Power System Fault Analysis using Fault Reporting Data of Numerical Relays

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***Abstract*—Digital protection relays provide comprehensive fault reporting data for the analysis of power system faults and relay operations. Meanwhile the share of digital in the total relay population has reached a substantial figure. Thus the utilities can gather valuable information from relays throughout their grid. After a fault the operating personnel wants to obtain a most precise fault location to narrow the search for possible damage on the line and to cut the down time. An easy-to-use software system for relay fault records can provide the desired precision to the utility personnel. The system is open to fault records of any relay, which is accomplished via the Comtrade data format.**

Especially a new approach is included for fault location. This also covers transmission lines which consist of several segments of different properties like a cable continued with an overhead line. Furthermore it may also handle the typical asymmetry of untransposed overhead lines. By a special algorithm the load condition, the fault resistance and the zero-sequence impedance component and the mutual coupling, which all caused fault location tolerances in the past, can be effectively excluded such arriving at excellent precision.

***Index Terms*—fault location, power transmission lines and cables, high precision, line and cable segments, untransposed line, positive sequence**

I. Introduction

In the past the fault record analysis was en vogue after the implementation of the first digital relays providing such fault records. But the interest diminished as soon as we have accustomed ourselves with the typical grid signals during a fault. Nowadays fault records are analysed only to examine and explain an unexpected behaviour, which has become very seldom and usually indicates some error in wiring or in relay setting. But there also lies a new benefit in the relays according to Alan and Cheung [1]: to get more information about the fault, the line and the grid, which can reduce down time and can expedite re-establishing the power supply. Power interruptions are characterized by two standard measures:

SAIFI – System Average Interruption Frequency Index

$$SAIFI = \frac{\sum N_{sustained}}{N_{served}} \tag{1}$$

The number of consumers affected in each interruption is added up for all interruptions in a year and the total is divided by the average number of customers, giving the average number of interruptions that a single customer experiences.

CAIDI – Consumer Average Interruption Duration Index

$$CAIDI = \frac{\sum \left(N_{sustained} \quad D_{sustained} \right)}{\sum N_{sustained}} \tag{2}$$

The number of consumers affected is multiplied by the duration and the customer-minutes result is added up for all interruptions. The division by the number of customers affected gives the average length of each interruption experienced by the average customer during the year.

The duration of the interruption consists mainly of the long time necessary to locate the fault together with the short time necessary to take the corrective switching action. A very high precision at an offline calculation of the fault location can therefore help to improve the CAIDI index. But to obtain that quite a number of obstacles have to be overcome intelligently.

II. Obstacles To A Precise Fault Location

The vast majority of the faults are single phase-ground faults. Most commonly the location of the fault is calculated by means of some impedance measurement of the faulted loop either directly with the absolute phasors, or with the delta change between pre- and post-fault phasors, sometimes also the feeding grid is taken into account as a source model in the affected loop. But all these approaches are limited in precision due to several physical effects.

1. Residual Compensation ($\underline{Z}_G/\underline{Z}_L$, $\underline{k}_0$)

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

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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

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. According to Saha [2] the distribution lines are usually inhomogeneous, built as a chain of several segments for economic and environmental reasons. A typical example for that is a line starting with single core cable for some length which is continued by an untransposed overhead line at horizontal conductor arrangement. Up to today no commercial fault locator takes such common arrangements into account.

5. Even if all data of the line and the grid were known, there is one further significant influence on measured impedances: the infeed from both ends on the fault resistance.

Transmission of load across long transmission lines results in a phase displacement between the voltages $\underline{V}_1$ and $\underline{V}_2$ at the two line ends (Figure 1 and 2).

In the event of a short circuit, the EMFs (Figure 1) 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 R_F causes that the relays will see the fault resistor as resistive and inductive impedance due to this phase displacement.

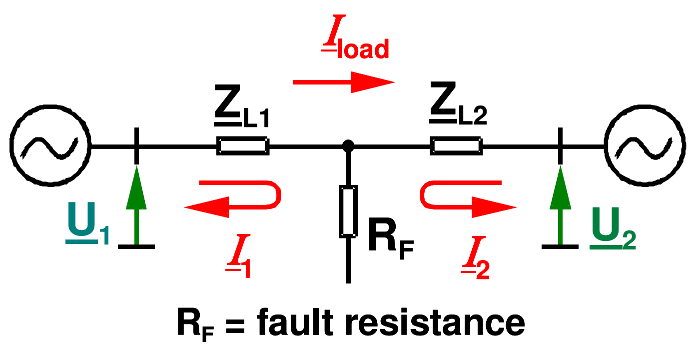

Fig. 1: Simple model for the effect of fault resistance at double-ended infeed (load flow from left to right)

