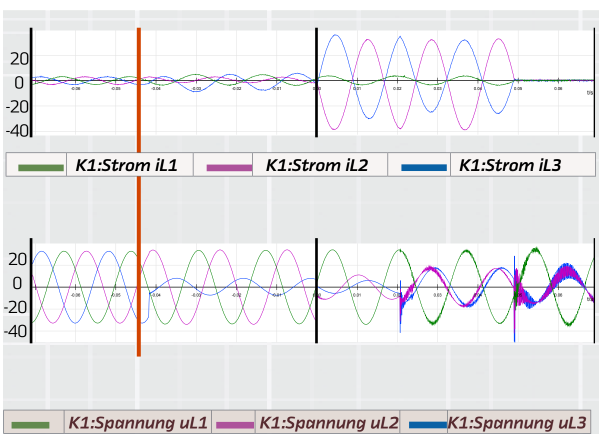
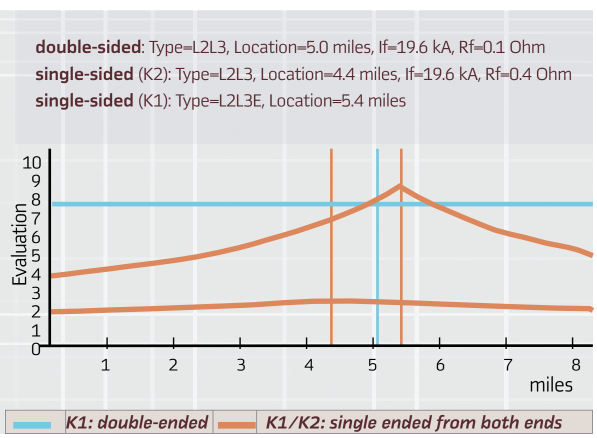
1 Currents and voltages

signals of a C-G fault on the parallel line and BC evolving fault on the actual line after 2.5 cycles



2 Fault locator results

from single ended fault location from both ends and double ended fault locator



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A new approach for fault locator is developed for relays with a communication link between each other.

3. Tower geometry and transposition of the conductors

The geometry of the overhead line towers as well as the phase conductor transposition technique may introduce impedance measuring errors of up to 10% /1/. Extra high voltage lines in transmission networks are often symmetrically transposed with 3 sections. In total, the same impedance for each phase is then approximately achieved for the whole line length. This influencing factor on the accuracy is in this case kept within an acceptable range. In HV systems however, non-transposed lines may be found on short line lengths due to cost constraints.

4. Fault resistance in conjunction with two ended in-feed and load flow

Transmission of load across long transmission lines results in a phase displacement between the voltages V1 and V2 at the two line ends (Figure 5).

In the event of a short circuit, the EMFs (Figure 5) feeding onto the fault will therefore have different phase angles. In a first approximation, the short circuit currents from the two ends are also displaced by this angle. The short circuit current flowing from the two line ends through the ohmig fault resistance RF causes that the relays will see the fault resistor as resistive and inductive impedance due to this phase displacement.

At the line end that is exporting the load, the measured reactance is reduced, the phasor (I2/I1) RF is rotated downwards (Figure 5). At the line end that is importing load, the measured reactance is increased, the phasor (I2/I1) RF is rotated upwards. The smaller the phase displacement between the currents I2 and I1 is, the smaller the influence on the measured reactance will be. In the case of an unloaded line, the EMFs and the currents at both ends are in phase. This assumed that the angles of the fault impedance loop are equal on both sides of the fault, which is on transmission lines normally fulfilled. On faults without ground, the fault impedance will be measured only with an additional resistive part what will not effect the result of the fault locator.

On fault involving ground the method of the zero sequence compensation can effect the reactance calculation, and therefore the fault locator accuracy. By using zero sequence compensation methods which compensate the loop reactance and the loop resistance separately, a poorly ohmic fault resistance on an unloaded line will not cause a calculation error for the reactance. If a complex zero sequence compensation factor is used, the fault resistance is seen as a complex impedance and the reactance calculation which is important for the fault location will be influenced. The compensation using a complex zero sequence compensation factor is only correct for metallic faults.

