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FAULT AND DISTURBANCE DATA ANALYSIS

INCLUDING INTELLIGENT SYSTEMS

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Appendix – “Questionnaire on data recording devices and their applications in fault and disturbance analysis”

1 Introduction

Utilities have traditionally analysed network disturbances as a way to check and improve grid performance. Protection staff is commonly the one responsible for this analysis, paying especial attention to relay performance, and providing other departments with useful information such as fault location, fault duration, measured current level, breakers time response, tripping sequence and restoration sequence, among others. The inclusion of numerical technology in protection and control equipment observed in the last years has brought consequently a great growth of the recording capability. The amount of data recorded, not only in disturbances but in normal service also, is overwhelming. This fact has permitted both to extend the scope and to improve the analysis results. The analysis scope has extended covering regularly other areas that were in the past either exceptionally treated or not treated at all; such as maintenance management based on condition, monitoring, customer assessment or planning based on power quality and dynamic performance. However, retrieving and processing that information require considerable time dedication from high-qualified personnel, and consequently, should be automated in some way to keep costs down. Due to market pressure, utilities need to review their procedures continuously in order to improve service quality and become more cost effective. Of course, disturbance analysis procedures are not an exception. Provide real time elaborated information about fault and protection behaviour to the dispatcher is a very convenient way to improve the making decision process and reduce restoration time in a disturbance. How have utilities taken advantage of technology advance to improve these procedures? How do they use all the information available? Have they automated disturbance analysis implementing expert systems, neuronal nets or fuzzy logic?

Technology development has given us the opportunity to get better, wider, deeper and faster knowledge of grid performance in common disturbances, but facts have proven that the analysis of major network disturbances requires new data and recording equipment units, which combine the characteristics offered by local instrumentation with proper studies to simulate the power system dynamic performance. It is becoming more and more obvious that increased use of computerised disturbance simulation requires a high degree of confidence in modelling grid parameters. As shown by important USA disturbances in 1996, there is a great need for a valuable tool to develop models through measurements taken from the power system. Some recordings of recent years have shown great differences obtained between results from computer simulation and real values from the field recorders. The comparisons between recordings and computer simulations probe the increasing necessity to set up power system monitors that have the capability to capture accurately both pre and post-disturbance data. This is the only sure method of determining simulation accuracy.

The increasing interest of these subjects encouraged SC B5 to create the WG B5.03 “Fault and disturbance data analysis including intelligent systems”. This WG must elaborate a report on the requirements for monitoring the system protections and the dynamic performance of electric power system, combining the possibilities and characteristics offered by local instrumentation with the adequacy of system dynamic simulation studies. The report scope should cover the following points:

1. Identify the characteristics of the existing recording equipment.
    - Gather information about existing units and classify them according to their application and technical characteristics.
    - Review procedures for integration of information from equipment from different manufacturers and systems, as well as formats for data exchange.
2. Make recommendations to optimise disturbance analysis system architectures.
    - Establish criteria to optimise the installation of recording equipment and type of information provided in terms of application.
3. Gather methodologies and experiences for processing information and applications.

- Automatic analysis of information.
- Centralised and decentralised application software for analysis of faults and disturbances.
- Improvements achieved by automated analysis in both system monitoring and operation.
- Methodologies and techniques applied to simulation studies of the dynamic performance of the electrical system.

4. Identify future trends.

To cover its objectives the WG decided to distribute a questionnaire designed to learn from utilities around the world about their present practises and future trends in relation to disturbance analysis. The survey was structured in five parts:

1. Company data.
2. Recording equipment used.
3. Data used.
4. Data processing (gathering, storage, management …)
5. Present applications of the analysis.
6. Future trends.

Answers from 25 utilities from 12 countries covering Transmission, Generation and Distribution have been received. They have been analysed and summarised in a document that is included in this report as an appendix.

Waiting for the answers arrival, the WG began to prepare this report from the knowledge of the WG members and the bibliography available about the matter. Of course, the results obtained from the study of the survey responses support in the contents of this report. It is structured in five chapters:

1. Introduction.
2. Recording equipment. This chapter classifies the devices that provide information about disturbances pointing out the differences in performance among them. It describes data provided and finally extracts some conclusions about practises on use of recording equipment.
3. System architecture. This chapter describes the system architecture paying special attention to communications and data integration and includes some conclusions.
4. Applications. This chapter classifies and describes the present applications of the information provided by recording equipment, and extracts some conclusions.
5. Future trends. This chapter provides a vision about immediate tendencies to match technology possibilities with utilities needs.

In September 2003 the SC B5 Annual Meeting and Colloquium took place in Sydney (Australia), with a selected topic “Automated fault and disturbance fault analysis” as a preferential subject for this colloquium. This WG contributed to the colloquium with one of its members, Mr. M. Kezunovic, as special reporter for the above-mentioned preferential subject [2], and with two papers, the first [3] summarizing the present practises for fault and disturbance analysis, and the second [4] presenting the future trends in the use of advanced technologies in this area.

Although the WG task has finished, it has not completely been solved and some questions keep open, such as:

1. Costs analysis of existing fault and disturbance analysis systems.
2. Guides for building up new system architecture for fault and disturbance analysis and costs analysis of the project.

2 Recording equipment.

2.1 Introduction

A variety of devices may be used for disturbance analysis purposes. The available devices differ by their inputs, their recording capabilities and their performance characteristics. Some of them have been specifically designed for disturbance analysis applications. For some other types of devices, the digital recording capability is more like an auxiliary function, or the type of recordings do not provide a comprehensive view of the disturbances. Therefore, it is important to understand the recording technology and its corresponding limitations before planning any application.

2.2 Classification of devices providing fault and disturbance data

2.2.1 Types of devices

Fault and disturbance data can be gathered from a number of devices, or data sources. Several technologies are commonly found, ranging from older paper recorders to modern digital recorders. The newer devices generally offer several functions. Fault and disturbance data acquisition may represent the main function for some of them (e.g. a fault recorder) or just an ancillary function (e.g. for a digital protection relay).

Although the device types evolve very quickly, it is possible to classify recording devices according to their main functions (see Table 1).

Group*	Acronym	Device name
T	SER	Sequence of events recorder
T	EMR	Electro-mechanical (paper) recorder
T	TAP	Tape recorder
C	**DFR**	Digital fault recorder (disturbance recorder, fault recorder)
E	DSR	Digital dynamic swing recorder
E	PQ	Power quality recorder
E	PMU	Phasor measurement unit
T	FL	Dedicated fault locator
E	DR	Multiple-purpose digital recorder
T	PR	Electro-mechanical or electronic protection relay
C	**DPR**	Digital protection relay
E	COM	Substation computer with storage, communication and processing functions
C	**RTU**	Remote terminal unit
E	SA	Substation automation system (integrated control and protection)
C	**PPC**	Power plant computer

Table 1: Device types.

(*)In this table, a first column has been added in order to classify recording devices in three main groups:

- T: Traditional devices group that includes:
  - All those devices commonly used by utilities for disturbance analysis but do not support remote access to data, so it would be difficult to include them in automatic analysis systems.
  - All those digital devices supporting remote access but not commonly used by utilities as it comes out from the answers to the questionnaire summarized in the appendix.
- C: Common devices group includes all those digital devices that are extensively used by utilities, provide at this moment most of the information for disturbance analysis, and support remote access to data, so they could be easily included in automatic analysis systems.
- E: Emerging devices group includes new digital devices and systems.

2.2.2 Types of data produced by the devices

Devices are better described, for analysis purposes, by their outputs than by their inner structure. Table 2 summarizes the kind of information that is typically produced by each type of device. Most devices of the specified class will be able to deliver at least the outputs indicated by the grey cells in the table.

Information \ Type of equipment		SER	EMR	TAP	DFR	DSR	PQ	PMU	FL	DR	PR	DPR	COM	RTU	SA	PPC
Targets (relay contacts, LED’s...)	**A**		■	■							■	■				
Paper plots of binary or analogue signals	**B**	■	■							■						
Digital records of binary signals or events	**C**			■	■	■				■		■				
Digital records of analogue signals (slow)	**D**			■		■				■						
Digital records of analogue signals (fast)	**E**				■					■		■				
Calculated derived quantities (phasors, power, harmonics...)	**F**						■			■						
Power quality indicators, statistics or compliance report	**G**						■									
Synchronous quantities (especially synchrophasors)	**H**							■								
Fault information (position etc.)	**I**								■							
Equipment diagnostic	**J**															
Standard **process data**, e.g. messages according to IEC-60870-5-10x	**K**													■	■	■
Special messages or reports related to **system faults**	**L**															

Table 2: Typical device outputs.

All data listed in this table is assumed to have been captured and stored in such a way that it is available for off-line analysis without any particular time constraint. In this discussion, we have not taken into consideration volatile data, such as on-line measurements.

2.3 Difference in recording performance.

This chapter is a discussion of various device-related factors which influence the nature and quality of the disturbance data and thus, indirectly, the quality of a subsequent disturbance analysis.

2.3.1 Data acquisition

Possibly the least understood issue in relation to the analysis is the data acquisition performance and its effects. Although the basic recording function of different devices may be the same and the same signals may be recorded, however the type of recorded data and their recording performance may be quite different. The following are some typical recording approaches that are found in different equipment, which in turn make the difference in their recording performance:

- Continuous recording vs. triggered recording
- Triggers and history
- Synchronised data sampling vs. scanning
- Low precision vs. high precision A/D conversion
- Low sampling rate vs. high sampling rate
- Recording of pre-calculated values vs. recording of samples
- Pre-filtering of data (beyond the needs for anti-aliasing filtering) vs. only the anti-aliasing filtering

Continuous recording vs. triggered recording

Some devices are designed to record permanently the power system condition. They may either provide a continuous flow of digital data (like phasor measurement units and RTUs) or detect and record significant changes and perform data compression compatible with the application (like power quality recording, with a reference to standardized thresholds). Other devices like digital fault recorders, power swing recorders and protection relays, are designed to capture finite data sets with high resolution with respect to so-called trigger conditions.

Triggers and history

The performance of triggered recording depends on the available trigger possibilities, on the maximum total length of the recording, and on the possibility of including pre-trigger data (so-called "history") in the record. Some devices, especially new multiple-purpose digital recorders, have advanced triggering rules, which ensure that nothing noteworthy for disturbance analysis goes undetected. On the contrary, digital protection devices typically trigger their digital recording functions only when they detect a fault with some certainty, so they are less sensitive and the length of the history is very important because the analysis requires the observation of the very beginning of the disturbance. In order not to loose data it is important to adapt triggering conditions to the recording length, the storage capacity of the device and the data retrieving frequency.

Synchronised data sampling vs. scanning

It is well known that some recording instruments perform synchronised data sampling on all the channels connected to the instrument. In this case, a sample and hold (S/H) circuit is provided on each input channel, and all of them are captured at the same time via a common sampling clock signal. The signal samples obtained this way can be used to recover not only the basic properties of the signal, but also to establish a phase difference between the signals presented at different inputs. In the analysis, knowing the phase difference may be critical. On the other hand, some instruments use the data scanning techniques where the samples are taken from each channel with the same S/H circuit. Using this technique, the samples are taken at different time points on each of the channels hence preventing an easy way of establishing the actual phase difference among signals connected to various channels. Digital protective relays (DPR), digital fault recorders (DFR), fault locators (FL), some sequence of event recorders (SER) and some intelligent electronic devices (IED) typically perform synchronised data sampling, while remote terminal units (RTU) of a supervisory control and data acquisition system (SCADA), and some other types of sequence of event recorders (SER) and intelligent electronic devices (IED) would typically use data scanning techniques.

Low precision (8 bits, 10 bits, 12 bits) vs. high precision (14 bits, 16 bits, 20 bits) A/D conversion

Obviously, this discussion is related to the recording of analogue waveforms. The “vertical“ A/D converter resolution vs. “horizontal” resolution is the issue which affects accuracy of the signal measurement vs. signal representation respectively. The horizontal resolution is determined by the sampling rate and will be discussed in the next paragraph. The vertical resolution is associated with the dynamic range of the signal. The larger the dynamic range, the higher the need for a more precise A/D converter. If the analysis requires very accurate representation of a wide dynamic range of the signals, a high precision A/D converter may have to be used. Another point to be understood is the signal scaling technique used in some recording devices to adjust signal dynamic range before the A/D conversion is applied. For the analysis purposes, the scaling technique may have to be known in advance to be able to interpret the recorded waveforms and perform the analysis correctly.