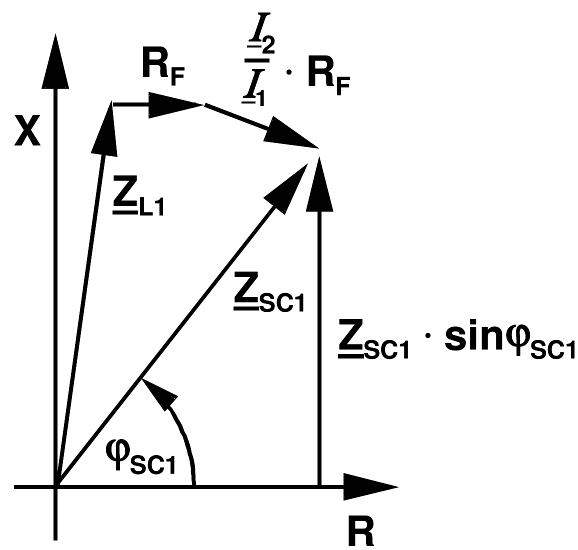

Fig. 2: Double-infed fault resistance RF affecting the measured reactance X (right side I_2 is 20 degrees behind the source I_1 due to load flow)

At the line end that is exporting the load, the measured reactance is reduced, the phasor $(\underline{I}_2/\underline{I}_1)\bullet R_F$ is rotated downwards (Figure 3). At the line end that is importing load, the measured reactance is increased, the phasor $(\underline{I}_2/\underline{I}_1)\bullet R_F$ is rotated upwards. The smaller the phase displacement between the currents $\underline{I}_2$ and $\underline{I}_1$ 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. 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 X_0/R_0 – and therefore the angle of the zero sequence impedance- to the left of the fault location is the same as the ratio X_0/R_0 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.

6. There are a few other influences on impedance measurement like

- capacitive line/cable charging current,
- CT and VT errors,
- transients of the voltages,
- declining DC component of the currents,
- load taps along the faulted line.

These are either of minor importance, or can be eliminated by calibration, or are covered appropriately today by signal processing.

III. How To Obtain The Precise Fault Location

If the fault location is known to high degree of precision, the service people can save much time in searching the line for possible damages. The supply of power for the other parts of the ring can be re-established quickly, giving higher revenue to the utility and lower outage time to many customers such improving the CAIDI index. A precise fault location is now available for everyone who employs numerical relays recording currents and voltages, which every directional overcurrent or distance relay does.

After a fault it is necessary to collect the records of both ends. This can be performed from the remote office via on-demand or permanent communication. A simple modem infrastructure at each station would be sufficient and affordable for this job, but the comfort technically available today goes up to a substation-LAN accessible from each office desk at the utility via secure utility-WAN. In any case the fault records of both ends of the line are collected via communication within a few minutes and stored in a simple data structure “one directory per relay”.

After receipt of the fault records, one usually is interested in some graphic representation of the oscillograms, reading the fault time, duration, amplitude, some phasors, phase angles etc. like the quantities shown in Fig. 3. To get the Fourier-transformed phasors of the signals at a high precision the actual grid frequency is needed. The software system has to automatically determine the actual system frequency before the fault at a very high precision of much better than 0,2%. Otherwise the phasors established with a frequency, which is different from the actual one of the system, would vary their amplitude and phase angle over time following a cycloid curve at the speed of the frequency deviation. The software system should establish the phasors of the signals in line with the actual power system frequency, in original quantities: A, B, C, G and in symmetrical quantities: positive, negative, zero sequence at each time instant the user indicates interactively. Usually two times are of interest, before the fault and at a period of clean signals during the fault.

The software system should be capable of impedance calculations of the various loops and its locus curves in the impedance plane over the recorded time in Fig. 3. Up to that it could be done by standard signal analysis software, but the user will get his benefit only if the software is adopted to grid applications with grid data handling and fault location calculation. For distribution applications the software system has to manage multi-segmented lines consisting of cables and untransposed overhead lines. The input effort is restricted down to the absolute minimum possible. Information about the current and voltage transformer are taken directly from the fault record. It is possible to save the settings for each line, so the data has to be entered just once per line.