The effect of the fixed resistance on the reactance measurement may be compensated to a degree with the single-ended fault locator based on certain assumptions.

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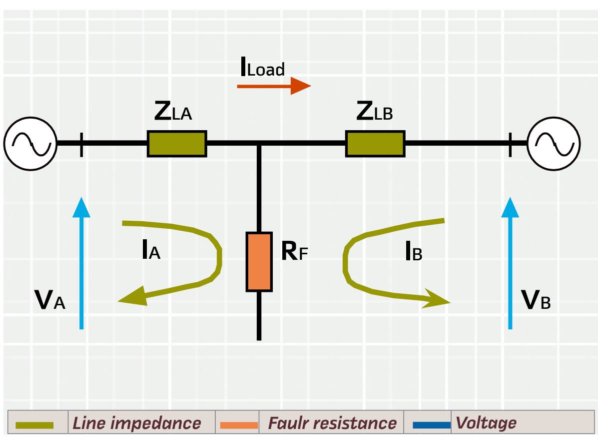
3 Infeed from both ends

At the line end the measured reactance is reduced and R_F is rotated downwards



4 Double circuit transmission line

The fault location becomes calculated with the processing of the synchronised current and voltage vectors from both sides.

Some solutions require setting the source impedance parameter. This can however not be considered as a constant in most cases, so that this technique is not recommendable. Other principles are based on delta quantities; these utilise the load conditions prior to the short circuit. The results are however only correct if the system topology and the load current do not change during the short circuit condition. This also does not always apply. Other solutions include a load compensation for single phase to ground faults. This technique assumes that the ratio of X0/R0 – and therefore the angle of the zero sequence impedance- to the left of the fault location is the same as the ratio X0/R0 to the right of the fault location. In EHV systems this is often the case. Close to transformers this assumption will however also result in inaccurate result from the fault locator.

Fault locator using measured values from both line ends

Direct digital communication between relays not only facilitates the exchange of protection data, but can also introduce a significant improvement of the fault location.

The advantages of the "two ended" fault locator are:

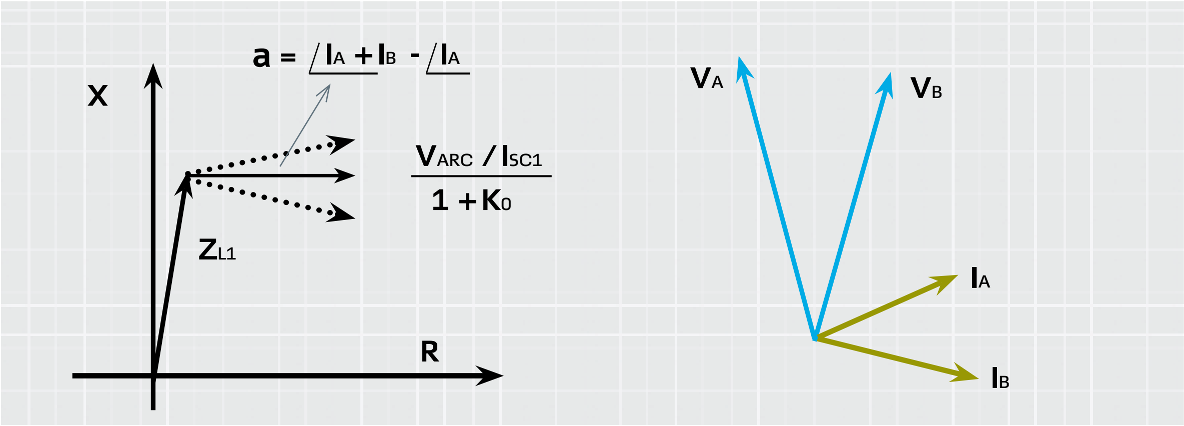
- The fault location of resistive fault is, independent of the load current and line length accurate.
- The algorithm only utilises the positive and negative sequence impedance. The zero sequence impedance is no longer required for the fault location calculation in the event of ground faults.
- The influence of inductive coupling from parallel feeders may be neglected.
- Non-symmetries due to the absence of line transposition and the combination of different tower geometries may be compensated for.

