Computer-aided Fault Analysis (CAFA) dedicated to the power transmission system

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Abstract — **the computer-aided faults analysis expert system has been designed to automatically process fault records monitored in high voltage transmission power system. It provide useful information to control centre, protection engineers with the fault conditions immediately preceding any alarming condition or breaker operation. The protection engineers will also detect hidden failure. Not correcting them may cause significant incident in near future. Historical fault data will permit Asset Management Department easier decision making process for condition based maintenance focus on circuit breakers and protection relays. The CAFA is an analysis tool with special emphasis on automatic selection of the most critical events, fault location also on underground cables, protection systems, circuit breaker monitoring as well as fault signature analysis. Fault analysis experts will avoid spending time on data management and will allow them to focus on the core competencies, fault investigation.**

Index Terms-- **High-voltage techniques, Fault location, Power system faults, Power system protection, Power system reliability, Power transmission.**

I. INTRODUCTION

Fault analysis can be either an intensive work and/or a very long procedure in case of multiple or major disturbances in the high voltage power grid. In most cases, the operator has to go through all recorded data to identify the faults with a potential impact on the grid operation.

Some power companies are spending precious time and resources dealing with system recovery while data are being collected and analysed, and the faults located. Moreover, unplanned electrical power outages are major concerns to power utilities throughout the world. Unfortunately, power outages will continue to happen and cannot be fully prevented.

Outages are usually caused by the incorrect behaviour of assets, because of wrong settings or external stimuli such as lightning strikes, tree encroachments, etc.

Their impact can be reduced if the power system operators use appropriate tools to quickly analyse the most critical events, their location and the root cause of the outages.

II. SITUATION TODAY

System operators have to deal with multiple vendor solutions, each one presenting an increasing complexity as the variety and the technology of the connected devices evolve.

The fault recording devices called IED's are from various natures and coexist in Transmission companies' substations at different voltage levels: DFR, DPR, PMU, RTU as can be seen on Fig. 1. For example, some PMU, which are normally managed as continuous recorders instead of triggered devices, could deliver data "packets", collecting phasors recorded over a predefined time window (e.g. one hour). Other devices such as sequence of event loggers (SER) may contribute to extend the data coverage, but their use is dependent on compatible communication protocols as well as compatible data formats.

These devices may have several feature variations, some of them different technology generations, providing several formats of data, at different sampling rates and binary resolutions. On top of that, the IED's may have different timestamps and may be unsynchronized.
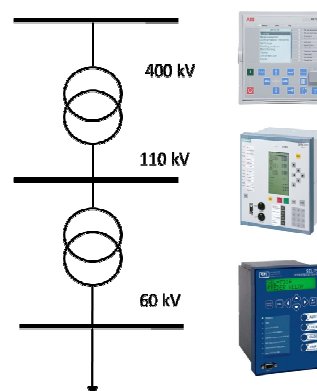

Figure 1. Multiple vendors' technologies at different voltage levels

The first task of the operator consists in collecting and re-aligning the data on a common time scale, starting from the fault inception until the end of the incident. Depending on the recorder's capabilities, it can be necessary to include additional records with the circuit breaker auto-reclosing or manual reclosing attempt.

Searching, collecting and managing data in this ever changing, heterogeneous environment, to finally get clear and trustworthy information out of it often appears more like looking for a needle in a haystack. Thanks to the expert system, which offers a common platform to collect and compare data from multiple vendors and from devices placed at different voltage levels, oblivious of device specific features, the operators automatically get a global view of the incident and may then focus on their core activity.

III. DATA COLLECTION, CONVERSION AND VALIDATION

A typical architecture for implementing an CAFA system consists in collecting the various records at the substation level, then organizes their transfer to a regional or national centre after conversion and data pre-processing. Recent communication technologies such as Ethernet, TCP, IEC 61850, ICCP... [1] will be used to achieve optimum data transfer capabilities. Fig. 2