IV. Double-Ended Positive-Sequence Algorithm

The idea of a fault locator using the records of both ends of the affected line is present since the installation of first digital relays in Ziegler [5] and Klotz [4]. The idea is to make use of twice the amount of information to eliminate some disturbing effects. But this has to be complemented with a second innovation: to restrict the calculations to the positive sequence system only. The main advantages of that combination are:

• The data for the positive sequence system are the best and most precisely known grid data, as it can be validated by a three-phase load measurements

• The algorithm is invariant to fault resistance, as the fault is represented by a current source only.

• The signals of the positive sequence system are invariant to mutual coupling to adjacent circuits (2 or more systems close together) as this affects the zero system only.

The software system has to perform several steps to obtain the precise fault location. At first the two independently obtained records of the both ends or the signals have to be synchronised in time. The two fault recordings are usually synchronized automatically, but the user also has the possibility to perform the synchronisation manually if desired. As the relays at the two ends sample the signals at their own independent sampling frequencies, a precise phase shift and resampling would be necessary to get the signals of both ends into one synchronized record. Instead working on the oscillograms it is much easier to synchronize the independently obtained signal phasors during the fault by appropriately calculated phase angles. Before building the phasor it is quite essential that the software selects the time window with the most clear fault signal in both records (together with some plausibility check). This can be found usually close to the end of the short circuit before the first current interruption and for precision reasons the window should be 2 or 3 periods long. With the two synchronized phasors of the positive sequence system at the left and right end of the faulted line we now can start the double-ended fault localisation.

