THE USE OF A MULTIPLE STATES, AUTOMATIC FAULT LOCATOR SOFTWARE BASED ON DFR RECORDS

Presented at the 1998 Georgia Tech Disturbance Analysis Conference

by

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1. SUMMARY

The purpose of this paper is to share the experience gained with the use of a simple, though efficient, fault location software using DFR records and a line database as inputs. The software was developed following the request in collaboration with EII which equipment represents the majority of the installed DFR's in the transmission grid.
ELECTRABEL (the Belgian utility) specifically requested that the application be compatible with all past and present DFR's generations, contributing favorably to their return on investment in DFR technology.
The main requirements are specified under § 4. (speed, multiple fault types, multiple fault states, accuracy,…). They were laid down initially to meet with LABORELEC's and the Belgian Grid specificities. The results show a performance that may be of interest to other utilities limited in capital equipment expenditures (dedicated fault locator devices) to solve intricate fault localization.

2. KEY WORDS

Digital Fault Recorders, DFR, Fault Location, Dispatcher, Supervision Software

3. LABORELEC AND THE BELGIAN GRID

LABORELEC, the "Belgian Laboratory of the Electricity Industry", is the central laboratory for scientific and technical research in the electricity sector.

It was created in 1962 with the merger of laboratories from twelve Belgian electricity supply companies in one single co-operative company. Since that time Laborelec has been charged, beside other research activities for the Belgian electricity sector, with the task of:

- conducting a systematic, indepth analysis of any failure which occurs on the Belgian transmission networks.

- conducting tests on new protective divices submitted by the manufacturers in order to check whether they meet the requirements of the protection plan, which is defined according to the characteristics and specific features of their network.

Both tasks are gathered within the Fault Analysis and Protections Departement of Laborelec.

The **Belgian Transmission Grid** is mostly made of 380 - 220 - 150 - 70 kV lines and associated substations. Belgium is about 30 000 square km wide and has a high population density. This makes that the Belgian Transmission Grid is characterized by:

- A heavily meshed network and relatively short lines (5 to 50 km).
- A lot of multi-circuit lines (mostly 2 circuits) together with a large number of multi-ended lines (mostly tapped transformers)
- Tied parallel lines at the 70 kV level and mixed structures of overhead lines and underground cables
- 70 kV and 150 kV network are in a loop through the MV system.
- Nuclear generation plants tied to the 380 kV network and large thermal plants connected to the 150kV-220kV network.

The system experiences about 400 short circuits per year distributed as follows:

Voltage level	**% number of faults**
380 kV	2.29
220 kV	3.07
150 kV	12.57
70 kV	82.07

(data: 1995)

Of all these faults, 89% are happening on overhead lines.

The total length of overhead lines is as follows:

Voltage level	**kilometers of lines**	**# of substations**
380 kV	1386	12
220 kV	428	9
150 kV	3273	76
70 kV	3558	206

(data: 1995)

The origin of faults on overhead lines can be summarized as follows:

Fault origin	**380 kV**	**220 kV**	**150 kV**	**70 kV**
Lightning strike	59 %	54 %	57 %	61 %
Weather condition other than lightning strike	19 %	24 %	17 %	14 %
Equipment failure	16 %	7 %	10 %	4 %
Human factor	0 %	0 %	1 %	0 %
Pollution	0 %	0 %	2 %	0 %
Others	6 %	15 %	13 %	21 %

The protection philosophy can be outlined as follows:

- single phase/ three phase opening and single-shot autoreclosing on 380 – 220 and 150 kV transmission lines
- three phase opening and single-shot autoreclosing on 70 kV transmission lines
- no autoreclosing on cables, transformers and busbars.

Speed is important for limiting damage. Moreover, on 380 kV network, all multi-phase faults should be tripped in less than 250 ms (including back-up) in order to assure stability of the nuclear power plants.

Almost 100 DFR's are installed in the Belgian transmission substations.

An important note is that all lines are patrolled following an incident (even short incidents)

0 4. BASIC REQUIREMENTS OF THE AUTOMATIC FAULT LOCATION SOFTWARE

- The software has to be operational in the Regional Transmission Centers (RTC) where the different grid areas are supervised. Since it is directed to provide dispatchers with a clear information about where to start their inspection, the software has to be very user friendly and manipulations have to be mostly limited to the selection of a substation.
- The software has to run based on **data coming from different generation DFR's** without modification of the equipment installed in the substations. Change of software parameters in the recorders is allowed. The Belgian Grid is mostly equipped with BEN™[1] DFR's since 1982. Two generation of equipment co-exist in the system.
- The software has to remain compatible with other brand DFR's by means of **COMTRADE[2] file imports**.
- The result has to be available within **10 minutes following the call of the DFR**.
- The overall **precision must be better than 15%** and supplemented with an indication of the **reliability factor** of the result.
- The substation and line database has to remain compatible with the LABORELEC database.

1 5. BASIC OPTIONS

- Since older generation DFR's did not have the computing power of today, we have elected to use a software package running in a regional-central location rather than at the substation.
- For the same reason, all channel information is transferred. The resulting transmission time can be reduced using various compression algorithms available on the DFR's of all generations.
- The localization software (AUTOLOC™[3]) has to remain independent from the full blown Master Station Analysis software.
- Keeping in mind the requirements for speed, user friendliness and precision, as well as the number of substations where a DFR is available at both line ends, and the large number of lines with multiple ends, a single ended algorithm was preferred.
- The overall requested precision is not high but one has to consider the complexity of the application (short lines, double lines, T-lines and lines with tapped transformers, …) as well as the accuracy of the line parameters introduced in the database. Based on these possible restrictions and eventual missing information, the resulting distance has to show a reliability indication.