This configuration, where the data are made available in a file repository by the Remote Access System (RAS), offers an ideal decoupling between communication and data processing.
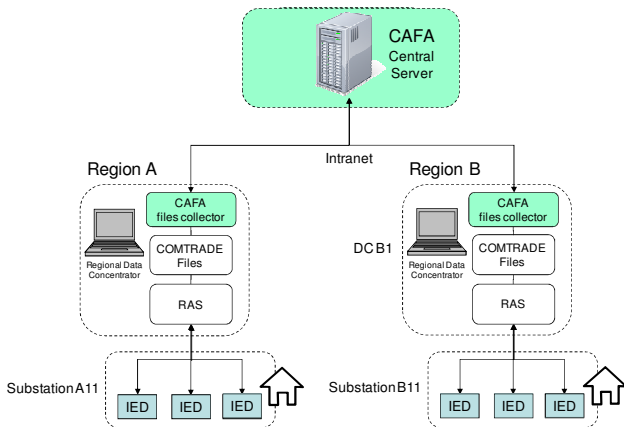

Figure 2. Communication infrastructure from the IED's to the central server

The RAS agent is responsible for importing the recorded data from the devices and converting them to COMTRADE if they are not directly retrieved in this format. The RAS stores the COMTRADE files in a per-device directory structure in the Substation Data Concentrator (SDC) where the file collector modules collect and process them.

To deal with these many records that may not necessarily be available at the same time, depending on the communication sequence with the devices, and to provide some results as quickly as possible, it processes every record as soon as it arrives.

When a new record becomes available, e.g. from another feeder impacted by the same incident as well, the CAFA looks for other records which may possibly be related to the same event and proceeds with the data aggregation and event prioritization: the previous analysis results are enhanced with the new information and update the report in the form presented on Fig 3.
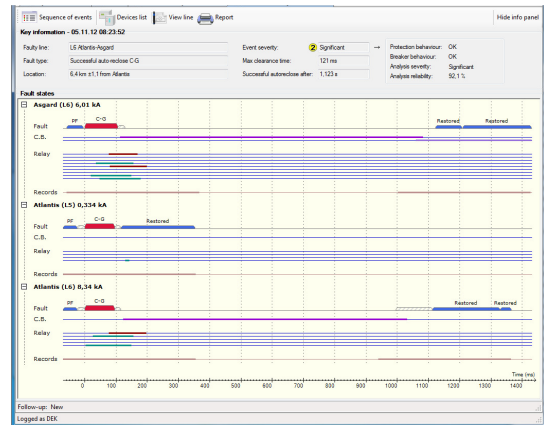

Figure 3. Example of a report generated by the CAFA system
(all the fault records from the same event, originally not synchronized, are consolidated into one view from different substations and are automatically synchronized)

Only a few events really need either an immediate action or, on the contrary, in-depth analysis. Most of them appear as normal network operations or simple trip-auto-reclosing operations following a transient fault. The system uses an efficient classification method to automatically select the faults based on the following criteria: current level, relay operating zone, location reliability, protection system response and auto-reclose operation.

This allows to automatically setting a priority depending on the following issues:

- for the operator: prioritize the events with short circuit, select permanent faults rather than transient faults, locate the fault, with the indication of the faulty phase(s), understand the cause of the fault and help restore the power as quickly as possible in case of a long line,

- for the protection engineer: unexpected response time of the protection system, inconsistency between the fault location and the relays' operating zone, wrong behaviour of the protection transfer scheme, etc.

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IV. DATA SYNCHRONIZATION

To successfully proceed with record aggregation, it is desirable that all the records come from time-synchronized devices, because the obvious criterion used to group them in a single event consists in watching if they fall within a given, adjustable time interval, typically a few minutes.

However, it may be useful to remember here some of the different meanings given to the concept of IED synchronization: the first one, which is the most common, synchronizes the timestamp of the record. This method is usually performed by synchronizing the real-time clock of the device's CPU and provides a typical accuracy of 1 ms, or 18° phase angle at 50 Hz.

The second one is much less frequent and consists in synchronizing the sampling clock of the analogue-to-digital converter, usually to a GPS receiver. This source of synchronization may provide a total accuracy of typically 1μs, or 0.02° phase angle at 50 Hz, and it is obvious that this difference in order of magnitude can have consequences on the rest of the processing sequence. The accuracy of some digital signal processing algorithms such as, for example, double end fault locators, will be significantly impacted by this phase angle bias.