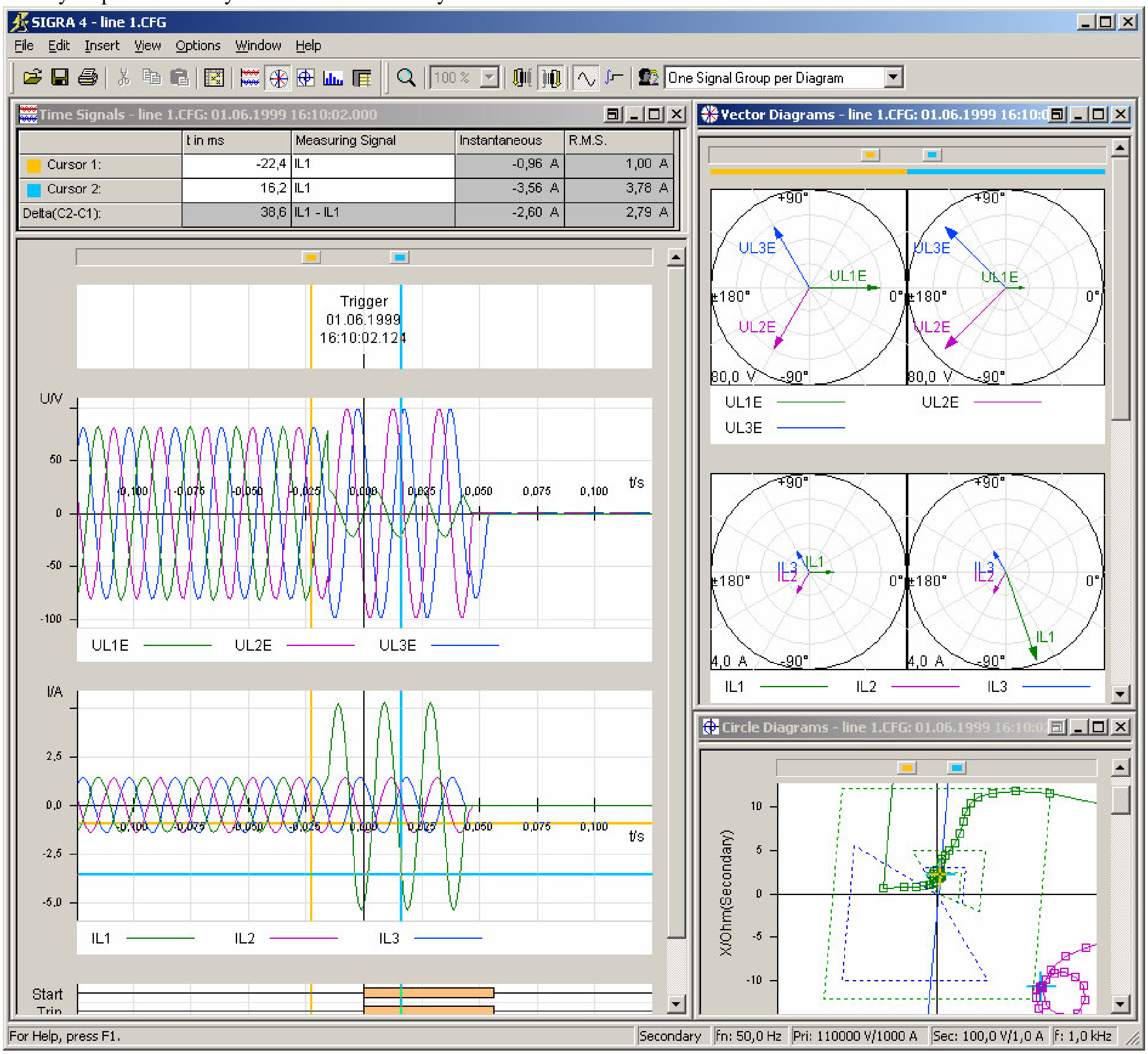

Fig. 3: Fault oscillogram, phasor diagram and impedance locus derived from one fault record

The voltage at the fault location x along an ideal line (length L, impedance Z, wave length γ) is induced by the quantities from either of both line ends l=left and r=right:

$$V_{f\,l}(x) = \cosh(\gamma\, x)\, V_l - Z\, \sinh(\gamma\, x)\, I_l \quad (3)$$

$$V_{f\,r}(x) = \cosh(\gamma(L-x))\, V_r - Z\, \sinh(\gamma(L-x))\, I_r \quad (4)$$

At the fault location *x* the difference between these voltages has to be zero

$$\varepsilon(x) = V_{f\,l}(x) - V_{f\,r}(x) = 0 \quad (5)$$

As a third innovation we now switch from solving the fault location analytically at one equation to estimate the most likely fault location at two equations. The voltage condition (5) applies for the positive sequence system as well as for the negative sequence system. Combining the information from both systems with the least-square criterion we get to a one-dimensional function

$$K_{fault}(x) = \left|\varepsilon_{pos}(x)\right|^2 + \left|\varepsilon_{neg}(x)\right|^2 \quad (6)$$

The minimum of *K* is solved for the fault location *x* using Brent´s method, a one-dimensional minimization featuring both a golden section search and a parabolic fit as it is described in Philippot [3]. This estimation is quite robust even against line data errors not only in the zero-sequence system, but also in the positive-sequence system. It always ends up at the most likely location together with the corresponding fault resistance and indicates the estimation quality $1/K(x)$ in Fig. 4 as well.

V. Users View Of The Fault Locator

The here presented software solution selects the appropriate line parameters, performs a single ended fault location calculation, and asks to select the record of the other end from the directory of the related relay.

With the two records synchronized automatically the system performs the fault location calculations usually giving three results with their quality rating:

- location from the double-ended algorithm
- location from the left impedance loop calculation
- location from the right impedance loop calculation

The user then considers the results and their quality rating in the graphics of Fig. 4. Usually the impedance loop calculations show some variation due to the various effects described in chapter II. Based on this picture it is easy to define the range of the line to be inspected for damages by the work force. For the first applications of the system there is a comparison of the actual location of the damage with the prior calculated location recommended to individually gain confidence in the highly precise results of the double-ended algorithm.

VI. Results

As the algorithm has by principle excluded a lot of the causes for the common errors in fault location, the results obtained are significantly more precise than ever known in the past. The major advantage lies not in optimizing the precision for one special condition only like load compensation or mutual coupling. Instead the algorithm shows a high robustness against all usual causes for errors. All zero-system related influences (data errors, fault resistance, mutual coupling) are excluded by the principle.

Even a data error of the positive sequence impedance only reduces the estimation quality and therewith enlarges the interval of confidence, but the indicated location remains correct. The more practical user gets his desired location combined with a rating of quality, the more sophisticated user can also obtain a visual impression of the rating over the line length in Fig. 4.

VII. Summary

The use of numerical relays enables the utilities to obtain precise fault locations. If the fault location is known to high degree of precision, the service people can save much time in searching the line for possible damages. The supply of power for the other parts of the ring can be re-established quickly, giving higher revenue to the utility and lower outage time to many customers. The effort necessary for such is some simple communication infrastructure and the PC software package indroduced here which gets its payback at the first application.

VIII. Acknowledgement:

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X. BIOGRAPHIES

Dr. Guenter Kiessling was born in Nuernberg, Germany in 1958. He received his degree in Electrical Engineering at the Friedrich Alexander University Erlangen-Nuernberg in 1984 and his Ph.D. in 1988. He is 14 years with Siemens AG in in various positions. He started as a HV Switchgear Project Engineer, was project leader for new outdoor circuit breaker development, and since 2001 he is product manager for SIPROTEC protection relays and systems. He is author of more than 40 papers published by CIGRE; IEEE; other technical Institutions and technical magazins

Dr. Juergen Holbach was born in Saarlouis Germany, on June 17, 1961. He graduated from the University of Berlin with a PhD in Electrical Engineering.