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[1] BEN is a trademark of Electronic Instruments International

[2] IEEE C37.111-1996, IEEE Standard Format for Transient Data Exchange (COMTRADE) for Power Systems

[3] AUTOLOC is a trademark of Electronic Instruments International

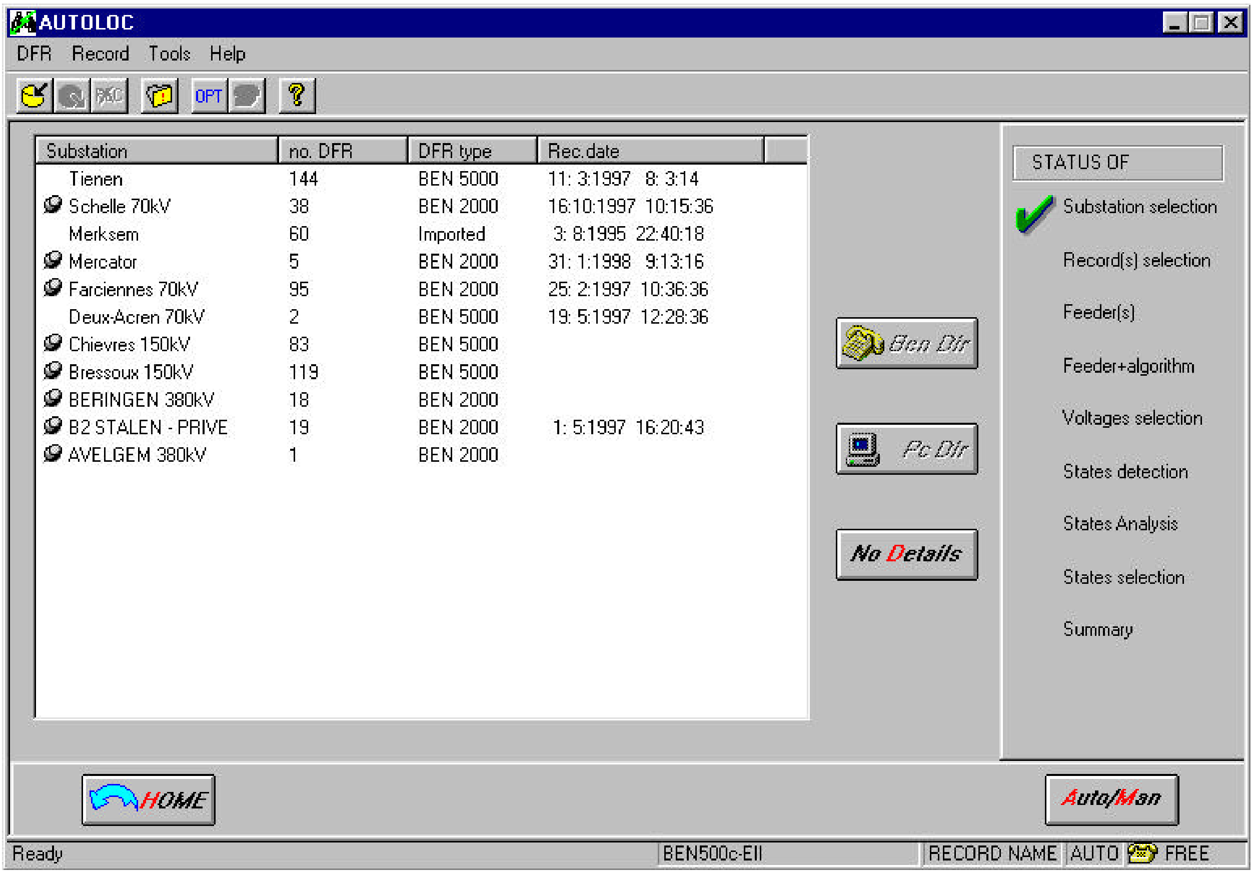
2 6. *OPERATION*

6.1. Selection of the substation

All substations where DFR's are installed have been introduced in the software database under ACCESS™[4]. The information about the various lines is structured as in Appendice A1. The substation access information has also been introduced (name, telephone number, passwords, …).

The versatility of the BEN[1] recorder allows it to handle several lines/feeders. Channels are logically tied together in the substation database.

⌧ The user will choose from the user interface, the substation where to perform a fault localization.



[4] ACCESS is a trademark of Microsoft™ Corporation
⌧ indicates an operator intervention
♌ indicates an operation conducted automatically by AUTOLOC™

6.2. Recovery of the fault directory and record selection

- The directory of records from the DFR is transferred automatically to the PC running AUTOLOC™.
  In this initial step, only the directory is transferred to reduce the data transmission.
- By default, the software is looking for criteria allowing an automatic identification of the record(s) to transfer. The fault identification may not be obvious: *(automatically adjusted recording times and large cyclic memories allow for numerous records to stay simultaneously in the recorder's memory)*

  - ◊ For each fault, two records may have occurred (breaker action, breaker re-closure). A re-closing on a faulty condition will typically give a better information about the fault location.
  - ◊ Upon bad weather conditions many faults may have occurred in a short period of time.
  - ◊ Although the recorders allow for real time clock synchronization, the signal may in some instances not be present or available. The recorders may not be synchronized. The time difference may range from a few minutes to an hour at the time of the summer/winter hour change.