In the real world, the most accurate GPS synchronization is only found on PMU and some high-end DFRs. In practice, most of the other IEDs and almost all the numerical relays only provide a reasonably good timestamp or are not synchronized at all.

To be thorough, another alternative has also been considered: when the record time significantly differs from the Substation Data Concentrator time, this SDC time value may be used as a reference. Indeed, in this case, the time difference between the IED and the SDC may be considered as a device clock drift and the new record can then be dated from the File Collector time. However, this last solution is not fully satisfactory because the time to transfer a record on a serial link, from a numerical relay to the SDC, may take a few seconds, resulting in a timestamp accuracy of the same magnitude.

One may be conclude from the above considerations that all time-synchronization methods are not equivalent and will not provide the same accuracy as far as data alignment is concerned. The expert system deals with all those synchronizing methods. However, to compensate for their lack of precision, it implements some additional resynchronization algorithms based on fault pattern matching. The result, as illustrated later in this paper, provides a timely, consistent adjustment of the calculated phasor sequences, enabling the subsequent use of an accurate double end fault location.

V. FROM OVERVIEW TO DETAILED ANALYSIS

The system offers a detailed overview of each event (see Fig. 4) and will gather and re-synchronize the selected records to provide a comprehensive view of the events, ensuring precise fault analysis and decision making.
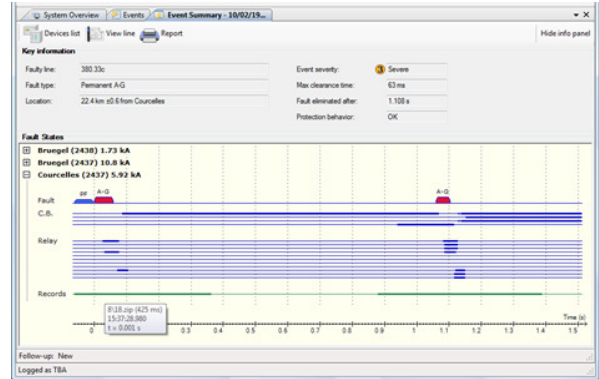

Figure 4. Event Summary including all records from each lines and substations involved in a specific disturbance

The fault analysis experts may easily reconcile the information they receive, and check precisely how the assets in the power network reacted. Those will raise warnings or recommendations to the power system operators. These indications represent a significant improvement as they allow future fault prevention.

On the basis of the collected information, the system can also automatically evaluate accurate fault location information, which is essential for the reliable operation of an electrical power system, together with the analysis of re-closing performance following a circuit breaker operation.

On-going work consists in extending the pattern recognition algorithms to distinguish some particular fault signatures such as flashovers caused by a lightning strike, trees or cranes touching the line, bird collisions or polluted insulators (due e.g. to salty atmospheres, dust, snow, bird excreta, etc.) [2].

The main goal is to provide correct and proven fault identification, evaluate the behaviour of the protection system and compare it with the performances expected by the electrical power public utility. Unexpected results may indicate bad settings or hidden failures, such as: wrong cabling, selectivity and auto-reclose issues, inconsistency between main and backup relays, discrepancy between circuit breaker poles and wrong behaviour of the transfer scheme.

Analysis results can be reported in the form of user-defined layouts and sent via any available telecom system (text message, email). The integration with a utility Intranet and SCADA system can also be achieved.

VI. USE CASE – PROTECTION FAILURE

It is worth emphasizing, that, nowadays, disturbance analysis is usually limited to the most critical events that obviously mean that the devices working in the station protection system did not behave correctly. Fig. 5 presents just that kind of behaviour, leading to the unexpected trip from a breaker failure protection (BFP) and an inconsistency in CB pole position.
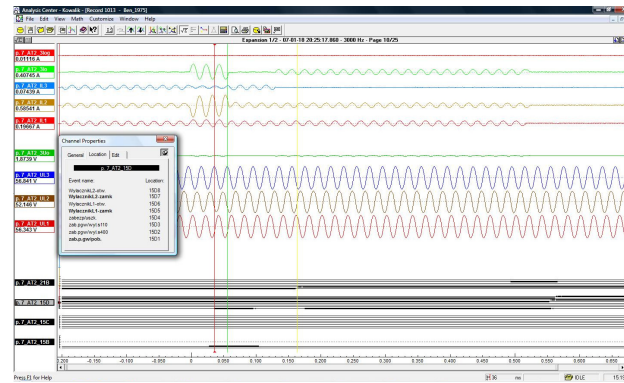