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Stefan Schwabe was born in 1971. He received his degree in Electrical Engineering at the Tchnical University Berlin in 1996. He is 7 years with Siemens AG in Power Transmission and Distribution. He started in 1996 working on a real-time network model for the test of SIPROTEC-relays. Following that he held the position of a R&D Engineer in the field of test equipment and software participating in several innovation projects. Since 2000 he is project leader for SIGRA (software for fault record display and analysis)

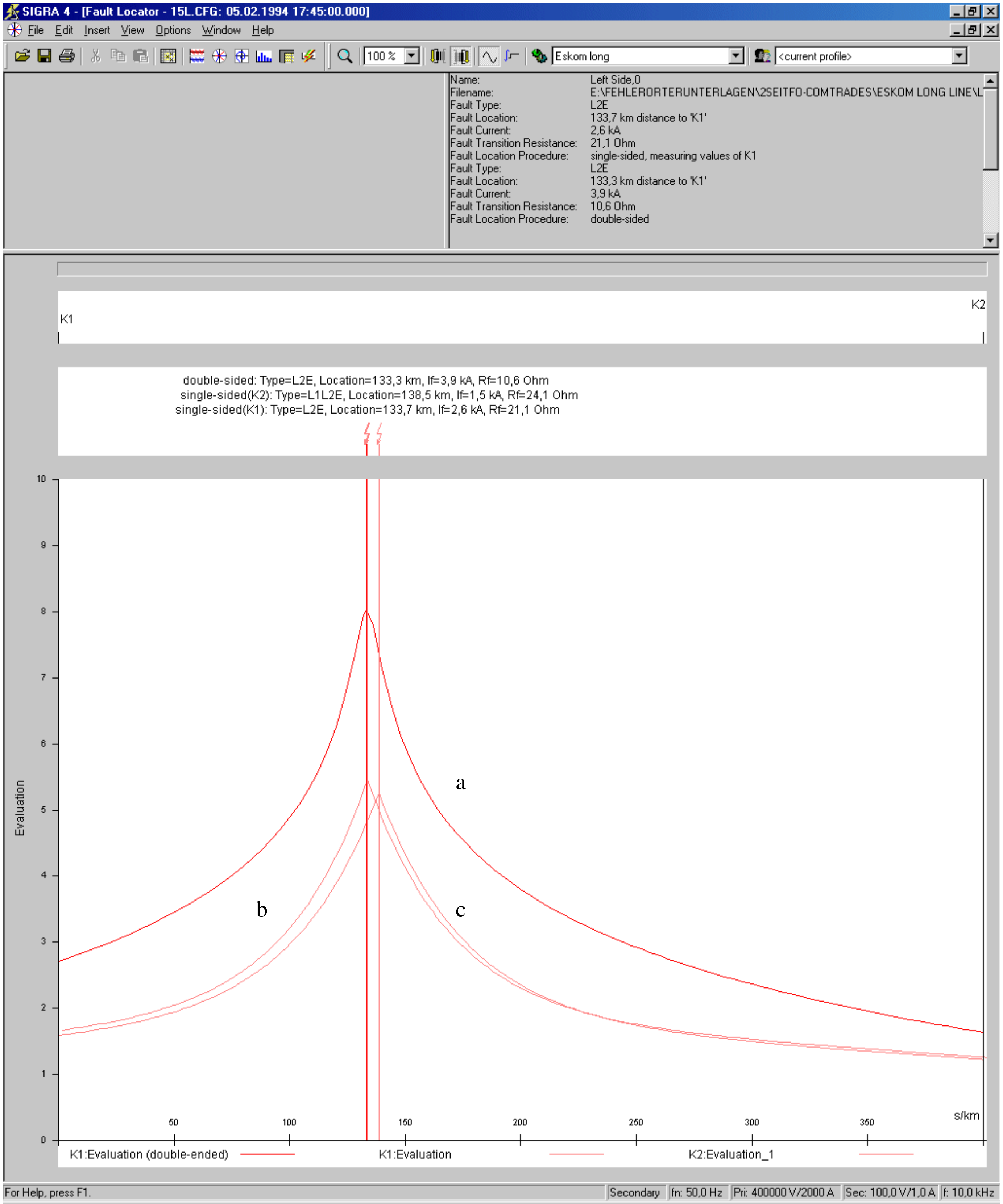

Fig. 4: Fault location results of the double-ended algorithm (a) and the 2 impedance loops (b, c) on a line with their estimation quality