Low sampling rate (typically 16 samples/cycle) vs. high sampling rate (typically 64 samples/cycle)

The issue of the sampling rate used in a recording instrument may be quite important for at least two reasons: the anti-aliasing filter selection and accuracy of signal representation. The anti-aliasing filter selection is associated with the requirement of a sampling rate at least twice the highest frequency in the sampled signal. Since some of the recording instruments have other applications implemented on the same device as well (DPRs are a good example), it becomes very important to understand the constraints caused by the main application when an auxiliary application is being defined based on the data coming from the same instrument. On the other hand, the accuracy of signal representation is also dependent on the selection of the sampling rate. In general, the higher the sampling rate, the better the representation. A higher sampling rate may not contribute to better measurement accuracy unless the selection of the A/D converter meets the dynamic range requirement. In addition, the anti-aliasing requirement may be satisfied with a lower sampling rate, but a better signal representation may be achieved by increasing the sampling rate. Therefore, the selection of the sampling rate is a multifaceted issue and needs clear understanding when the analysis applications are considered.

Recording of pre-calculated values vs. recording of samples

The analysis may require that some values already pre-calculated by the recording device were reconstructed for the analysis purposes using samples. In particular, calculated quantities like RMS current, harmonics etc. may be accurate and informative in steady-state conditions but wrong or misleading in transient or unstable conditions, due to the effects of transient components (like decaying DC) and power swings on standard calculations of such quantities. This poses an interesting question in relation to what is available from a given device - samples, pre-calculated values, or both - and whether pre-calculated values are trustworthy for the considered use. It may be important to understand the exact signal processing that has taken place in the recording device: calculation algorithm, time window, filters, frequency compensation or adaptation. This information may not necessarily be available to the end user, and the analysis may have to be simplified if such information is not available.

Pre-filtering of data (beyond the needs for anti-aliasing filtering) vs. only the anti-aliasing filtering

This issue is leading one further into the details of the signal processing undertaken by any recording device. If the details are known, the original input signals may be reconstructed more faithfully, and this in turn may lead to a better analysis, especially regarding transient phenomena. The pre-filtering process in some of the recording devices (DPRs in particular) may be quite involved and data difficult to reconstruct unless full design information for the data acquisition subsystem is provided. Some digital protective relays (DPR) have the filtering part separated from the part that reconstructs a measured quantity, while some DPRs have both functions implemented in the same digital filter. Being able to distinguish the differences may be an important part of the analysis, but again the required level of detail in the analysis may be the driving factor for wanting (or not wanting) to know the design details of the recording equipment. Of course, the recording equipment that uses only the anti-aliasing filters of a simple design may be doing the least of pre-processing and hence reconstructing the signal may be the simplest.

2.3.2 Time considerations

Differentiating power system events

The data sets provided by recording devices normally contain at least one time stamp, which may refer to the first measurement or to the trigger time, for example. Such time stamps can be used for identifying the power system event and grouping all associated records. Thus, it is important to ensure that the accuracy of time tagging is better than the time gap between power system events, which need to be differentiated. For instance, when single-pole reclosing is used in the system and when every reclosing cycle may trigger a separate record, the time accuracy should ideally be better than the duration of the shortest reclosing cycle in order to be able to compare easily data from different devices when analysing the tripping and reclosing cycles. To ensure this, the drift of every device clock from a reference clock should be kept within the specified bounds.

Time measurement

Many recording devices provide one or several means for automatically keeping synchronism (with a specified tolerance) between the device clock and an external time referential. When several devices are synchronised with the same time referential, this feature allows synchronising data from different devices based on their time stamps.

The external time reference is usually presented to the recording device by a local time source, for instance: a GPS (satellite) receiver, a DCF-77 (radio) receiver, or a slave clock tied to the master clock by communication links. The hardware can feature a special time input (electrical or optical) to read a time signal, which may consist either of periodic pulses (one pulse per second (PPS) and one pulse per minute (PPM) are common pulse rates) or of serial telegrams (modulated or demodulated IRIG-B, etc.).

Alternatively, a device may be continuously synchronised through its data line with a main station, or with a local device set at substation that is continuously synchronised with one of the aforementioned local time sources.

Continuous clock synchronisation vs. time setting

As long as a device continuously measures time, it can adapt its measurement clock by a continuous control. This provides the best possible time accuracy.
When a device loses its time input, the clock will start to run free. If the time input is discontinued too long, it may be necessary to set the new time when that input restores. This may lead to unwanted effects, like (apparently) missing or overlapping data in continuous records. This problem is a major concern when no time measurement is available and the device clocks are re-synchronized through the communication link with a main station. Dial-up links represent the worst

case; it can be necessary to establish a connection with a device several times per day just for synchronizing its clock, and every occasion the time tag will make a jump.

Time accuracy

The synchronisation accuracy of a given device with an external time reference depends on the accuracy of the individual synchronisation events, on the frequency of such events, and on the accuracy and stability of the device clock itself. For example, if a DFR is equipped with a low-cost quartz oscillator, without any clock supervision and correction function, and if the recorder is synchronised once a day with a master via a modem link, the worst-case time deviation occurs after the clock has run free for one day. It attains 4.3 seconds for a clock deviation of 50 ppm (parts per million). Such a high error is generally not acceptable.

The accuracy is usually improved by synchronising more often and using better time sources. This is more economical than building high-stability clocks into the devices. Fortunately, the use of high-speed TCP/IP networks for communication between substations and control centres becomes increasingly common. Such networks permit frequent re-synchronization. Using appropriate techniques, the time accuracy can be better than one cycle. Still, direct time measurement by the device yields a much better precision. A precision of a few milliseconds can be attained easily using radio receivers. Yet the best achievable accuracy with state-of-the-art technology is about 1 µs, attained by synchronising to the Global Positioning System (GPS) of satellites about 100 times per second. Most modern instruments in use today provide GPS receiver or IRIG-B for synchronisation, and in the future this feature may become standard [2].

One may think that GPS accuracy is more than enough for disturbance analysis. This is probably true, but the required accuracy always depends on the application. For the analysis of harmonic flows, for instance, one may need 5° accuracy on the 13th harmonic components, which imposes that the device synchronisation must be better than 20 µs. Furthermore, some special devices, such as travelling-wave fault locators, really need GPS accuracy.

Time tagging

Recording devices use their master clock to tag individual measurements (samples, computed values...) with the current time. Ideally, the time tag should include an identification of the clock, of the time frame (for local time: the time zone and whether daylight saving is in effect) and of the synchronization accuracy (or a detection of loss of synchronism), but this is seldom the case.

It is also important to understand the exact relationship of the data to the time tag in order to make the best possible use of the time information. For example, the possibility of synchronized sampling has been discussed in the previous section. It should be observed that the key issue is clock synchronization, not synchronized sampling. Indeed, as an alternative to synchronized sampling, synchronized data can be obtained by calculation (either in the device or by software post-processing) using asynchronous samples with accurate time stamps from a synchronized clock.

Local synchronising of sampling vs. system-wide synchronising

When the data acquisition clocks of several units are continuously synchronised in frequency and phase with a common time reference, one can distinguish two situations. In the first case, the common clock is installed in the substation; this local synchronization greatly facilitates the analysis of disturbance records related to the same substation, which is especially important for transient and harmonics analysis and advanced fault location. In the second case, all units (or all substation clocks) are precisely synchronized with a global time reference, like the Global

Positioning System (GPS) of satellites. System-wide synchronization is particularly useful for analyzing complex fault patterns, reclosing and teleprotection.

2.4 Digital disturbance recording

2.4.1 Disturbance recording using digital fault recorders

The digital fault recorder (DFR) is the preferred data source for fault analysis by many utilities, because it is optimised for capturing and handling fault-relevant data and it is fully independent from power system control and protection.

Overview of a DFR

A modern digital fault recorder includes data acquisition, processing, storage and output parts, as shown in Figure 1.

DFRs are usually available in several construction variants. Manufacturers commonly propose modular assemblies of digital acquisition units as well as fast inter-device communication, which allow tailoring the recording system to the application (bay modules, specified number of input channels...).

A common time base allows combining data from different subsystems when evaluating a disturbance.

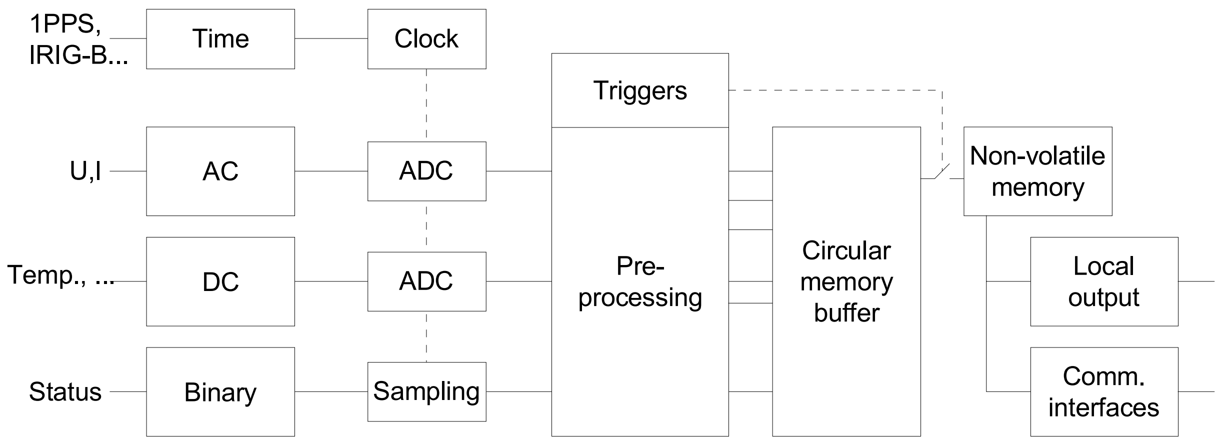

Figure 1: Functional architecture of a multiple-purpose digital recorder.

Basic data acquisition

The analogue input signals, either AC or DC, are first scaled down to low-level signals and band-limited in order to reduce aliasing effects. Sampling and 1-Bit A/D conversion also applies to binary inputs. The input converters are also responsible for galvanic isolation and for the suppression of electromagnetic interference.

In some designs, additional channels are produced by hardware. In this discussion, this feature is considered as being equivalent to a later digital processing.

Different sampling schemes exist. The different channels can either be sampled with the same rate or not; the rate can be fixed or adjusted by a controller; sampling can be synchronous or not, etc.

Note that sampling at a constant rate facilitates most off-line signal processing functions required for fault analysis. However, adapting the sampling rate to the measured power system frequency provides a much better basis for fast and accurate on-line calculation of steady-state quantities like harmonics and other power quality data. Selecting fixed or variable sampling is a hard design decision since it has an impact on the applications.

The A/D conversion may be implemented together with special hardware and signal processing solutions to improve resolution, linearity, time or spectral accuracy (programmable gain, multiple sampling, over sampling, resampling,...), and to provide additional calculated values. The improvements obtained by signal processing should not jeopardize the quality of recording in abnormal conditions of interest; devices may differ considerably as regarding the frequency range or their ability to monitor some types of signals like inter-harmonics.

The most important, from an application point of view, is the measurement range, the output rate and the accuracy (in time and frequency domain) of each measurement channel. The requirements depend on the application, as shown in Table 3, which means that multi-function devices face a difficult measurement challenge.

Feature / Application	Record length	Current dynamic	Acceptable relative error	Bandwidth
Basic fault analysis	Burst (up to 10 seconds)	High (up to 50*In)	from 0.5 to 2%	Nearly DC to 400 Hz
Power quality analysis	Continuous	Low (up to 2*In)	from 0.1 to 0.5%	True DC to 3 kHz
HF transient analysis	Burst (up to a few ms)	High (up to 50*In)	Up to 5%	Up to 1 MHz

Table 3: Comparison of some data acquisition requirements for three different purposes.

Pre-processing functions

Modern digital fault recorders (DFR) generally include on-line signal processing units which can carry out several tasks, including:
- Adaptation of the sampling rate
- Signal corrections, in particular "inverse filters"
- Calculation of "virtual channels" derived from the physical channels (phase-to-phase voltages, frequency, power...)
- Estimation of fundamental-frequency phasors (amplitude and angle) or RMS quantities
- Calculation of power quality variables (harmonics, flicker...)
- Evaluate trigger conditions (see below)
- Generation of events
- Data compression; for instance, transform binary samples into a stream of events.