Figure 5. Example of a record with a disturbance caused by an unexpected trip due to a breaker failure protection (digital signals as they activate, from top to bottom: 1-BFP trip, 10 inconsistency in CB pole position, 13 CB phase 3 open, 14 CB phase 3 closed, 15 CB phase 2 open, 16 CB phase 2 closed, 17 CB phase 1 open, 18 CB phase 1 closed, 22 energizing of an over current protection installed in the star point of the transformer, energizing of distance protection of the transformer, 23 transformer differential protection-trip)

Unfortunately, the behaviour of a protection system cannot be fully checked only by analysing DFR files which exhibit an incorrect behaviour. Every day, a power system has to withstand many disturbances, which are eliminated by the proper operation of basic protections. However, the disturbance will trigger all backup protections from the entire area. The analysis of the behaviour of all the protections in the affected area is very time-consuming, boring and, because of this, usually not performed.

Those disturbances can be treated as functional tests of protection systems that should properly react. Fig. 6 and Fig. 7 expose examples of "uninteresting" records which can be used for such purposes. Fig. 6. shows that there are no changes in digital channels, which means that, for those levels of signals, no protection triggered. CAFA software will check if in particular substations and feeders such behaviour of protection devices is really expected and correct. If not, the system will present appropriate report signifying that probably there is an error in setup of particular protection device. Fig. 7 shows another situation where one protection triggered. Such behaviour can also be used for checking the functionality of protection devices, because it clearly signifies that the protection system including digital outputs is working correctly. CAFA software will check such behaviour comparing measured signals with expected values and highlight failed behaviour in the report.
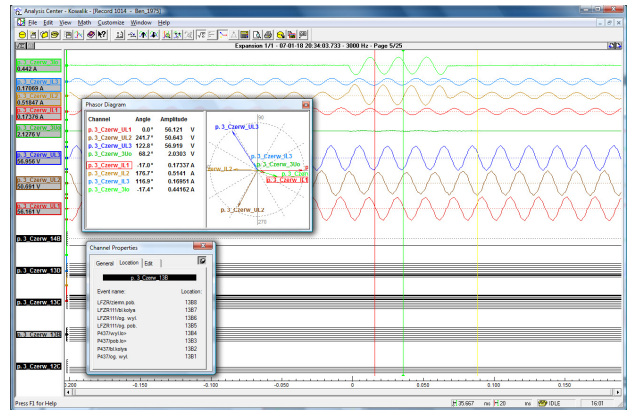

Figure 6. Example of record with a disturbance that did not cause any reaction of the power system protection devices
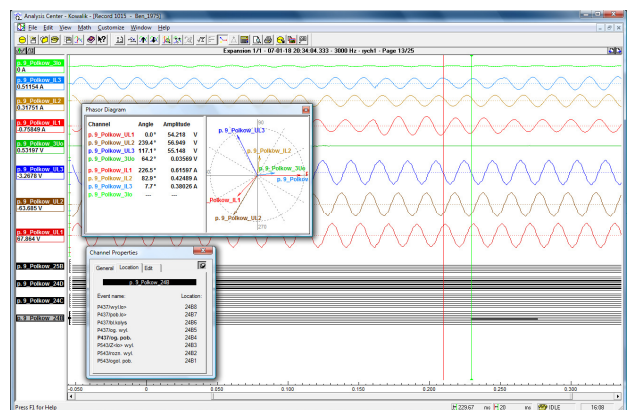

Figure 7. Example of record with a disturbance that caused a stimulation of the power system protection device

It is worth to underline that modern protection devices have usually DFR functionality, so in case of analysis of records coming from main and additional protections it is possible to check the behaviour of the protections system for the entire feeder.

An efficient automatic analysis system should therefore offer a practical solution, convenient for the control centre, and provide the system operators and protection engineers with the fault conditions and system overview immediately before and after any alarming condition or breaker operation. Such system should handle the very time consuming job of collecting and adjusting the data to a common database, allowing carrying out statistical comparisons. The system can also be a tool designed to analyse the faults and protection system, with a special emphasis on automatic selection of the most critical events, fault location, as well as fault signature analysis. So, such features of CAFA can be used to significantly improve the work of any protection system equipped with DFR devices or DFR devices regardless of theirs manufacturers.