Selection of the measuring data window

For accurate fault location computation the currents and voltages must exhibit as steady a state as possible. The selected data window may therefore not contain any abrupt changes due to fault condition changes or switching. For the fault location computation, a data window containing at least one but not more than three cycles of sampled values is used. The data window selection is carried out automatically by the algorithm. In the event of system disturbances that cause tripping by the device, the data window is positioned around the instant of the trip command. It ends shortly after the circuit breaker opens, immediately prior to interruption of the current. The start of the current and voltage data window is positioned such that the length of the data window is preferably three cycles without any abrupt changes of the current wave form. In the event of very short system faults, or short intervals until the fault condition changes, the measured window may be as short as one system, cycle for the

The financial returns for the company are optimised by the higher availability of the overhead line due to shorter down times and consequently the improved transfer capacity of the network.

5 **Phase shift between the sources voltages and fault currents**



computation. (Figure 6) Sometimes it is also desirable to indicate impedance measured value and fault locator data when there is only a fault detection by the protection and no trip command. In this case the data window is positioned at the end of the first fault detection data window. The end of the first fault detection data window is either determined by the re-set of the protection fault detection or by a change of the fault type.

Synchronisation of the phasors

The "two ended" fault locator uses current and voltage phasors of all three phases from both line ends. The numerical filters are designed so that the fault location calculation is done based on the fundamental component. The current and voltage phasors are provided with a time stamp, the actual system frequency and data window length information is added and then transmitted via the digital communication link to the corresponding device at the other line terminal. Protection device A therefore receives the values from protection device B and vice versa. With the time stamp, system frequency and data window length the phasors can then be synchronised to a common reference. Using the time stamp, the phasors are then checked to see if they belong to the same condition during the system disturbance.

Only if they both refer to an identical interval of the fault will the computation based on the "two ended" method be done.

Two ended fault locator computation with positive and negative sequence values

The here presented two ended fault location is based on the principle that the voltage decays along the line up to

> The location of the fault can be found much faster due to the increased precision of the fault location output. The time that the feeder is out of service is reduced.

the fault location. By means of the currents and voltages measured at one line end, the voltage along the line may be calculated using an RLC line model. If the cause of the voltage is now calculated from both line ends, a fault location may be indicated at the location where both voltages have the same value. In Figure 7 this is given by the intersection of the two curves.

To achieve high accuracy also for long overhead lines and cable sections, the voltage calculation is done based on the homogenous line impedance. The relationship of voltages and currents is given by the hyperbolic function

$$\underline{V}(x)=\underline{V}_m\cdot\cosh(\underline{g}\cdot x)-\underline{Z}\cdot\underline{I}_m\sinh(\underline{g}\cdot x)$$

whereby:

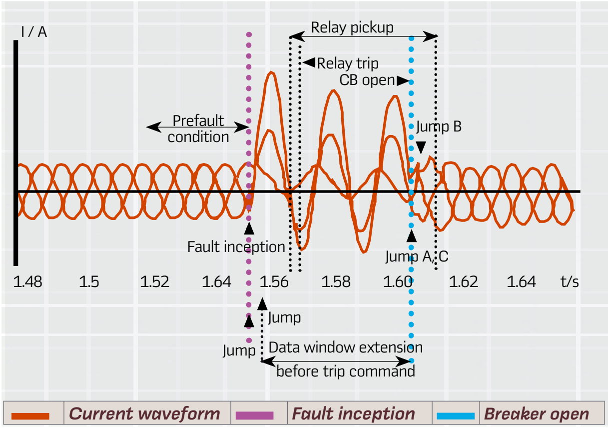
$\underline{V}(x)$ voltage at the position x

$\underline{V}_m$, $\underline{I}_m$ measured value at the corresponding line end

x distance from the beginning of the line

$\underline{g}$ propagation constant of the line

6 Positioning of the data window after trip by protection



The 4 decisive advantages of this "two ended" method are:

- Not influenced by inaccurate ground impedance compensation factors (XG/XL, RG/RL, k0)
- Not influenced by fault resistance on long heavily loaded lines.
- Negligible influence by parallel lines.
- Reduced influence due to non-symmetry of non-transposed lines.