Triggers

Traditionally, trigger conditions are selected in order to ensure data capture during the full duration of power system faults or disturbances, while keeping the amount of data produced below acceptable limits. Classical triggers include lower and upper thresholds as well as slope (or gradient or dX/dt) triggers. These conditions may apply to samples, to voltage and current magnitudes, or to derived quantities such as power and frequency. The triggering rules can be refined by defining which type of record should be produced (samples, RMS values, power quality variables...) and which channels (or channel groups) the record should contain. This can take the form of a triggering matrix.

The increasing data storage capacity (the cost per Megabyte of hard disk drives is roughly divided by two every year) and the tendency towards automatic data analysis tend to alter the role of the trigger function. The trend is to record more and to post-process the records to filter out what is not relevant. Defining multiple, sensitive triggers and storing detailed records in the devices ensures that nothing important is left unobserved. An off-line analysis can then take place for prioritising the records and/or setting some "markers" which possibly orient the further utilisation of the record better than the trigger reason. This philosophy is particularly promising if a decentralised archival storage is implemented, to avoid uploading an overwhelming amount of data to the evaluation centres. Further improvements of this technology include intelligent triggers and intelligent communication management.

Data storage

A DFR always includes a mass storage unit. The older types use floppy disks; modern types use hard disks or flash memories. The ability to remove and replace a floppy disk or a PCMCIA disk with a fresh one is important when no remote communication with the device is possible.

The use of the available permanent memory may be optimized by appropriate configuration of the device: allocation of data chunks, compression, variable recording length, triggers, record deletion rules... At the end, the mass storage of a pool of DFRs may contain several months of recordings and the disturbance analysis engineer may dispose of a reliable distributed database of disturbance records. It is not compulsory to transmit all data to a central location (one may only transmit the most useful records and look at the others only in special cases) and the reliability of communication and central storage is less critical.

2.4.2 Disturbance recording using digital protection relays

As an alternative to the deployment of DFRs, which are dedicated devices for disturbance recording, some utilities prefer to use the integrated disturbance recording function of digital protection relays (DPR). The comparison between the solutions based on DFRs and DPRs should consider the intrinsic capabilities of the devices, the existing device base, the refurbishment or extension projects and the intended application(s).

Recording capabilities

	Advantages of DPR with respect to DFR	Disadvantages
Recording channels	Reduced configuration effort.	Restricted to basic channels, which are required for protection. Permit only analysis based on information from one bay, not for the whole substation. Scaling cannot be optimized.
Digital data acquisition	Internal information from the protection is recorded.	Although in last years these features have been improved in DPRs, frequently they present slower sampling rate, lower resolution, lower bandwidth. As a consequence many transients cannot be seen/analyzed. Usually, synchronous sampling is not possible, even at substation level.
Data sets	Simplicity.	Less triggering sensitivity; difficulty to capture small transients. Less flexibility. Shorter recordings and smaller storage capacity. Limited history.

Table 4: Comparison of recording capabilities DPRs with respect to DFRs.

DPR-based systems

When a large number of DPRs are installed in the system to be monitored, which is a general trend, the use of the recording function of the DPRs globally reduces investment and wiring costs and may actually provide a very systematic coverage of the power grid. However, one has to check whether the control system provides the required performance and to decide whether it is acceptable to rely on protection devices only for disturbance analysis.

	Advantages of DPR with respect to DFR	Disadvantages
System coverage, cost	Use all available DPRs for disturbance analysis at no extra cost!	
Integration	Possibility to use the control system infrastructure for the transmission of disturbance records.	The integration of many units in the disturbance analysis system may be difficult if no appropriate infrastructure is available. Additional difficulties if the devices are from different manufacturers.
Reliability	DPRs are very reliable because they include self-monitoring functions and because they are monitored by the control system.	In case of relay failure, the required disturbance record is missing too! (Possibly implement recording redundancy)
Cyber security		DPRs require a higher degree of cyber security to avoid settings alteration whilst retrieving records.

Table 5: Advantages and pitfalls of DPR-based systems.

Applications

As far as the monitoring of ordinary short-circuits faults is concerned, digital relays provide very useful records of analogue and binary signals, in spite of their limited data acquisition capabilities. The limitations arise with respect to more advanced applications, including: analysis of system transients (like ferroresonance and transformer transients), low-current faults (especially in case of high-impedance grounding), fault location for parallel lines, study of power swings, power quality analysis...

Emerging DPRs have better triggering rules, a better data acquisition, longer records and even some integrated power quality measurement features, but they are limited by cost and design choices related to their main function, i.e. protection. Meanwhile, DFRs evolve towards multiple-purpose digital recorders. DPRs will thus remain a second choice for disturbance analysis, mainly justified in case a large DPR infrastructure exists.

2.5 Survey of present uses

This chapter shows some learning from survey answers concerning the physical infrastructure that utilities have developed in order to retrieve, store and analyse data for monitoring the electrical network performance.

As it was advanced in the introduction chapter, a survey covering all the aspects of disturbance analysis from the kind of data and devices used to the main final purposes of the analysis, was prepared and delivered by this working group. This survey, whose results and conclusions have been summarized in the appendix, includes in its second part information about recording equipment involved in analysis and installation criteria were inquired (models and types of devices, number of units installed, age, and voltage levels where they are installed).

Recording devices have been classified in the categories listed in table 1. From the survey responses, a population of 30839 device units has been considered, resulting in 44.87% of them being non-digital protection relays (PR), 28.22% being digital protection relays (DPR), 10.44% being remote terminal units (RTU) for SCADA, and 7.83% being digital fault recorders (DFR).

Non-digital protection relays are majority, and only the 28% of the utilities use them for analysis purposes.

Figure 1 presents the percentage of utilities that use each type of device for these purposes. Digital fault recorders (DFR) and digital protection relays (DPR) are the most frequently used devices, used by 84% and 72% of the utilities respectively. Power quality recorders (PQ) are used by the 56% of the utilities.

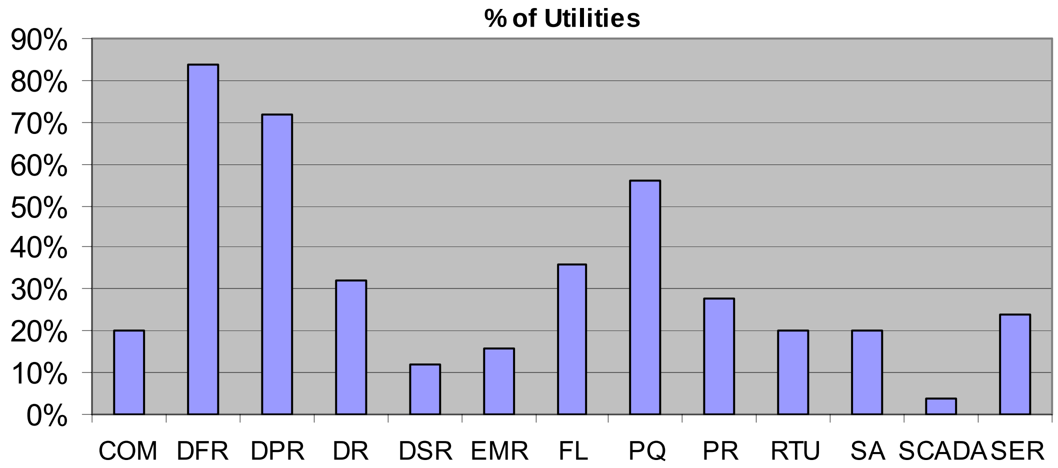

Figure 1: Equipment used for disturbance analysis

Figure 2 presents the mean device-type distribution in a utility. Digital protection relays (DPR) and digital fault recorders (DFR) are, with great difference, the most numerous types of devices, representing 31.87% and 28.64% respectively from the total of devices used by a company.

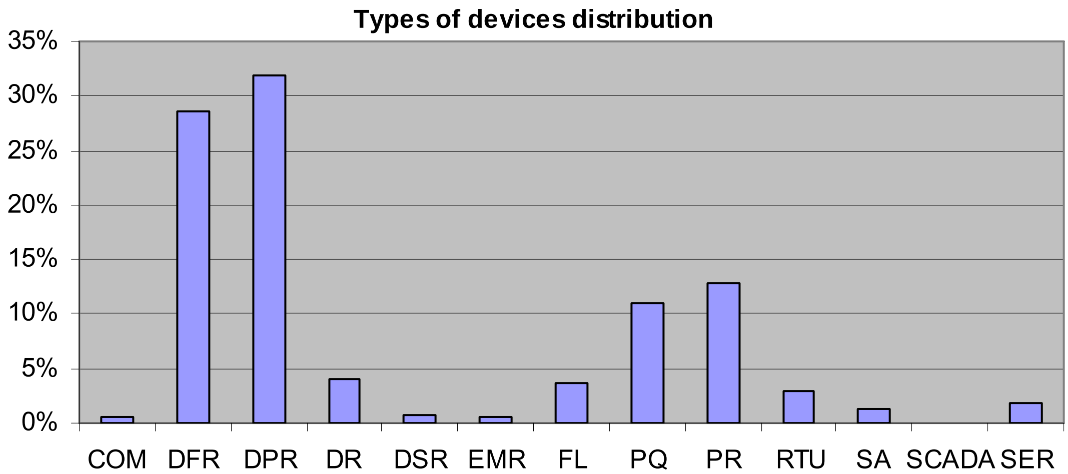

Figure 2: Company recording equipment

It should be mentioned that there is an increasing tendency in the last few years to replace non-digital devices for digital ones and that the tendency to install digital fault recorders (DFR) is stopping due to the availability of the fault-recording feature in digital protection relays (DPR).

Attending to the data used for disturbance analysis, 39% of the devices used record analogue signals (voltages and currents) and 91% of them generate those records being triggered by an event condition, by threshold or slope of the analogue magnitudes. Power quality recorders (PQ) and substation computers are the only devices used to record analogue magnitudes continuously.

With regard to data gathering practises, 33% of the devices that provide data for analysis are remotely accessed from an office far from their locations. 85% of them are accessed automatically and the rest (15%) are accessed by request with human intervention.

Figure 3 provides for each device type the percentage of the installed units accessed remotely. Data from digital fault recorders (DFR) are retrieved remotely by 88% of the companies and by 65% in the case of multi-purpose digital recorders (DR).

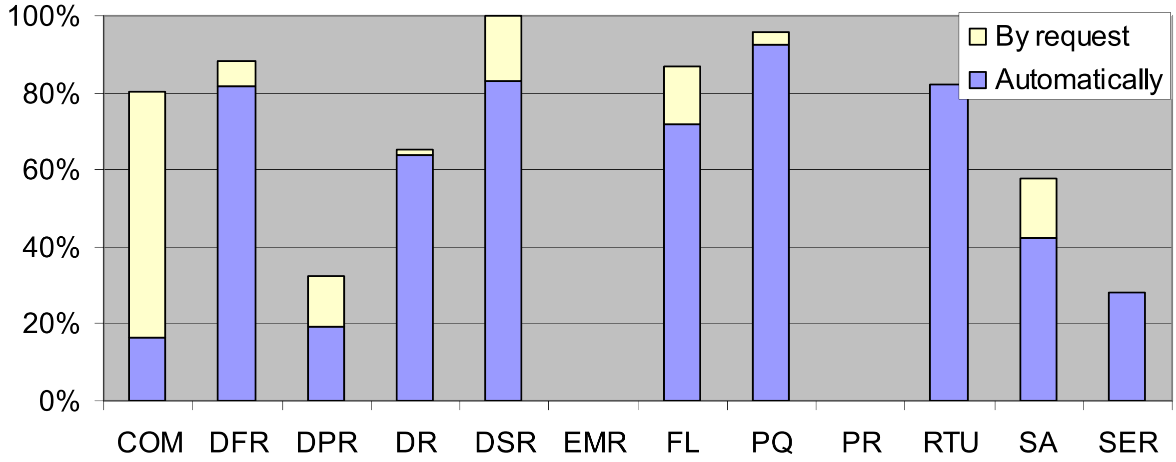

Figure 3: Data retrieval

2.6 Conclusions on recording equipment

Concerning recording infrastructure the following conclusions can be drawn:

- Due to the high number of digital protection relays (DPR) and digital fault recorders (DFR) installed, and their highly improved recording capabilities, these devices are preferred by utilities as data sources for disturbance analysis purposes.
- Obviously, the tendency to replace non-digital devices with digital ones has increased since the seventies and consolidated in nineties. (See figures 11 and 12 in appendix).
- Because of the improvement of the fault-recording feature of DPRs and their capability to record relay internal data, what is an advantage for the analysis of protection behaviour, there is a general tendency to stop installing DFRs and to use records from DPRs instead of those from DFRs.
- Continuous recording of analogue signal is unusual (see figures 14 and 15 in appendix). The triggering mode depends on the application; for power quality or dynamic performance analysis, threshold or rate triggering are common, but for fault analysis, triggering by contact is preferred although usually both modes coexist in order to get recordings in failure trip cases.
- Most of utilities have available the necessary communication infrastructure to retrieve remotely the information recorded by DPRs and DFRs.
- In most of cases, remote data retrieval is made automatically without human intervention.