VII. USE CASE – DATA SYNCHRONIZATION

The next practical case shows multiple, unsynchronized records coming from DFRs and Protection Relays, and displayed by the CAFA into a single view. They come from a 91.6 km long, 220 kV line impacted by a transient B-to-GND fault.

The table below shows the various recording devices available at both ends.

Line end	Device	Record trigger time	Sampling frequency
1	DFR	19:39:23.6	2000 Hz
1	7SA522	19:39:21.3	1000 Hz
1	P443	18:45:53.2	2398 Hz
2	7SA522	18:44:14.1	1000 Hz
2	P443	09:07:05.1	2398 Hz

This illustrates a typical situation: on end-1, a GPS-synchronized DFR is available, allowing to accurately timestamp the event. The other sources of data are unsynchronized numerical relays.
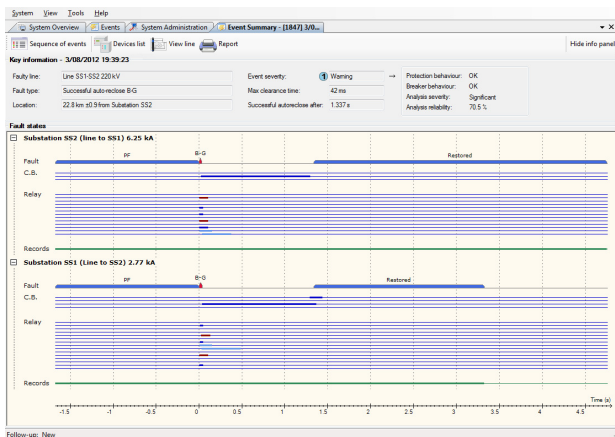

Figure 8.   Significant re-alignment by automated synchronization of two records displayed on the same fault overview

The monitoring records are aggregated together as they belong to the same fault. They have been automatically re-synchronized and prioritized with a low severity level because it is a transient fault, and the protection system behaved well. However, in the detailed analysis report, a warning indicates that a significant re-alignment occurred on one of the MICOM relays. All this pre-processing allows the user to save time because all the aggregation and synchronization work is done automatically, and the selection of the most critical event stored in the database can easily be sorted out using each fault's severity level.

As can be seen on Fig. 8, the fault is clearly presented in the form of analogue and digital signal states representing not only the behaviour of each protection device and CB, but also the evaluated state of line (PF – pre-fault, BG – fault type, Restored) , as well as the data contained in the evaluated records. The values presented on this page show the names of the affected line and substations, the date and time of the fault inception, the evaluated fault currents, the distance to fault and max clearance and auto-reclose process times. On top of this, a tooltip displaying all the digital signals' names appears whenever the mouse pointer passes over a trace. The system can produce a detailed text report on the basis of that data, as shown on Fig. 9.

Figure 9.   Text report of the fault presented on Fig. 8 containing protection and tele-protection devices' reaction times

This report shows the exact times of protections energizing and tripping together with the distance protection coordination signals as well as the CBs' states. The data evaluation can lead to conclusions regarding the behaviour and setting values of the power system protections and tele-protection devices involved in the clearing of the fault. When first looking at the case presented on Fig.8 and 9, everything seems to indicate that all the elements behaved correctly. The main protection relays (line distance function 21 in 7SA522 and in P433) energized correctly and rightly recognized the fault type and faulty phase. The relays closer to the fault (substation PL-SS2) correctly recognized the fault within their 1st zones, and sent the tripping signal to the local CB (in feeder named "line to SS1", which opened within 16ms) and to the tele-protection system.