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$$\underline{g} = \sqrt{(R'+jwL')\cdot jwC'}$$

$\underline{Z}$ characteristic impedance of the line

$$\underline{Z} = \sqrt{\frac{R'+jwL'}{jwC'}}$$

At the fault location, the voltages calculated from both ends of the line must be the same.
The set of non-linear equations is solved by determining the smallest voltage difference:

$$e(x) = \underline{V}_l \cdot (x) - \underline{V}_r(x)$$

whereby:

$e(x)$ error voltage (ideally equals zero)
$\underline{V}_l(x)$ course of the voltage calculated from the left hand line terminal
$\underline{V}_r(x)$ course of the voltage calculated from the right hand line terminal

Using proven mathematical techniques the fault location can be determined by means of the sum of the least squares in the symmetrical component system (least-square' estimation according to Clarke-Transformation)/2/.

The measuring technique contains several plausibility checks. They are:

- Faulty or missing communication telegrams are detected and eliminated
- Measured values that deviate extensively from the sinusoidal wave form are detected and not used for the fault location computation. A CT saturation detector additionally ensures that no gross errors in the fault locator are indicated.
- Short circuit locations outside the protected feeder can by principle not be calculated by the two ended technique.
- Multiple ground faults at different locations on the protected feeder can by definition also not be calculated with the two ended method.

Only when the measured results are plausible, will the two ended fault locator indicate a result. To provide the user with some assistance in locating the fault, an indication based on the single ended impedance measuring technique which is similar to the distance protection measurement, is provided.

Non-symmetrical overhead lines

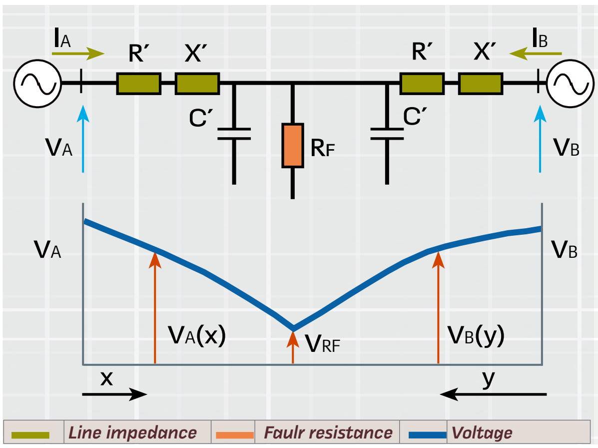
In connection with the fault location calculation it is often neglected to consider that the individual conductors of the three phase system are not spaced equally with respect to each other and ground. It is generally assumed that the impedance in all three phases is the same. By neglecting the existing physical non-symmetry of the conductors, the fault locator result will in practice vary, depending on the faulted phase. Ideally, the non-symmetrical inductive coupling between the three phases should be considered in the fault location algorithm. Setting all six coupling impedances would however be very complicated and not practical for the user.

In the two ended fault locator there is therefore a function that allows for the non-symmetry of the impedances of a non-transposed overhead line. When commissioning the fault locator, the central conductor must be defined.

Particularly good results are obtained with tower geometries having horizontal or vertical conductor spacing. In the following diagram the "central conductor is Phase B. If the conductors are properly transposed (refer to 3) no central conductor is defined.

The fault locator provides the user with substantial advantages.

7 Voltage along the line from both sides



8 Conductor arrangement on HV towers