3 System architecture

3.1 Introduction

Fault and disturbance analysis is generally applied to a whole power system. Thus, a fault and disturbance monitoring system should be considered as a wide-area supervision system, like a network control system or an energy management system. The analysis involves gathering pieces of information from a number of devices or subsystems. For several uses, it is also required that the information is collected and presented in a rather short time, or even be produced, transmitted or stored in a redundant way in order to reduce the risk of data losses.

This chapter examines a few design issues that address these system requirements. The main question is how to construct a technically efficient, yet cost-effective information system for fault and disturbance analysis purposes.

Technical efficiency of a disturbance monitoring system is mainly determined by the following factors:

- Systematic coverage of the monitored elements by digital devices with transient recording capability.
- Fast and reliable communication infrastructure.
- Easy-to-maintain software solution for data transmission, storage and retrieval.

The disturbance monitoring services are not as critical as protection and control. Therefore, cost optimization may be achieved by using shared resources and accepting a few technical compromises:

- Minimum cost of the disturbance recording function, either by using the integrated recorder of digital protection devices, or by optimizing the use of dedicated fault recording channels.
- Introduction of multiple-purpose recording devices, which support several applications (e.g. fault analysis, power quality monitoring and sequence of events recording).
- Use of shared communication resources: telephone network, Intranet, Internet.
- Integration of devices, servers and terminals into existing rooms and cubicles.
- Reduction of the amount of data to be transmitted, stored and managed, and other system simplifications.

Independently of these criteria, the design of optimum system architecture is usually greatly influenced by legacy systems. Often, two generations (or more) of communication and recording systems must be supported for a longer time. Physical and functional integration is a challenge and an incentive to a higher degree of standardization in this field.

3.2 Communication architecture

3.2.1 Overall structure

Power automation equipment is typically organised according to a multi-layer architecture. The main layers are

- the field (or bay) level
- the station level
- the network control level.

The control level may be split into further divisions if data gathering require additional steps (e.g. at regional level) or if different centres exist e.g. for power system control and fault analysis.

Process-oriented communication typically has a pyramid-like structure, although dedicated horizontal communication may additionally take place at the various levels.

Given the increasing importance of efficiently presenting the information to the end users, it is defined the "office level" where horizontal communication with client computers and various services (like E-mail) takes place. In a modern, internet worked utility, the network control centre is just one cluster of dedicated computers among many other networked services, and the relevant technical functions are integrated within the general information-processing framework.

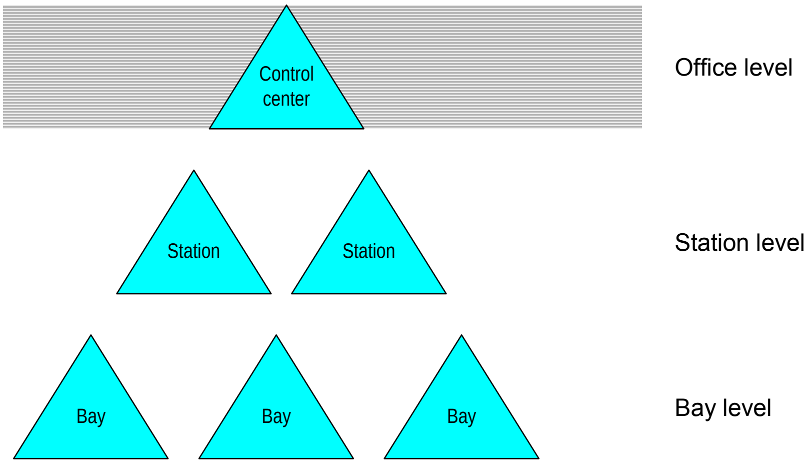

Figure 2: Multiple-layer system architecture.

Within this three-layer framework, a power system disturbance monitoring system requires three types of units or nodes:

- Data recording nodes (devices).
- Data processing nodes (process computers, data concentrators, servers…).
- Data evaluation nodes (client computers or terminals).

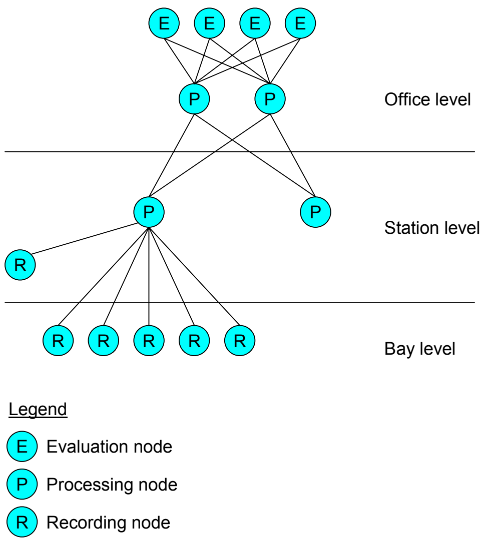

Figure 3: A disturbance monitoring system involves several types of "nodes".

The links deserve as much consideration as the nodes themselves, because one generally faces several technical constraints, including:

- available bandwidth
- communication protocol(s) and their degree of openness
- possibility of calling/notification upon inception of a new event
- peer-to-peer versus client/server structure

3.2.2 Implementation

The general architecture presented here above leaves room for many variants, which represent compromises between cost and efficiency, or between backward compatibility with legacy solutions and new solutions.

As far as the overall architecture is concerned, the variants will essentially differ regarding the following criteria.

Available communication infrastructure and interfaces

Traditional communication infrastructure of power utilities include a variety of solutions involving dedicated point-to-point links of various technologies and devices like star couplers, protocol converters and multiplexers [5].

The modern solution consists of building up a TCP/IP network, which offers a common protocol system-wide regardless of the physical links. Such networks are very flexible and may even accommodate for mobile users and wireless access points. IP-based computer networks are rapidly being deployed down to the station level [6].

The cost factor is a major limitation in medium voltage substations, where it is hard to dispose of anything else than a telephone line, which eventually may even need to be shared. Easy and fast communication with digital protection devices is the main prerequisite for effective disturbance analysis at lower voltage levels. This is only becoming possible with devices of the last generation.

Entry point at the station level

The data may be collected by direct polling of one or several recording devices, or through a data concentrator, or through the control system. There may be several entry points, depending on the devices installed. If the protocols are not compatible, and if no protocol-converters are available, then it may even be necessary to build up separate data gathering systems. The investment and operating costs are high, especially if different communication media are needed.

Number and type of processing nodes

System performance may be dramatically increased by two means: either by using a fast communication network (transfer from the stations to the monitoring centre through a high-speed backbone) or by distributing computational intelligence at the station level. System throughput and responsiveness can also be improved by increasing the number of central processing servers or by introducing an intermediate ("regional") processing level.

Degree of automatic centralization

Due to technical and economical reasons, some of the data that are required for a thorough fault analysis may not be collected at a central location – at least not automatically. Old paper recorders have virtually disappeared, but often utilities still need to record relay targets manually and gather some disturbance records by manual transfer via floppy disks, compact disks or memory cards. It is also very common that the disturbance records from protection devices are only collected at the station level by the local control system. Such legacy situations are evident hurdles to efficient analysis of power system faults.

Redundancy

When disturbance-related data is used by dispatchers or when multiple user groups need the data, reliability of the monitoring system becomes an important issue. It can be increased by implementing redundant communication ways and by duplicating the mass storage. Optimally, redundancy should start as early as possible (e.g. by communicating with a recording device across two distinct physical interfaces) and end at the user's computer (separate access to the main system and to the redundant system). It must be implemented in a consistent way, avoiding possible sources of common-mode failures: use of separate communication ways (WAN versus telephone), independent power supplies, physically separated facilities.

Type of evaluation nodes

It can be distinguished between conventional solutions, where dedicated software is needed for evaluating the disturbance-related data on a computer, and web-oriented solutions that use HTTP and other protocols from the Internet world for bringing the information to the personal computer of the end user.

3.2.3 Comparison with other data gathering systems

As indicated before, a fault and disturbance analysis system has several features which are common to other systems which need (or benefit from) data centralization. Such systems can be compared from the point of view of their communication requirements.

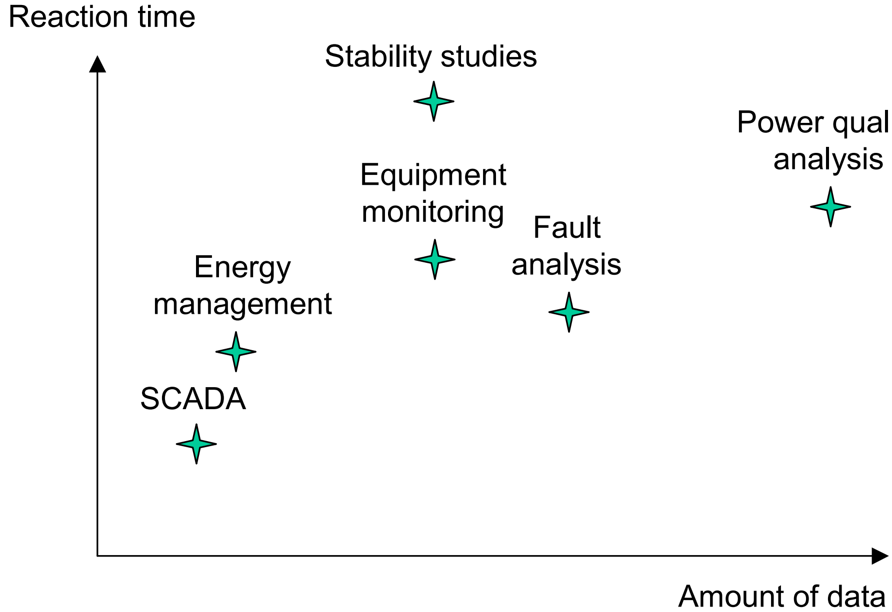

Figure 4: Technical requirements of various applications that need data centralization.

At one end of the application spectrum, Supervisory Control and Data Acquisition (SCADA) systems use a limited amount of data (coming in little chunks) but require a relatively short response time. The communication tends to be organized hierarchically and needs permanent data links with a moderate bandwidth. At the other end, the analysis of power quality is based upon huge volumes of data, covering various time spans (typically from one day up to one year). Communication and data processing tends to be organized as batch jobs, but a high average data throughput is needed if it is required to centralize all the data (which is not necessarily a good choice). Fault analysis and the related field of equipment monitoring stay at an intermediate position. The analysis of large disturbances requires a relatively high amount of data but response times ranging from minutes to hours are acceptable, since these functions are not as critical as SCADA and should actually complement and back up ordinary SCADA functions.

A fault analysis system may be technically coupled with another system either when the end users are the same, or when the same devices, communication channels or processing architectures are used. In particular:

- The fields of fault analysis and stability analysis are related because the same records may be used.
- The fields of fault analysis and equipment monitoring may be combined if the users consider fault analysis primarily as a means of verifying equipment performance.
- Fault analysis and power quality monitoring are related and complementary, since one focuses on the causes and the other on the consequences of power system disturbances. They may even use the same devices.

3.2.4 Existing communication standards

Due to their functional importance and to reliability concerns, digital protection relays and bay controllers have historically been developed within closed systems with limited internal and external communication capabilities.

This has led to the proliferation of proprietary communication protocols, interface designs, data representations etc. Many vendors have developed their own protocols to increase the interoperability within their proprietary product range. Some have captured more or less success in other industries (Modbus of Modicon, Profibus of Siemens, Fast Meter of SEL…).

From the physical point of view, these protocols can run across various types of links: serial, Ethernet or other specific hardware. Depending on the available links and protocols, two architectures may be implemented: a bus structure (or multidrop network) or a star network. In case of a bus, the implementation may ask for a bus arbitration (like with Profibus) or provide for collision recovery (Ethernet).