In the recorders directory, the following minimum information is available:

- ◊ Date and time of the record
- ◊ Length of the recording

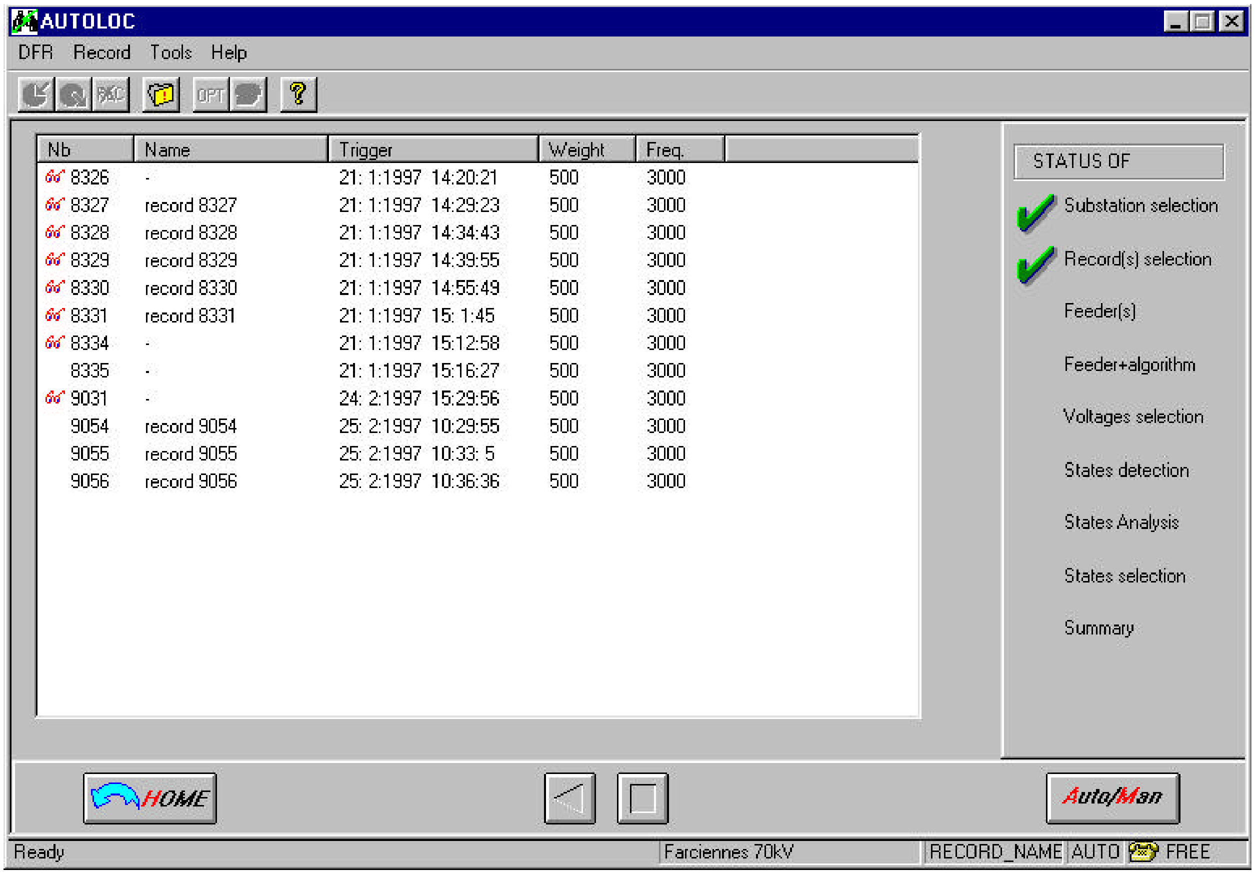
- AUTOLOC is choosing by default the **two last** records of the recorder's memory providing that it is within one hour of the real time clock of the PC running the software and they are within 30 seconds from each other. ✉ In case of re-closing on a faulty condition, and multiple triggers, the user has the possibility to choose the records manually.

The last generation recorders also transfer with the directory an identification of the record's importance (priority level) based on the triggers activity and combination thereof. A standardized use of the priority levels within the utility is then required. They have been defined by LABORELEC.

✉ *Should the automatic selection not be possible, the user is then prompted for a manual selection of one or more records.*

- Transfer of the recorders data is then performed automatically with or without data compression according to the line transmission speed without compromising the quality of the following calculations.

The recorders allow for a transfer rate up to 115,200 bps, though the transmission lines seldom allow it. The last generation of recorders allow for the partial transfer of a group of signals (e.g. signals pertaining to one line/feeder) further reducing the data transfer time (to be used in conjunction with the priority levels).