The tele-protection system correctly sent and received the signals from the corresponding protection devices at the opposite substation SS1, then forced the 7SA522 protection to send a trip signal after a few additional ms. The CB in the feeder named "line to SS2" at substation SS1 opened within a few ms. Most importantly, there was a successful autoreclose process initiated on both sides, after almost the same time (ca 1336 ms according to the information from the text report and SoE Fig.10.). The text report presented on Fig. 9 does not show any incorrect behaviour of the devices working on the fault clearance (no value is outside the specified limits) despite the lack of time synchronisation of protection devices and

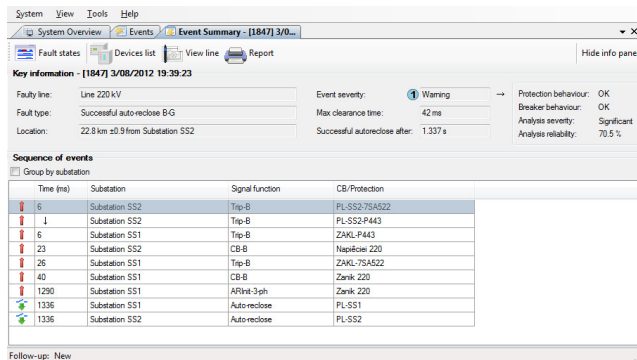DFR recording the fault and different sampling rates used by them.

Figure 10. Sequence of Events (SoE)

VIII. CONTRIBUTION TO REAL-TIME ASSET MANAGEMENT

A. Operational fault analysis

As the presented use cases showed, the featured piece of software can do short-term fault analysis. It helps achieve an effective and fast power-system restoration, as well as an efficient decision making process, hence minimizing the probability of widespread blackouts. It allows getting the equipment quickly back to service, and consequently the quick restoration of the power to the users. This, in turn, reduces the amount of un-served energy and increases the assets' availability.

B. Tactical fault analysis

The system can do medium-term fault analysis, with a set of features which is usually referred to as a CAFA system: fault records consolidation, faults prioritization, fault location also on high voltage underground cables, signature analysis and protection system analysis.

Detection of hidden failures: the data presented here clearly showed that many hidden failures existing in secondary side system can be discovered and corrected, such as: wrong settings, wrong cabling, selectivity and auto-reclose issues, inconsistency between main and backup relays, wrong performance of the transfer scheme, erosion of the circuit breaker contacts. The system can also be used to monitor the devices measuring the analogue signals and enable early

detection, for instance, of VT problems such as faulty VT fuses or failure of the ferroresonance suppression circuit [3].

C. Strategic fault analysis

The long-term fault analysis, involving aggregation of event data over time is implemented in the highlighted piece of software [4]. For instance, the aggregation of an I^2t energy integral for a breaker will give insight for a Condition Based Maintenance (CBM) of the Circuit breakers. Other types of aggregation will help for the maintenance of Protection relays, Power transformers, Overhead lines and other equipment.

IX. CONCLUSION

Computer-aided Fault Analysis (CAFA), also known as Automated Fault Analysis System (AFAS) is the use of expert systems to assist in fault records consolidation, fault prioritization, location of disturbances as well as the root cause investigation and analysis of the protection system.

As power systems become more stressed, complicated and equipped with a larger number of devices, the possibility of disturbances increases. More complicated protection systems need more efforts to check their behaviour. More work can be done by additional staff or using more advanced technology such as expert systems. End user should choose their CAFA, which includes many features allowing for an efficient use in many fields of interest be they fault identification, protection performance evaluation, fault location, flash detection, or operational fault analysis, or even strategic fault analysis. One can have a look at those features and realize what the future of fault analysis systems designed for transmission grid should look like, and understand that it will probably become necessary within the next few years.

Unpublished Papers:
[1] D. Maragal "Automated Fault Data Collection, Analysis, and Reporting" New York Power Authority

Periodicals:
[2] J.T. Burnham "Birds streamer flashovers on FPL transmission lines" IEEE Transactions on Power Delivery April 1995

Technical Reports:
[3] Euan M. Davidson, Stephen D. J. McArthur, Tom Cumming, Ian Watt "Automated Analysis of SCADA and DFR data: Post-fault Diagnosis of Power System Disturbances and Condition Assessment of Plant"
[4] M. Kezunovic, L. A. C. Angulo, F. Lhomme, F. Franceschini, J. Walseth, M. A. M. Rodrigues "New Trends for Automated Fault and Disturbance Analysis" Cigré Working Group B5.20, August 2010, ISBN: 978 – 2 – 85873 – 112 – 1