Device integration faces some considerable hurdles, which are typical of information technology:

- For every layer of the OSI communication model, several applicable standards may exist. A communication solution is defined by the combination of the choices made for each layer, which accounts for a huge number of technical possibilities.
- The definition of the high-level protocols is necessarily application-related, i.e. non-standard. Protocols are first developed by a small technical group and for a limited (specific) set of services (example: SCADA functions). This naturally causes the appearance of many concurrent solutions, which will eventually compete for founding a general standard.
- The definition of standards for the higher OSI levels requires considerable effort and co-ordination (e.g. within international committees). Not all users push for the development of such standards and not all manufacturers are enthusiastic since they generally have to adapt their systems.

Originally, power system control, protection and measurement have been three independent fields of activity. In each field, devices, data links and protocols have been defined without caring too much about future compatibility issues.

In the 1980s, there has been a pressure from the utilities to achieve certain compatibility for operating digital devices of the same type but different manufacturers (excluding configuration). In the 1990s, this requirement has extended to the search of common protocols for protection and control.

Due to the pressure to attain interoperability, in order to avoid repeated huge costs by refurbishment and to facilitate system operation, much of the standardization effort in the field of power automation has been devoted to integrating the devices at the substation level.

Two main standards for transmission of commands, messages, on-line measurements or disturbance records emerged form early standardization work, under the direction of leading relay manufacturers, for the sake of: inter-operability, availability of the communication, security and speed. IEC 60870-5 is used mainly in Europe and Asia, and DNP 3.0 in the ANSI world.

For instance, the information exchange interface IEC 60870-5-103 for protection relays (60870-5-101 is for SCADA, 60870-5-102 for metering) has been used successfully for integrating digital relays from various manufacturers into a common fault analysis system, with a focus on disturbance records and event-related messages.

Are these protocols suitable for the transmission of large data sets such as those coming out of digital fault recorders? Serial transfer of disturbance records from protection relays works fine with IEC 60870-5-103, but is one order of magnitude slower for DFRs. DNP3.0 provides some capability for file transfer but it is not generally implemented.

Another major limitation of the existing protocols is their limited support of power quality measurement (or new data types in general) and their lack of flexibility regarding the control of the communication channel. For instance, IEC 60870-5-103 only works in polling mode.

3.2.5 Emerging standards

Differentiating itself from the definition of first-generation communication protocols, the work of EPRI in the Utility Communication Architecture (UCA) covers the aspects of direct interoperability from devices to devices.

Work at the IEC also took new directions towards the definition of wider communication standard, inspired from IEC 60870-5, UCA and IEC 60870-6 (Tase.2). The emerging standard IEC 61850 [7], which is going to be officially released soon, goes beyond ensuring device interoperability for protection and control functions [8]. It also aims to support all power automation functions, to provide high configuration flexibility by supporting either centralized or decentralized location of functions, to ensure long-term stability by decoupling the physical implementations from the underlying data model, and achieve global recognition, breaking the barrier between the IEC world and the ANSI world.

IEC 61850 offers very promising perspectives for integrating fault and disturbance systems within a global communication framework. In particular, it may finally allow the use of all available disturbance-related data, provide flexibility regarding centralized vs. decentralized data processing, and help saving engineering costs such as those required to describe substation equipment. Some benefits obtained with the standard are [9]:

- Open power-market and international activities – The standard promises essential data necessary for secure operation of the grid, low maintenance costs over the life-cycle, worldwide substation applications.
- Specification – Reduce ambiguity and misinterpretation of technical specifications for automation systems.
- Design – Standardised data models can be carried forward directly into the design stage. Thus, saves time, enhance clearness and reduce the costs.
- Manufacturing – Due to the system configuration language, the configuration task is easier, becoming automated.
- Installation and commissioning – It is easier.

- Operation and maintenance – It is easier due to user friendly navigation and remote operations possibilities for fine turning of device settings, retrieving data and device interrogation.

Yet, IEC 61850 may not fully cover the needs for transmission from substations to control centres, at least in its first phase. Other emerging standards which need to be mentioned in the context of utility control systems are IEC 61970 (Energy Management System Application Interface – EMS-API) and IEC 61968 (System Interfaces for Distribution Management), extending the same information model (CIM, Common Information Model). These standards are helpful to bring the data from substations to control centres. Unfortunately, CIM and IEC 61850 evolved quite independently and some work is required for unification [10].

Although the work on these emerging standards is still in progress, parts of it have been adopted and implemented by system vendors and, more importantly, utilities require conformance to them in their current invitation for tenders.

3.3 Integration and data management

A utility typically uses between 100 and 800 devices (of all types), which may produce a wealth of data, especially during a disturbance.

For system-wide fault and disturbance analysis, it is desirable to integrate data sources of different types, and generally of different manufacturers, within a common architecture.

The integration requirement is twofold:
- Device integration: ensure that the installed devices or subsystems (e.g. a substation control system) can be interfaced by the software, which implies physical and logical addressing and support of the required protocols.
- Functional integration: ensure that the various pieces of equipment produce similar data, complying with some common rules about format and contents, so the data can be processed on a unified basis. Implement processing functions at the desired level (station, regional, or central).

At the end, it should be possible to use master data analysis software for evaluating all-important data from the system.

Some common problems and a few techniques used to achieve integration of disturbance data are discussed in the following chapters.

3.3.1 Data types

As discussed in chapter 1, Intelligent Electronic Devices (IED) such as digital fault recorders (DFR) and digital protection relays (DPR) are connected to the power system through analogue and digital inputs. The analogue inputs are mainly used for measuring voltage and current signals from the secondary of voltage and current transformers. The digital inputs collect status information from DC wet contacts of circuit breakers, communication equipment, auxiliary relays etc. The IED perform local processing of the measured signals and produce their own original information. Both measured and computed data can be stored or buffered (the most of digital IEDs have built-in recording functions) and communicated to human operators or to other devices and systems.

These data are used to protect, control and monitor the different devices of the power system. From this point of view, the collected data could be classified in protection data, control data and monitoring data.

Protection data are those data that enable protection devices (DPRs) to operate according to certain algorithms. The data include currents, voltages and discrete digital inputs. The source of protection data may be local from CTs, VTs, and primary apparatus or remote such as data for communication schemes. Local data are used to make a certain protection decision while remote data are computed by another DPR and communicated to the relay for protection decision.

Control data are mainly the results of operator-initiated functions that perform control actions. The result is a change of state of relay contact outputs. The initiation command could be local or remote. One typical example is the change of a parameter set (settings group) to match a change of power system conditions. Another example is manual circuit breaker close command conditioned by a synchronism-check relay.

Monitoring data are any data types within the DPR or DFR used locally on the human-machine interface or communicated to a remote control centre for supervision purposes. These data, that enhance power system supervision, are mainly additional inputs to the DPRs and can be analogue, digital or calculated data. Examples of such data are the position of the transformer load-tap changers, the status of circuit-breaker motor driven mechanism, the transformer fan and pump status, and the insulating oil dissolved gas monitor status.

Calculated analogue data that give a snapshot of the power system status are usually referred to as ***metering data***. Such calculations include filtering, scaling, and integration over time; and they are mainly used for control and monitoring purposes. From this point of view, these data are considered as monitoring data.

Other data or information processed inside the DPR like total circuit breaker number of operations, circuit breaker interrupted current, results of internal self-test procedures, current transformer and voltage transformer supervision, used as diagnostic data are considered as monitoring data, too.

DPRs store data about power system over time or to a certain event. Collections of system profiles, event reports, sequential event recordings, power quality reports and protection quality reports stored by the DPRs are also included in monitoring data.

Environment data such as lightning strikes, weather and seismic activity, can greatly facilitate a comprehensive fault analysis. These data do not originate from power automation devices, but they may be provided automatically and integrated into a fault and disturbance monitoring system. The main use is to perform time correlation with power system events in order to determine whether a fault has originally been caused by environmental disturbances, and to infer whether further system faults can be expected, like when a thunderstorm moves across an area. Although this issue mainly concerns system operation, environmental information should obviously be recorded in order to be processed at later stages of analysis, including for fault statistics.

Given this wealth of data of different types, the question from a disturbance analysis perspective is to determine what fits into a global recording scheme. A discussion about the data requirements of various applications can be found in [11]. In the following, we shall focus on integration-related issues.

3.3.2 Logical data structure

Depending on the device type, the communication possibilities and the data type, data may be logically structured in different ways:

- Finite data sets of measured (or computed) analogue and binary quantities, or *records*. A record usually includes a time stamp, duration and several recording channels of various types (sampled voltage, apparent power, frequency, etc.). It is necessary to distinguish:

  - *Disturbance records*, which are related to a precise event that caused the recording function to trigger. Among the disturbance records, one can further distinguish between sampled data and computed data (like active power). The distinction is less relevant since multifunctional digital recorders have come to the market, but it is important to know whether high-resolution samples of the most important voltages, currents and binaries are available.
  - *Continuous records*, which are arbitrary chunks of continuous data streams – like a frequency record over one week. The most of power quality data and of the outputs of swing recorders fall into this category.
- Online process variables, like measurements, equipment status or counters. A time stamp is generally added by the processing node, if not by the source device itself. Process variables can be transmitted and even recorded, but have a limited useful lifetime by themselves.
- Messages and alarms, including SCADA commands.
- Message lists and logbooks.
- Summary reports (event summary, power quality report) and similar high-level processed data.

It is important to recognize that the integration of all disturbance-related data within a common scheme is a considerable task, due to differences in data structure and corresponding interface problems. Therefore, most data streams generally continue to be processed separately according to the traditional barriers between manufacturers or between protection, control and monitoring.

3.3.3 Data integration using file standards

When field data are available as data sets – such as disturbance records – it is possible to solve the integration issue by converting the data sets produced by different systems to a common data standard, prior to their final use for fault and disturbance analysis. With this solution, it is possible to use separate software and communication architectures (of different manufacturers, different technological generations and different domains, e.g. disturbance recording and protection) and still operate high-level evaluation tools on a common basis. This is what most utilities used to implement before the existence of any common standard, pushing the manufacturers to propose documented output interfaces for the data sets of interest.

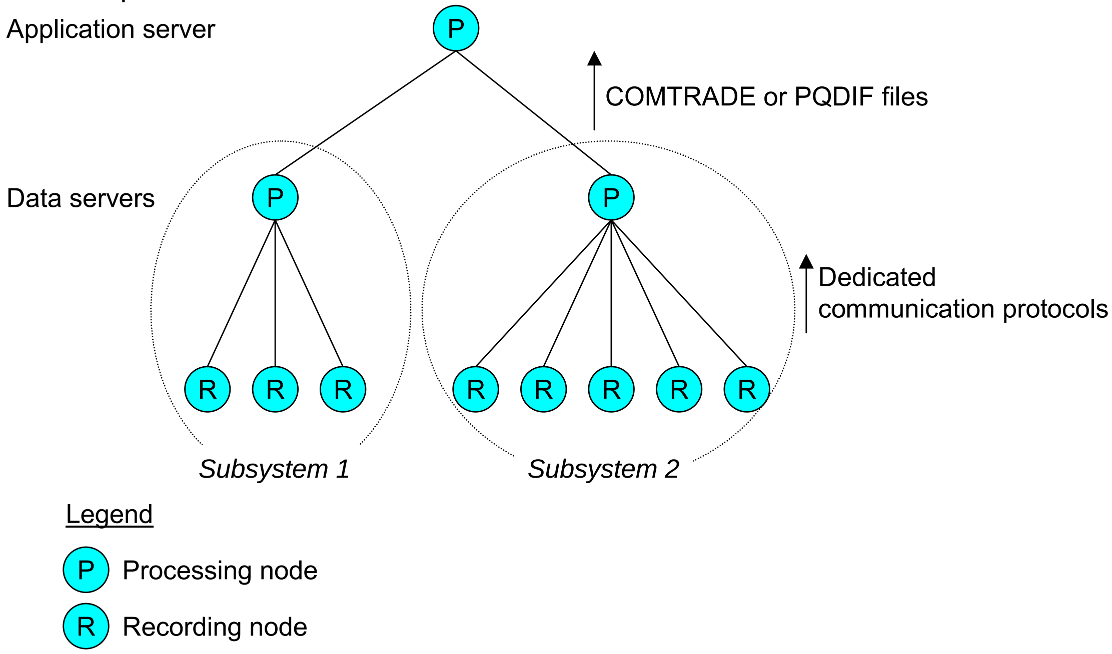

Figure 5: Use of standardized file formats for integrating disturbance data originating from different subsystems.