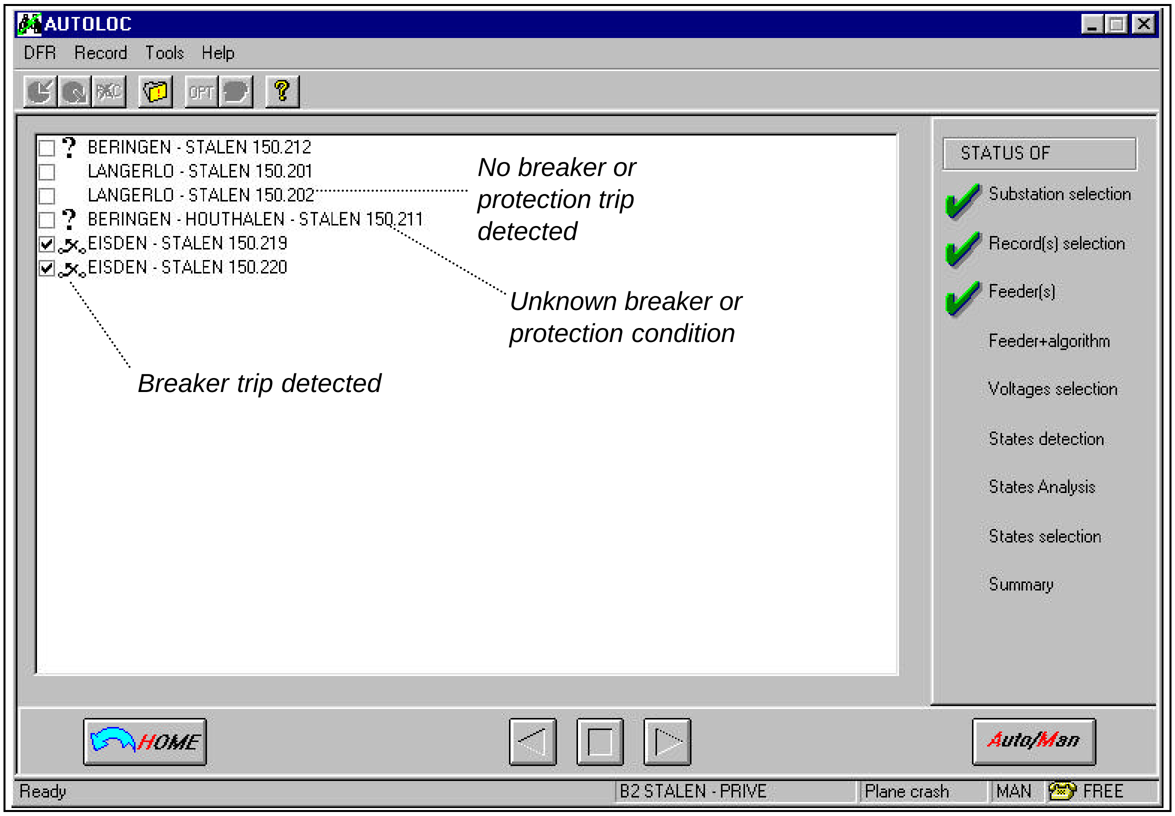
6.3. Line/feeder selection

♌ After the transfer of the fault information, it is compared with the information stored in the existing substation and lines database.

♌ The line/feeder selection is confirmed based on the operation or not of the circuit breaker or protective relays. More than one line/feeder may be selected in case of multiple fault conditions.

✉ *Should there be no detected circuit breaker or protective relay operation (position not recorded, wrong record selection among several) the operator may then manually select another line/feeder within the same or another transferred record.*

♌ Based on the information stored in the substation and lines database, current and voltages are matched to build the line/feeder 3 phase system. Care has been taken in the construction of the database to accommodate differences in the recorders configuration and scaling (primary/secondary units, …).