File formats

The IEEE common file format for transmission of disturbance records (COMTRADE) of 1991 [12] was the much-needed standard which opened the way to compatible software solutions. COMTRADE viewers and tools are available from a number of sources (manufacturers, universities, software companies). COMTRADE is refined periodically by the IEEE in order to overcome its limitations. It evolved into an IEC Standard [13].

COMTRADE files can grow very big – even in the binary version of the data file – because no compression algorithms are included in the standard. This may restrict their use in some cases.

COMTRADE files cannot carry semantic information about the data source. File naming conventions for time sequence data, which facilitate the precise identification of a record among a huge number of files, have been proposed by the IEEE [14]. Yet, a COMTRADE file does not explicitly indicate to which physical signals the data channels are related. This is because the use of the (optional) header file is not standardized yet. Consequently, the application that reads and processes a COMTRADE record may need to refer to an independent catalogue of device and power system data.

PQDIF is a recommended practice for the transfer of power quality data [15]. It is mainly used to exchange complex PQ data – together with a possibly accurate description of the measurement method – between a data server and application-specific software.

Online data are not standardized as such, but together with communication protocols. The IEEE standard for synchrophasors and the IEC 60970 standard for energy management are applicable to the respective applications.

Logbooks and reports are not standardized but the variety of file formats used tends to decrease. The most common formats are ASCII for non-formatted documents like sequence of events logs, HTML and PDF for formatted documents. These formats are independent of the computer platform. In new applications, the XML format is also used extensively.

Technical integration

Several techniques can be used to transfer automatically files from one application or subsystem to another. For instance, the File Transfer Protocol (FTP) can be used.
Besides the choice of a protocol, data integration faces several technical hurdles, including:

- Different organizations of the data files (naming conventions, subdirectories).
- Little differences in use of the file formats.
- Data management: indexing, concurrent access, buffering, cleaning.

At the time being, the possibilities of data integration without the support of a communication standard are limited and they require custom adaptations and a careful verification of the compatibility, case by case.

3.3.4 Integration of non-digital data

Traditionally, fault analysis is a manual process which takes into account field measurements (on paper, tape etc.) as well as information from dispatchers, maintenance and repair crews, and customers. This heterogeneous information is not well suited for automatic analysis. Although paper plots can be scanned for electronic archival, it is generally not possible for analysis programs to correctly decode the information contents from such data.
Therefore, modern fault management systems are based on digital measurements, yet complemented by some essential manual input like comments about the disturbances. Integration of non-digital data in the systems makes sense in the following cases.

Non-digital devices

Some useful sources of information may be non-digital devices without a digital communication link. This is the case, in particular, for electromechanical and static relays, special fault detectors or directional units.

These devices can usually communicate their status by relay contacts. If the corresponding information is important for fault and disturbance analysis, it is desirable to capture the binary signals with a DFR or a SER for further processing.

The alternative, which is still common practice for many utilities, is to record the relay targets manually and to centralize manufactured reports from different stations. This process is acceptable as long as a fast fault analysis can be made by other ways. Then, the protection staff will examine the reaction of the protection devices in a second stage of analysis.

Manual input

Other interesting non-digital data include customer calls reporting on power outages or apparent damage to the power system, manual observations from operators and maintenance staff (e.g. about true fault location), etc. Many utilities record such inputs into an outage management database, which is used to support all activities related to power system disturbances. Then, a link between such digitized data and the power automation data can be made.

3.3.5 Synchronisation of data sets

The ideal situation when analysing field data would be to dispose of a complete picture of the power system with no measurement errors.

This would require collecting records from all data sources of interest – possibly from different locations – and bringing them to a common time frame. The common synchronisation methods are:

- Method 1: to use the time stamps of the data sets
- Method 2: to synchronise upon common events (changes of analogue data or binary signals)
- Method 3: to use voltage and current phasors and a model of the power system

These three methods are useful, respectively, for three successive steps in the data synchronisation process:

- Pre-synchronisation or record grouping: determine which records (or sections) pertain to the same power system event
- Coarse synchronisation: position the data sets in time with a relative accuracy comprised between the slowest sampling rate and about 2 ms
- Fine synchronisation: attain an accuracy comparable to the original measurements (less than 4° error i.e. about 0.2 ms) over the whole duration of the records

In the future, accurate data synchronisation may be available as a standard, and completely based on accurate device synchronisation, e.g. using GPS. For the time being, accurate device synchronization is not available for most devices. Moreover, first-generation implementations of the synchronization disregard system requirements and exhibit the following weaknesses:

- When a time tag is associated to the data, it generally comes without any formal reference to a time referential and without any indication of the accuracy. This is acceptable only if the clock of the device, which produced the record, is a valid time frame for all data of interest and if timing errors e.g. due to clock drift can be neglected. Problems may arise if mixed synchronization solutions are used.

- When a device clock is synchronised to an external time source, it is often not known when the synchronisation takes place. In the worst case, the clock may run free for a long time before the contact with the time source is re-established. Therefore, the effective accuracy of synchronisation is poorly known. Later data synchronisation on system level may provide unreliable results.

A fully hardware-based synchronisation is desirable because the other methods have limitations that are less easy to overcome:

- Method 2 based on analogue signal transitions requires a correct pre-synchronisation and its accuracy is limited by the sampling rates.
- Method 2 using logical signals faces the additional problem of unknown delays for signal generation (contacts), propagation, and sensing (e.g. optical couplers).
- Methods of the third type using a power system model (e.g. a line model) are complicated and need accurate models and many parameters.

3.3.6 Data organization

Not surprisingly, the integration of disturbance-related data in a heterogeneous environment face many practical problems related to different technical or operational conventions.

System modelling

Most advanced processing functions, like fault location or the analysis of voltage sags, will need to know the relationship between measured signals and the primary system, as well as some data about the primary equipment. Compiling a complete, exact and up-to-date information basis containing these data may be difficult. A reference model needs to be built and the maintenance of this model is possible only if consistency rules are enforced when configuring the different parts of the system. Generally, it is attempted to share the power system database among several applications.

Naming

Devices, but also feeders, transformers, stations, lines, etc. should be given unique names within the scope of disturbance analysis. Furthermore, details of naming convention, like identifier lengths, case, character sets and use of special characters (like "/", "$" and ",") may seriously complicate the automation of data gathering and storage process.

Scaling

Some systems may deliver secondary-side values, other primary quantities.

Percentage or per unit values are also used and they can be tricky if the definitions of base values are not consistent, which may be the case if disturbance monitoring extends beyond the assets of a single utility, or if nominal values of primary equipment are used instead of system-wide base values.

The recommended practice is to try to convert all quantities into primary values before storing or using them. Some quantities are not very understandable when given in primary values, like a field current. In this case, percentage or per unit values with an explicit reference to the base value are generally appropriate.

Identification of the phases

The identification of the three phases is often not consistent between one station and the other. This does not play a significant role until data grouping and system-wide analysis is demanded. Phases may also be labelled differently (A-B-C or L1-L2-L3 or R-S-T).

The recommended practice is to use unique labelling and to define the phase shift (in hours or degrees) with respect to a common reference in order to consider transformer shifts.

Polarity

Common definitions for a "positive" phase current or ground current are needed. Since the polarity may vary from one relay manufacturer to the other, and even between product ranges of the same manufacturer, it is often necessary to correct the signals when integrating them into the same processing or evaluation framework.

3.3.7 Data processing architecture

The main automatic data processing functions of a fault and disturbance analysis system can be classified as follows:

- Data transmission with a device or importing from a data source.
- Data enhancement, like synchronizing, rescaling, renaming etc.
- Data conversion, including reformatting, splitting, merging.
- Calculation of derived quantities, like power, frequency, average values etc.
- Analysis of the measured data, including weighting, fault location, reporting etc.
- Data storage and buffering.
- Data distribution, publishing or forwarding from one node to other nodes.

A software suite will also include a few dedicated tools, like

- Device configuration (e.g. for DFRs).
- System configuration: definition of stations, lines etc.
- Data evaluation, including graphical display.

As far as system design is concerned, the software components can thus be sorted into "server" (or processing) functions, "client" (or evaluation) functions and administration tools. The following discussion is focused on server functions.

In the simplest form, all processing functions can be implemented on a central processing node, which is assumed to dispose of communication links to devices, subsystems or data servers. The node can be duplicated for safety reasons, or there may be several main nodes at regional level, without any further centralization.

The single-server (or isolated server) solution has some intrinsic limitations regarding response time, data throughput and dependability. It is most appropriate for a limited number of devices and is generally not capable of handling major disturbances.

To overcome these limitations, without changing anything to the existing data sources, one can use the following techniques:

- Multilevel processing: introduce distributed processing nodes that carry out a part of the task, usually restricted to a region, to a station, or to any other subset of devices. The efficiency of this solution is optimum when the distributed nodes can offer local evaluation services and when they can filter or prioritize the data that they forward to other processing nodes [16].
- Clustering: several processing nodes carry out the server function altogether, with the possibility that some of the processing nodes fail and their functions are taken over by the other nodes.

3.4 Case studies

In spite of the high diversity of infrastructure and operating practices worldwide, it is possible to discuss a few possible implementations that illustrate the data integration and system architecture issues.

Disturbance monitoring with the control system

The inception of severe power system disturbances is usually recognized by detecting protection-induced tripping in the system. The control system is designed to transmit and present all relevant signals in the appropriate form (alarms…). It may be operated either locally or centrally, depending on the degree of power automation. Most modern control systems offer the possibility to view disturbance records produced by digital protection devices and to scrutinize event logs, using appropriate filters. The combination of these two types of information is normally sufficient for understanding high current short-circuit events.

Download of disturbance records from digital protection relays

When digital protection devices have been introduced without a simultaneous modernization of the control system, or if no digital control system is available, there is still a possibility of downloading disturbance records through a free serial link of a digital protection device. The first possibility is to fetch the disturbance records through modem links. The second possibility, which is faster and easier, involves gathering the disturbance records locally, on a data concentrator, which can typically call a central processing server and send all new data.

Centralization of disturbance recorder data

Digital fault recorders (DFRs) and multiple-purpose digital recorders (DRs) are optimized for fault analysis. Therefore, they usually support fast communication with a central processing server through analogue telephone (with data compression), ISDN or TCP/IP. By using dedicated software provided by the manufacturer of the DFR or DR, an independent disturbance monitoring system can be built up easily. It is important to be able to gather all significant data from the most important substations.

Beyond these three cases, which have been isolated in order to distinguish the main alternatives, every utility is facing different constraints, different integration options and, of course, different priorities regarding the applications. There cannot be a prescribed solution, and every disturbance monitoring system will require a good deal of engineering.

3.5 Enterprise integration

A fault and disturbance monitoring system as a whole can be considered as one among many information systems of a utility (or it can be a shared resource for a bundle of utilities).

The monitoring system naturally tends to be open and to share resources with other applications:

- It uses digital devices that serve other purposes.
- It may share communication links and computing infrastructure with other applications.
- It uses catalogues of data (like station lists) which are of general interest.
- It produces only a part of the information needed for processing disturbance events, thus it could or should be coupled with operation and maintenance.
- It produces data that are useful for disturbance statistics.
- It provides information about power system quality.

At its upper level, disturbance monitoring produces very interesting "first-hand" technical information about the power system. It may also produce usable data for management-related applications. Potentially, many users may be interested in this information, eventually according to their specific view and requirements (consolidated reports, alarms...).

Of course, one must be aware of the limits. In particular:
- Depending on the number of devices used, their type and locations, the data coverage of the system may not be balanced and hence produce biased overviews.
- Distinctions should be made according to the quality of information: raw data versus processed data, automatic processing versus manual input, not validated versus validated information, ongoing work versus classified cases.

Technically speaking, it makes sense and it is not overwhelmingly difficult to integrate a disturbance monitoring system into the enterprise information system. The difficulty rises from the need to coordinate different groups of people and to obtain the co-operation and commitment of the key players in different departments like operation, maintenance, communications, information systems...

3.6 Conclusions on system architecture

Fault and disturbance analysis is a broad discipline that is very demanding of process data of different kinds, therefore, to get technical efficiency is necessary to have a system that provides centralized gathering, analysis and evaluation of disturbance records, and supported on a fast and reliable communication infrastructure. System solutions provided by a unique manufacturer are available, but to build a comprehensive system is more difficult. In order to ensure a satisfactory performance, the design must carefully consider all constraints that will come mainly from the legacy systems, the available communication infrastructure, the scale of the grid and the variety of devices and sources of information.

At designing its communication architecture, decisions about the following features of the system must be taken: number of layers (bay, station, regional control centre, global control centre,…), number, type and location of nodes, technical features of the links available among nodes, degree of automatic centralization and redundancy degree.

Although most data streams generally continue to be processed separately according to the traditional barriers between manufacturers or between protection, control and monitoring, some systems have been successfully developed by using standardized communication protocols (like IEC 60870-5-103) or file formats (like COMTRADE). Progress in the field of communication standardization suggests that integrating more data from different available data sources may become possible with a reasonable engineering effort, at least with new processing systems and data gateways. Data should ideally be collected automatically and should be available in a reasonably short time and with a good reliability.

However, communication standards do not solve all problems related to data integration. Data from non-digital devices and manual inputs must be integrated also. Precise system-wide timing is desirable too in order to get synchronized data. Disturbance analysis also benefits from a consistent information basis regarding equipment identification, recording channels identification,… When more automation is required, information management must be improved accordingly.

4 Applications

4.1 Introduction

The system architecture with its communication structure and data management should serve applications. The existing analysis practices are various, in time frame and users. This chapter, based on the survey, gives an overview of the main applications.

Fault analysis generally requires gathering the disturbance-related data (digital or paper recordings, targets, SER data, human reports) at a regional or central analysis centre. Since this process is greatly facilitated by digital technology, it is essential to consider the existing digital fault-recording infrastructure, in particular recording devices and communication links. The most widespread legacy solutions are the Digital protection relays (DPRs) and the Digital fault recorders (DFRs).

After concentrating disturbance-related data, several kinds of analyses are possible. Beyond the traditional task of understanding the causes of every power system fault, fault and disturbance analysis is progressively being connected with other disciplines in order to address the expanding requirements of modern utilities. As shown in Figure 1, the disturbance itself is no longer the only centre of interest.

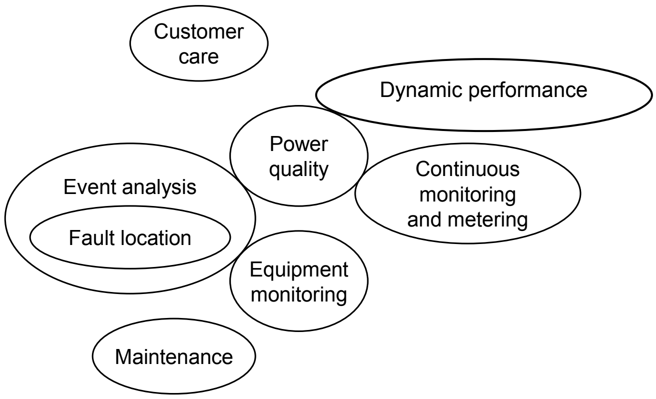

Figure 1. Present uses of the fault and disturbance analysis

4.2 Protection and control uses

Fault data are mainly used to determine the cause of disturbances. Special interest is given to the fault location either to know where to repair or to determine if the fault occurred in a customer plant or in external network. Recording devices help to determine the sequence of events and to analyse the current levels and duration. The study of the network equipment performance is very important and most of the observed devices are protection relays and circuit breakers, which are exposed to a high level of stress conditions. Reliability of fault clearing and operating time are generally considered.

Usually, protection engineers analyse fault data and send their conclusions to the maintenance staff if repair is necessary or to dispatching engineers in order to minimise fault effects in the future. As far as possible, all available data are used for fault analysis. In most cases, the observed signals are voltages, currents and frequency.

Depending on the goal and on operational requirements, the processing of fault and disturbance data may take place in different periods. The applications are classified according to this criterion:

- **Short-term use** of fault and disturbance data. The short-term applications are motivated by the urgent requirement of reducing the duration and the consequences of an outage.
- **Medium-term use.** The applications listed in this category are related to processes or procedures that are less time-critical, yet require a manual decision or intervention in a reasonable time (within a couple of hours or days). The general concern is quality: investigating or solving a recognised problem that indicates poor system performance may help to avoid future outages or damage.
- **Long-term use.** This class of applications is concerned with the knowledge and the documentation of power system behaviour, as well as with the education and training of the personal dealing with technical and economical optimisation.

4.2.1 Short-term

Automatic data analysis may be applied to derive alarms from protection, control or monitoring data. An application based on automatic alarm processing continuously observes the flow of protection, control and monitoring messages and derives additional messages or alarms based on pre-defined rules and thresholds. The weaknesses of alarm processing are that it only considers logical data and that all data must be sorted chronologically, i.e. marked with accurate time stamps.

However, the great strength of alarm processing, when it is integrated in a control system, is that any new function can benefit of available, general-purpose data processing architecture (system-wide data gathering, message transmission, organisation and storage, functional building blocks, computer terminals). Ideally, the effort needed to detect a particular logical condition is limited to include a corresponding detector at the suitable location in the message processing chain.

The most interesting application in the field of alarm processing is the determination of equipment failures either to assist system restoration or to orient post mortem repair and maintenance tasks.

In the simplest form, one could post an alarm if a particular logical combination is observed, e.g. when more than two lines have been tripped in the same substation. The recognition of such disturbance patterns may usefully complement the existing rule set of the control system. It is a kind of careful customisation.

The focus on failure detection gets sharper with time analysis. One can measure a variety of delays, like the time to reload a circuit breaker spring, the dead time of a recloser, and the total duration of a fault (with a view to system stability thresholds); these delays can be compared to standard tolerances. The corresponding alarms may be helpful for quickly analysing what happened after a major failure.

Finally, advanced failure detection is possible by logical analysis of all data of a given type, in particular all protection signals. For instance, one can assume that unselective tripping is due either to protection or to breaker failure and examine all possibilities in order to find out which one is the most likely. This process, typically manually executed, can be automated up to a point but is technologically quite complex.

The practical implementation of diagnostic functions based on alarm processing faces several hurdles, including the difficulty of applying a logical rule to all elements of the power system (due to natural diversity of the population of equipment), making the system fault-tolerant (in particular with regard to missing or conflicting information), and performing a practical validation.

Moreover, common sense says that the main goal of message processing during and after an outage is to avoid overloading the system and overwhelming the operators. Additional alarms are not welcome unless they provide reliable, first priority information and successfully push a wealth of insignificant messages into the background. This approach raises the stakes by putting intelligent alarm processing at the centre of the control system. It also sets the limit of application of simple message processing with regard to short-term disturbance analysis.

4.2.2 Medium-term

After fault and eventually system restoration, i.e. when the smoke is gone, the control and monitoring systems will usually have gathered all fault-related data (although, if some older equipment is still in place, data disks or paper plots must be manually fetched) and the analysis work can start.

The concerns of the medium-term applications are to understand the damage or consequences of the fault, to check correct system operation based upon a set of rules (maximum fault duration etc), to evaluate operators actions, to perform condition monitoring of important equipment, to produce a validated analysis, to write internal or external reports, and obviously to organise conditional maintenance activities.

Fault analysis is a general expression covering different activities.

Analysis of the original disturbance

Strictly speaking, the subject of the analysis is a physical fault (mostly a short circuit) which needs to be understood and characterised: determination of the faulted piece of equipment (e.g. a line or a transformer); precise fault location (position on the line); faulted conductors; fault pattern (permanent, transient, self-extinguishing; evolving; resistive; arcing; "complex" fault type). It is often possible to determine the physical causes by crosschecking environmental data (weather conditions, time and position of lightning strikes), performing manual inspections, or looking for some typical signatures in the recorded waveforms (which requires a lot of expertise).

Analysis of the sequence of events

In a broader sense, fault analysis includes the analysis of the whole sequence of events that starts with the original fault inception (or the actions that caused the fault to occur) and ends when the power system has fully resumed normal, stable operation.

A "fault" may stand for a single event, like a transient single-phase to ground on a transmission line (the most common fault type), or for a long sequence including automatic reclosing, migration of an arcing fault to neighbouring elements, loss of transmission or generation etc.

The manual analysis usually proceeds in several steps. First, one determines the most evident patterns like the prefault state, fault inception, line clearance etc. At this stage, one can refer to a catalogue of the most usual fault sequences. This leads to a rough scenario that can be validated by crosschecking analogue and logical signals. When the scenario stays, one seeks anything which may sound abnormal, first globally and then by shifting the focus from one element to the next (among the protection relays, circuit breakers and other important equipment close to the fault) and replaying the chain of causes and consequences for every subsystem, knowing its operational rules.

The result is a fault scenario, i.e. the reconstruction of the complete sequence of events. In the process, one will probably detect the most evident equipment failures (if any), but a verification of all the available data, including the messages of the control system and starting signals of remote relays is generally out of scope because it is very tedious and time-consuming.

4.2.3 Long-term

Education and training

The disturbance data are also a good opportunity for educational and training purposes. Several personnel categories are concerned, in particular:

- The dispatcher engineers, who directly and rapidly collect the fault data in the control room and must determine the faulted element and decide as quickly as possible how to restore the electrical system.
- The operation engineers, who could be called anytime by the dispatchers and must give a permanent support.
- The specialist engineers (protection, commissioning, etc.), who improve their knowledge and compare the reality with the theory.

Education staff takes benefits of the representative or otherwise interesting faults for training purposes. Records for this purpose are retrieved from all the available devices.

Statistics

A common use of the disturbance data is to provide statistical information. Annual and multi annual analysis are performed in order to determine the statistics of occurrence of the different fault types (single- or multiphase fault, permanent or fleeting disturbance, etc.) and finally to know if the problem concerns:

- The network – for instance overload in connection with trading activities or operation mode,
- The infrastructure or equipment – it could be the high voltage devices or the power automation (for example protection relays) and lead to maintenance activities or replacement,
- An external cause like storm or lightning strikes, trees, birds, nests ... – this information allows the utility to identify and launch corrective actions to improve the network performance.

At the end, it is very important to determine the impact on the final customer.

The statistical analysis allows interesting **reliability assessments** of the different pieces of equipment. Probability indices like the MTBF (Mean Time Between Failure) or the MTTR (Mean Time To Repair) give a global picture of the electrical system.

Statistical data allow taking decisions about equipment improvement, for instance to install a ground wire on an overhead line which is often struck.

4.3 Other uses

4.3.1 Operations

System restoration

The main concern of system restoration, after some parts of the network have been disconnected, is to re-establish normal operation of all equipment while avoiding actions that could represent a new danger for equipment and personnel. This application requires sets of rules for the operators. It heavily relies on the truth and completeness of the information about the power system condition, including hints about the original disturbances, or sequence of events leading to the disruption of normal service.

The following disturbance data are particularly important:

- Chronological, system-wide sequence of event logbook including:
  - all circuit breaker events

  - all protection trip events
- Additional or derived information produced by dedicated functions of the equipment, or otherwise available through the control system:
  - additional protection signals: fault direction, teleprotection, blocking signals
  - explicit fault classification data: faulted element (e.g. a transmission line), faulted phases, fault type (self-extinguishing, transient or permanent)
  - transmission and distribution status: loss of lines or transformers, overload condition (monitor the condition with respect to the thermal limits)
  - generator status
  - detection of power swings and out-of-step operation during the events, system stability margin
  - fault location information

Even if these data are complete and trustworthy, it may sometimes be difficult for the operators to take a good decision since they need to undertake appropriate corrective actions in a short time (a few minutes).

The most difficult situations arise either when the fault pattern is not clear (inter-system faults, evolving faults, multiple faults, rare faults like circuit breaker flashover) or when the reason for the sequence of events is unclear (especially due to unwanted or unexpected operation or failure of protection relays). In both cases, manual or semi-automatic analysis of disturbance recordings or SOE records may bring an answer. Manual analysis requires rapid intervention of skilled personnel and is typically time-consuming. Therefore, it is not systematically applied duration the restoration process. Computer-assisted analysis based on automatic message processing is possible if the control system trustfully implements an appropriate set of rules. In transmission system, given the consequences of wrong decisions, the focus is on crosschecking and validating logical data streams and raising the appropriate flags to orient the operators. In distribution systems where tripping is not very selective, the search for the faulted section itself – often involving hand-controlled switching sequences - may greatly benefit of computer assistance.

The specific requirement of system restoration is that a short, reliable and understandable indication about faults and equipment failures should be given in a short time. Typically, only dedicated protection relays (distance protection, transformer differential protection…) – especially digital – may provide this kind of service. The quality of the information partly depends on the selectivity of the protection scheme. Complementary processing needs to be intelligent enough to handle logical conflicts between different data and understand complex tripping sequences, yet it must be reliable and fast. Such a system requires careful design and validation and can only be cost-effective if implemented to monitor a large number of units with similar characteristics, that is, it is adapted to unified protection schemes and operating practices.