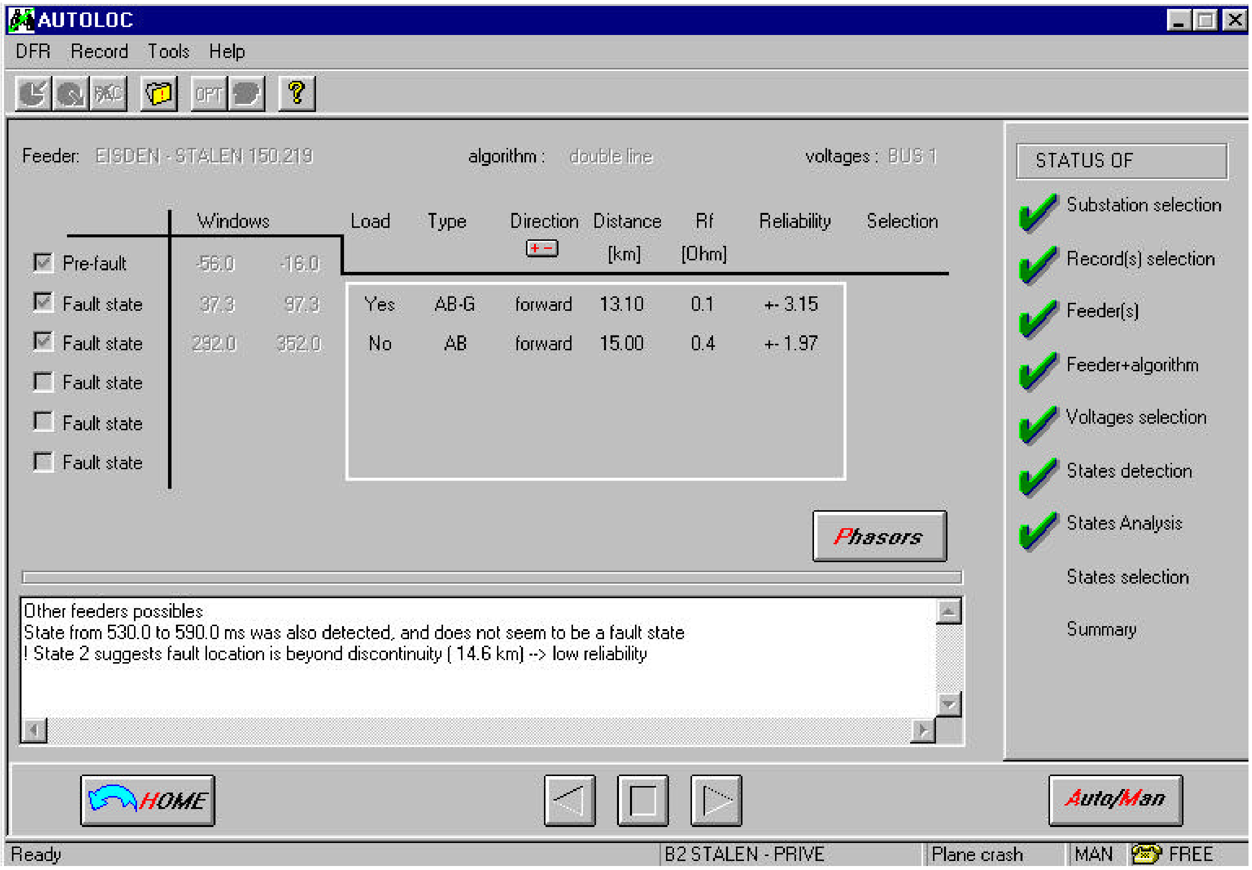


6.4. Fault states recognition

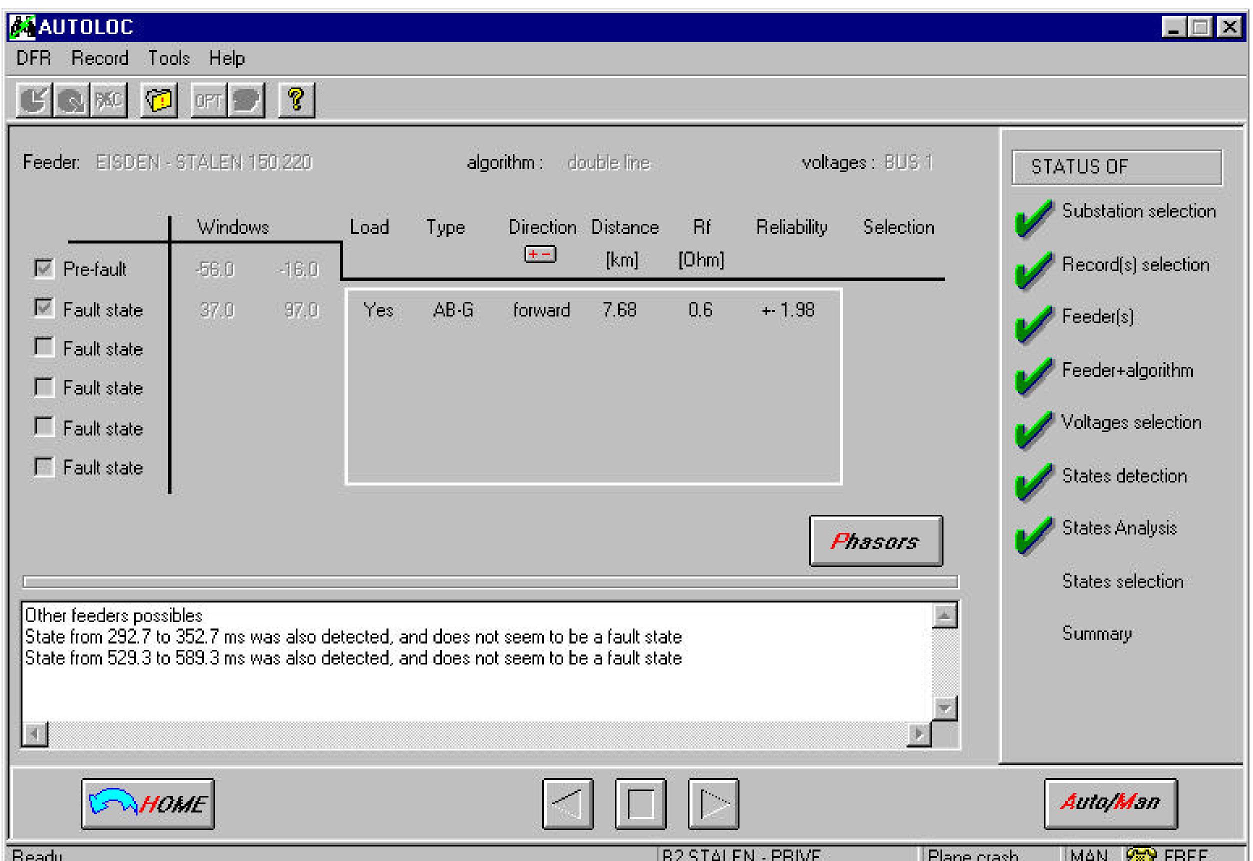
- Once selected, the record information is analyzed and sliced in different fault states. Typically three fault states (pre-fault, fault and post-fault). They may not exactly reflect the recorder pre-fault, fault and post-fault states since the recorder may have been triggered late (high impedance fault) and the recorder's pre-fault may already be a line fault condition. Sequence components, signal stability, … will determine the various real fault states. Often, more than three fault states can happen and may be detected within one record. This allows for the discrimination of different fault states when protections on the other line end have operated or the fault is evolving by itself.

- The various fault states information (vectors, load, …) are handled separately.

On the line 219:



On the line 220:



6.5. Selection of the right voltages, direction of the fault

- When the line/feeder voltages are directly available, the selection is immediate.

- When, together with the line/feeder currents, only the busbar voltages are available, and multiple busbars may alternatively be connected to a single line/feeder, the software automatically analyses the signal patterns to make the combination. Should this combination not be obvious, the software carries on with multiple parallel calculations based on the various combination possibilities. The results will eventually determine the best combination.

- The direction is determined by means of all the loop impedance calculations.

6.6. Choice of the algorithm

- Based on the database substation and lines information, AUTOLOC is choosing one of the following algorithms:

  - ◊ Single line
  - ◊ Double line
  - ◊ Grounded Double line *(✉ requires indication of the actual grounding)*.

When a pure pre-fault state has been recognized, the software compensates the load current on fault states preceding breaker operations.

The source impedance was not considered since they may significantly vary along time.

6.7. Computation of the distance to the fault and reliability index

- The result of the algorithmic calculation is an impedance that is compared to the line impedance.

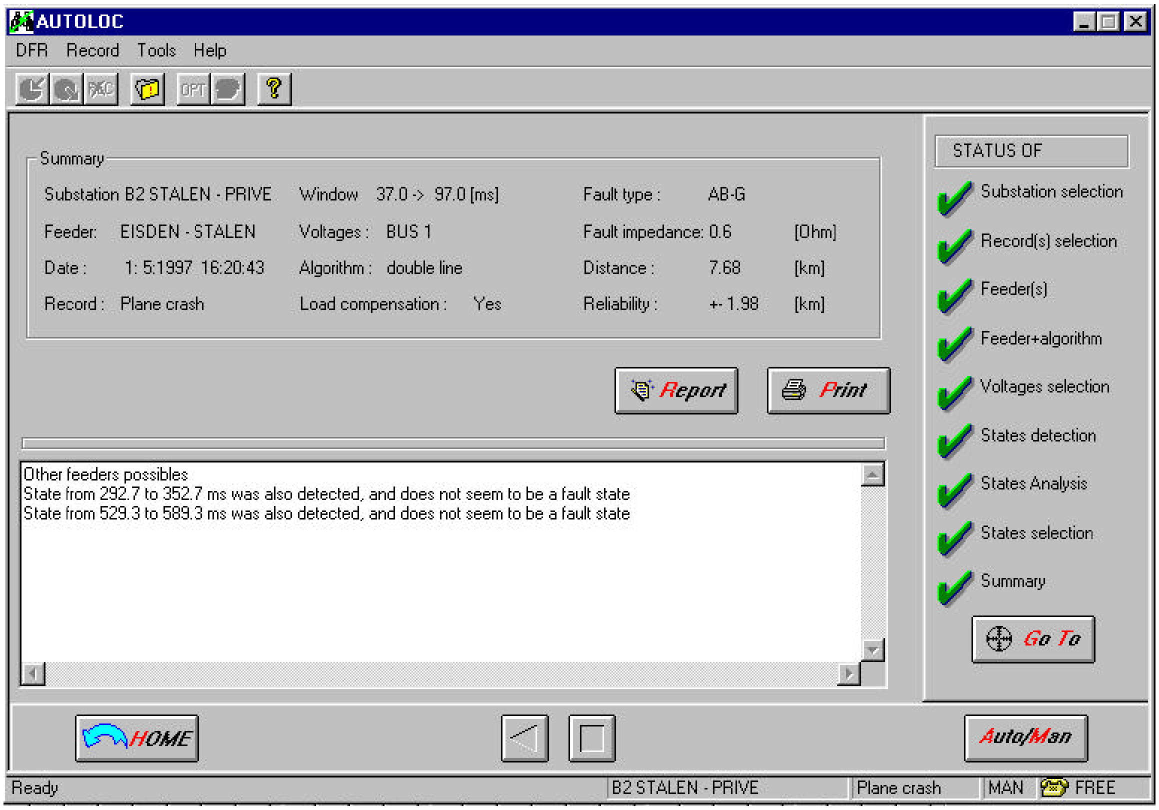
- A reliability index is also computed. It appears as a potential error (in km) on the distance and is based on the following sources of uncertainty:

  - ◊ Error on the measured signals
  - ◊ Precision of the signal filtering
  - ◊ Presence or not of a pre-fault state
  - ◊ Intrinsic errors of the algorithms
  - ◊ Homogeneity of the line
  - ◊ Plausibility of the result (distance smaller than the line length, closer than the first tap, …)

  In order to keep up with a pro-active attitude on behalf of the dispatchers, the reliability index is always reflecting the most pessimistic error margin. A few results out of the error window will deter them from further using the system.

ᘯ Two reports are produced to support the distance calculation

◊ One is supporting the choice of record, line/feeder as well as fault states. It is immediately available in the result screen

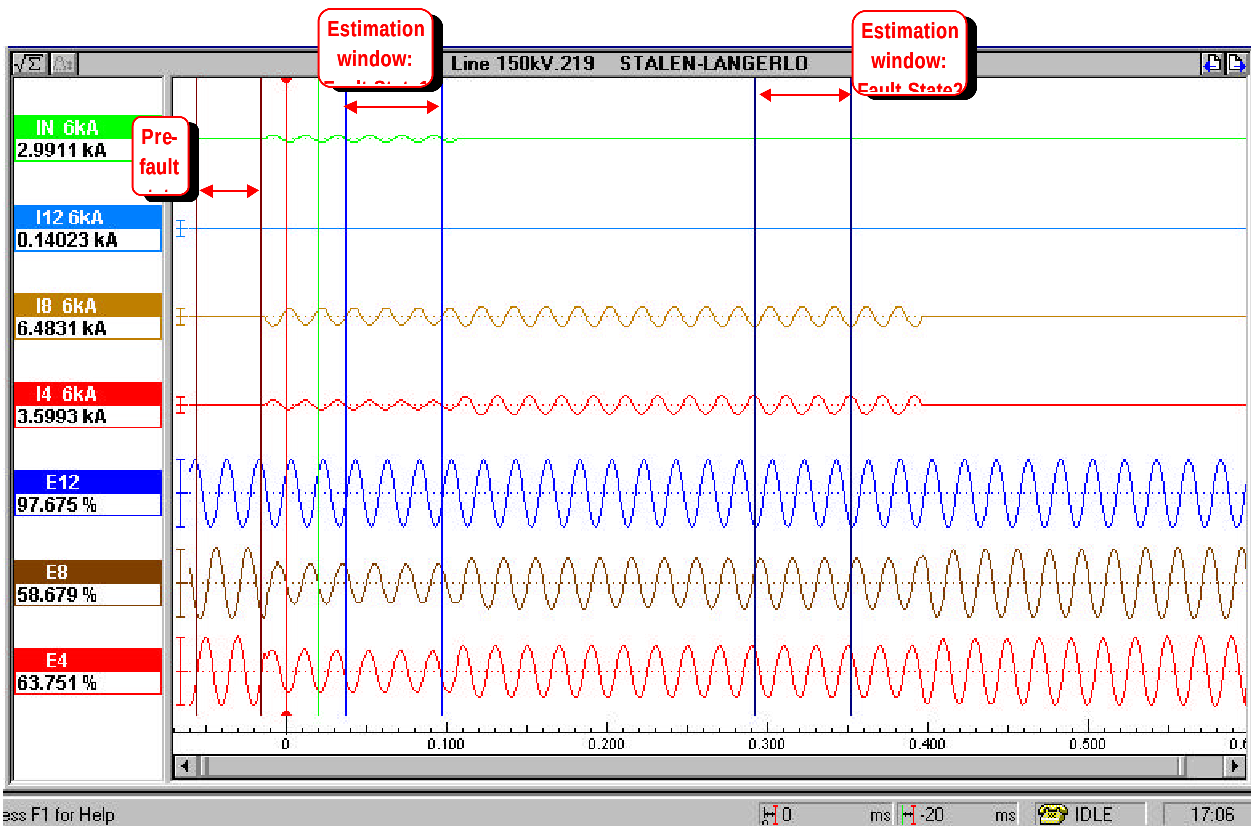


◊ The other one is illustrating the various phasors, impedance and distance calculations for each fault state. See Appendice A2.

6.8. Manual operation

At all steps of the computation, an educated operator may overrule the software to deal with intricate situations.

While the analysis performed by AUTOLOC is not graphically represented, the files can easily be exported and graphically analyzed with the BENLOC function of the BEN32™ Master Station software. The picture below shows an example of multiple fault states detected within one record.



3 7. FEEDBACK FROM OPERATIONAL EXPERIENCE

Since its installation in mid '97 in a Regional Transmission Center in Belgium, the system has produced the following results:

Substation	Line	Line length (km)	Record #	Fault Type, origin	Actual distance (km)	Computed distance (km)	Autoloc Reliability indication (±km)
Havendok	150kV .119	6	220	S-G, Crane	2.6	2.7	3.0 (1)
Scheldelaan	150kV.119	6	551	S-G, Crane	3.4	2.9	2.0 (1)
Stalen	150kV.219	15.8	**399 (2)**	**Multiple line faults**, plane crash	9.1	7.7	1.9
Stalen	150kV.220	15.8	**399 (2)**	**Multiple line faults**, plane crash	9.1	14.9	1.9 (3)
Langerlo	150kV.234	12.8	772	S-G, broken isolator	2.5	2.4	0.2
Langerlo	150kV.234	12.8	**774** (4)	S-G, broken isolator	2.5	2.4	0.6
Schelle	70kV.711	16.6	439	R-G, Crane	4.8	4.5	0.7
Schelle	70kV.711	16.6	**440** (4)	R-G, Crane	4.8	4.5	0.4
Lier	70kV.790+.791	**15 + 7.6**	447	R-G, Crane	22.5	21.7	19.4 (5)
Kallo	150kV.267	0.6	602	S-G, Surge arrester	0.6	3.4 (6)	0.7
Scheldelaan	150kV.119	6	867	**Evolving fault**, CT explosion	6.0	6.1	0.5

(1) High impedance fault not affecting the distance calculation but well influencing the resulting reliability.
(2) Multiple lines fault affecting several lines recorded in the same DFR record.
(3) Reliability result not in accordance with the computed fault distance due to the nature of the fault.
(4) Reclosing on the same fault as in the previous record.
(5) Low reliability resulting from a fault beyond the line end
(6) Wrong parameter introduced in the line database

4 8. *LIMITATIONS AND BENEFITS*

The overall system is limited by the accuracy obtained at the time of the introduction of the line parameters.
It remains a single ended fault locator.
Since it assumes a linear distribution of the line impedance, any non-homogeneity will increase the resulting error or, at least, the reliability factor. An homogeneity factor as well as the distance to the first major non-homogeneity are introduced to partially handle this issue. The lines will be automatically selected on the basis of the breaker or protective relay information when available.

This approach makes successful use of an existing base of installed DFR's of past and current technology. Some of them are in operation for more than 15 years.
It provides an original alternative to indications given by distance protections and is specially efficient in intricate situations such as evolving faults or generally speaking multiple states faults.
For those who can afford the above illustrated errors, it is a cost effective alternative to more expensive dedicated devices using other technologies to determine fault distance.
It clearly meets and exceeds the requirements expressed under the Basic Requirements §4.
It allows for a faster site inspection and the level of trust on behalf of the dispatchers is high.

5 9. *BIOGRAPHY*

Patrick De Cuyper is born in 1964 in Belgium. He graduated in 1987 as Industrial Engineer in Electromechanics from the KIH De Nayer (Mechelen, Belgium) and started working in 1988 as protection engineer within the Protection and Fault Analysis Department of *LABORELEC*. Since 1995 he is Head of the Fault Analysis and Statistics Group within the Protection and Fault Analysis Department and as such is directly responsible for extracting all what as to be learned from fault records from the Belgian grid.	**Ben. J. Trémérie** is born in 1962 in Belgium. He graduated in 1986 as Industrial Engineer in Electricity & Electronics from the ECAM (Brussels, Belgium) and worked in the field of DFR design and applications for *Electronic Instruments International* since 1989. In 1990 he conducted a major survey of the DFR technical requirements within the US utilities from which he produced the specification of EII's latest generation DFR's. As Business Development Manager for EII he is responsible for meeting the utilities requirements with equipment performance.

APPENDICE A1

LIST OF LINE SPECIFICATIONS

FIELD	**REMARKS**
Name of the line/feeder	
Type of line (line/cable)	
Description of three possible voltage 3-phases systems.	Phases V_A, V_B, $V_{C,}$ V'_A, V'_B, V'_C and V''_A, V''_B, V''_C in case of multiple bus bar system. In case of line voltages, only V_A, V_B, V_C are used.
Description of current phases and neutral	I_A, I_B, I_C. The neutral current I_N is computed by the software.
Description of current phases and neutral of an eventual parallel line.	I'_A, I'_B, I'_C. The neutral current I'_N is computed by the software.
Per 3 phase system: earthing side of current transformer and scale factors	
Association of the breaker contacts or the tripping contacts of protective relays wired to the DFR digital inputs. *Priority is given to the breaker contacts if wired*.	
Line length	
Line impedances	Z_1 and Z_0
Mutual coupling between parallel lines (if any)	Z_{0M}
Distance to the first tap	
% homogeneity of the line	

APPENDICE A2

COMPREHENSIVE FAULT LOCATION REPORT

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Automatic fault analysis
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Substation............... : B2 STALEN - PRIVE
Feeder................... : EISDEN - STALEN 150.220
Trip..................... :  1: 5:1997  16:20:43
Record................... : 399
Fault appearance......... : -11.0 ms
Voltages................. : BUS 1
Algorithm................ : double line
Load compensation........ : Yes
Fault type............... : AB-G
Fault impedance.......... : 0.6 [Ohm]
Localization............. : 7.68 [km]
Reliability.............. : +- 1.98 [km]


<Pre-fault state>
-----------------

1) Analysis window : -56.0 -> -16.0 [ms]
2) phasors (kV_kA) :

      Vr=87.5<-124      Vs=89.3<118       Vt=86.4< -4
      Ir=0.1<-131       Is=0.1<108        It=0.1<-16        In=0.0<180

<Fault state 1>
---------------

1) Analysis window : 37.0 ->  97.0 [ms]
2) phasors (kV_kA) :

      Vr=54.1< 83       Vs=50.3< 14       Vt=83.8<-130
      Ir=9.9< 70        Is=6.9<-107       It=0.1<-155       In=3.0< 65

3) impedances seen [Ohm]  :

Zre= 4.56 + j*  1.05    Zse=-4.75 + j*  8.33    Zte=-49.88 + j* 18.38
Zrs= 1.52 + j*  3.16    Zst=-15.01 + j* 11.32   Ztr=13.14 + j* -1.69

4) type of fault :  AB-G
5) estimated fault distance :  7.68 [km]  {with load compensation}
6) estimated fault impedance :  0.6 [Ohm]
7) selected state :  Yes
```