High impedance fault detection

The protection and control systems are designed to protect power system equipment from fault-induced damage, to keep the overall operating point within a safety zone (no overvoltages, no power swings etc.) and to permanently clear the equipment which may threaten human health. Due to a variety of technical reasons (sensitivity and selectivity limits of measurement equipment and principles, protection co-ordination, reliability levels) that reflect the necessary compromise between investment costs and performance, the protection and control system cannot clear all faults. Consequently, some of the faults may stay unnoticed and undetected for a longer time, threatening human life and possibly causing equipment damage in the end.

It is highly desirable to implement a second level of protection in order to clear most if not all low-current faults, especially the so-called high-impedance faults (which are common in some types of distribution systems) which represent a great hazard to by-passers. DFR equipment could be used for high impedance fault detection.

4.3.2 Maintenance

Performance analysis of protection and control

In the continuation of fault analysis, which is described above, the available data may offer the possibility to perform a complete performance assessment of the protection schemes after every major fault. Not all utilities choose to do so, and two methodologies can be distinguished. The first school triggers recording "on protection trip" and restricts the analysis to the disturbance records from power system nodes that are directly involved by the fault. The second school thinks that it is better to measure too much than too little, sets recording triggers accordingly (on overcurrent, undervoltage, voltage change, protection start…) and uses such DFR features like cross-triggering of recording units in order to gather complete pictures of the events in several substations.

A declared goal of the second group of utilities is to verify correct operation of all protection devices, including those who should have started (without tripping) and those that should not have started. This is especially interesting with respect to critical protection co-ordination schemes, like distance protection in densely meshed subtransmission networks and the protection of parallel lines. The verifications should extend to blocking signals, teleprotection etc. In addition, the breaker operations should be checked in order to determine the operating time and the opened poles.

In practice, wiring all useful binaries, gathering all data at a regional or national level and performing the analysis represent huge investment and operational costs and requires a corresponding organisation (quality goals, etc.). Therefore, comprehensive analysis of the protection scheme is only feasible for the upper voltage levels.

Virtually every power system disturbance represents a stress for the equipment. At the same time, it may give a chance to observe its condition and to verify that either a particular piece of equipment, or a subsystem, or the power system as a whole behaves in compliance with the planning guidelines before, during and after the disturbance.

Fine-tuning of protection settings

The difficulty for a protection engineer is that despite all the testing possibilities, one often has to wait for the incidents and disturbances to check the protection settings. Then the performance analysis and the statistical information should be carefully examined and changes in relay settings or configuration should be considered.

Protection testing

Traditionally, the relay commissioning and testing is achieved with a testing device to inject typical default currents and voltages. This standard procedure is sufficient for the majority of the default, but does not cover special cases as current transformer saturation or dynamic phenomenon. The modern testing devices are able to replay transient signals that can come from simulation programs (for example EMTP) or fault recorder, see [17].

The new trend to use the current and voltage waveforms from a disturbance recorder has the advantage to represent a real situation.

On-line supervision including operational (e.g. thermal) monitoring

A new trend is to perform event-oriented maintenance or predictive maintenance and no more only based on a periodical rate. It is desirable to increase the lifetime of power system equipment (detect transient overcurrents, abnormal harmonic levels etc.). For these reasons, more and more suppliers propose monitoring devices to verify continuously the primary equipment state. Currently it is possible to find different monitoring systems for transformers and circuit breakers. However we should keep in mind that a monitoring device must be more reliable than the equipment it surveys; also the interpretation of the monitored data is quite difficult.

Monitoring systems are more and more integrated in the new devices, but also older equipment could be covered in order to keep it on longer.

It can be dangerous to wait until a piece of equipment is disturbed before maintaining it, because it could be difficult to take important elements like transformers out of service and the repairing time could be long. That is a good reason to organise a good spare part programming.

There are three possibilities for online verification or assessment of primary equipment reliability:

- To use a monitoring device or system provided by the manufacturer of the HV equipment (especially for turnkey projects).
- To apply a dedicated monitoring solution, including monitoring devices, to existing HV assets.
- To use existing IEDs and build up an appropriate software solution for condition monitoring.

The latter option is an emerging one and it is closely linked with disturbance data analysis.

4.3.3 Customer assessment

Prepare fault reports for internal use

Most utilities file all disturbances that caused protection tripping or circuit breaker tripping (there may be other, detailed definitions of "important disturbances") in transmission and subtransmission systems. For every such disturbance, it is expected that a complete, certified analysis be appended to the disturbance records of interest. At lower voltage levels, where the number of disturbances increases while the consequences tend to decrease, disturbances are typically documented with fewer details or with a less systematic coverage.

The internal reports usually cover all aspects of the fault: its physical causes, the way it developed, the final consequences for the equipment and for the customers, lists of failures (or other helpful remarks), lists of actions (in particular: search for the fault spot, verification of protection condition or settings, and various maintenance work). These actions are started while the analysis is in progress, and additional verifications on the field may be required. The investigation about some complex events may require a considerable energy and a close co-operation within the company. The report should not be closed until all related actions are completed. In practice, the reports could be archived into a common documentation pool after a few months.

Indeed, the final goal of the internal reports is to provide a documentation basis for external reports (see below), economic studies, reviews of maintenance and investment strategies, and yearly fault statistics. These applications extend across longer time spans and generally will not refer to individual events any more. Instead, they will proceed statistically. Therefore, it is of great interest to dispose of a well-structured faults database, which in turn is possible only if the fault analysis process is given enough consideration (skilled personnel, tools, careful design and quality control of the process).

External reports

When a particular power system disturbance affects some important (or mighty) customers, or a significant market for a long time, it may be crucial to provide a correct explanation of the problem to the affected customers and to the Administration in a short time. The observed disturbance at the endpoint may vary from a simple voltage drop to a blackout. The number of disappointed customers and the economical damage may also vary considerably, possibly raising commercial and legal issues of great importance.

The focus of an external report is responsibility and proof, whereas the underlying internal report is centred on full technical understanding. Therefore, the external report is based on physical records and logs and aims to provide a logical explanation of the sequence of failures, which should help to determine shortcomings at various levels or in relation to the different assets.

Power quality

Different international standards, such as European Normative EN50160, require electrical companies to assure and to evaluate the quality of supply at selected locations (voltage sags, unbalance, harmonics etc.) and verify or prove that the quality is within specified bounds. Every time voltage variations or harmonics are recorded, and principally when a customer complains, the disturbance must be analysed in order to clarify the causes and to eliminate them in the future. Transformer and tap changer performances are studied in relation to power quality.

It is now possible to network many different recorder devices (protection or fault recorder), with automatic data acquisition, in order to help the dispatchers, the protection engineers and the maintenance personnel. A complete realisation is described in [18].

4.3.4 Planning

Refinement of equipment and system models

Planning computations require good models of the pieces of equipment; the true relay characteristics with the delays of logical signals as well as the power system models (generators and controls, source impedances, cables and overhead lines, etc.) are necessary.

For modelling purposes, the records of permanent faults the location of which is perfectly known are used. Large disturbances and instabilities are events of interest too. In general, the most interesting disturbances are those that can be precisely reproduced using computer models of the network. Also long records are used to evaluate the response in a long timeframe, in order to calibrate not only the immediate response of the network model, but also the long-term time response including restoration. The performance of the network model is evaluated by reproducing a fault for which a record is available in a database. Afterwards, a comparison is made between the results of the computer network model and the fault record.

Analysis of network dynamic performance

Only disturbances involving major power, voltage or frequency deviations are of special interest for dynamic analysis. Faults located in neighbouring networks are studied to analyse the response of the electrical system against an external disturbance. The analysis covers the working of the protection system (relays and breakers) and the power plants. The study of the performance of devices such as automatic voltage regulators (AVRs) or power system stabiliser (PSS) gives information on the system stability. It is also important to evaluate the safety margin (e.g. N-1 stability).

Planning engineers carry out stability and frequency analysis, as well as primary and secondary regulation performance while the protection engineers study the protection dynamic response and performance. The signals studied are mainly active and reactive power, voltage and frequency. They are obtained from different sources like digital protection relays (DPR), digital fault recorders (DFR) and power quality recorders (PQ).

4.4 Conclusions on applications

As have been mentioned in the previous chapter, fault and disturbance monitoring system can be considered as one among many information systems of a utility. It tends to be open and to share resources with other applications. At its upper level, disturbance monitoring produces very interesting technical information about the power system and may produce usable data for management-related applications too. Potentially, many users may be interested in this information, eventually according to their specific view and requirements. Figure 29 in the appendix shows that more than 70% of the utilities declare that disturbance analysis concerns Protection department, but almost 45% declare that the results of this analysis concerns Maintenance department, around 35% point to Planning department, almost 30% allude to Dispatching department and 8% mention Construction department.

Technically speaking, it is not overwhelmingly difficult to integrate a disturbance monitoring system into the enterprise information system, but the difficulty rises from the need to coordinate different groups of people and to obtain the co-operation and commitment of the key players in different departments like operation, maintenance, communications, information systems...

As described in this chapter, many applications exist using the disturbance data. Applications may take place in different time frames (short, medium and long-term uses) and concern every category engineer of the electrical domain. Many interesting applications of fault data are described in [19] and [20].

Disturbance data analysis is time consuming, that is why intelligent and expert systems are desirable. At the end, only when we can be confident in these systems they will be implemented in a wide scale.

5 Future trends

5.1 Introduction

Looking at the state of art of fault and disturbance analysis systems we find out that most of them are rather old and outdated, not exploiting all possibilities offered by technology. The recording devices are typically not computer based and flexibility in communication, data storage, automated analysis and user interfacing is limited. The role of operators in analysing the events manually is prevailing in today's practice. An increased amount of recorded data and reduced availability of time to analyse it create a bottleneck in the ability to analyse the recorded data efficiently and timely.

A major development in the last decade is the deregulation, restructuring, liberalisation and privatisation of the utility industry. Irrespective which of the mentioned trends is present in a given country or region, it is clear that an increased competition is imminent. As a result, an increased emphasis on system performance and reduction in cost are clear goals. The reflection of these goals on the data analysis has resulted in a need to improve the analysis through automation and broader use of the data and information [18].

To answer the mentioned needs, the utility industry and vendors are carefully evaluating new technology trends to identify the best solutions for the future. The CIGRE Working Group has discussed the technology impacts and future trends and the main points of the discussion are presented in this chapter. Data integration and information exchange are considered the two most important drivers for the new technology consideration [21].

This chapter gives an overview of future trends in utilising advanced technologies for fault and disturbance analysis. Special attention is given to the constraining issues of the existing solutions, new needs resulting from recent industry changes, the technology impact and future trends. It is indicated that the transition to the new technology requires definition of retrofitting strategy as well as new standards. Moving towards solutions that are more “open” and support data integration and information exchange is an important trend. An example of the integrated fault analysis is given at the end.

The new needs came about because of industry deregulation, restructuring, liberalisation, and privatisation. The mentioned trends did not occur simultaneously in any given country or region, but are rather a reflection of specific local circumstances. However, the outcome is almost the same across the world. The increased competition has resulted in an emphasis on achieving higher performance while curtailing new investments in the infrastructure and human resources if possible. More detailed list of impacts and consequences is given in Table I.

Table I. Cause-effect relationship of the new developments in the utility industry

Changes	Impacts			
New Utility Business Models	Increased Performance	Reduced Investments	Customer Focus	Stiff Competition
Reduction in Human Resources	Loss of Expertise	Need for Automation	Need for Re-training	Multiple Users of Information
Increased System Loading	Enhanced Monitoring	More Complex Event Analysis	Improved Maintenance	Documenting of Problems
New Company Needs	Data Integration	Information Exchange	Data Archiving and Viewing	Retrofitting Legacy Systems

From Table I, it appears that the new developments in the industry are posing a variety of requirements on the new generation of fault and disturbance analysis solutions:

- “Open” solutions that will allow integration, upgrading, retrofitting and other levels of flexibility in designing future systems
- Automated analysis implementations that will enable savings in man power and reduction in response time
- Multiple uses of the same equipment justifying the investments and even sharing the future investments among various utility departments.
- Utilisation of advanced Internet and Web applications combined with database and communication technologies to achieve system-wide, easy to access, solutions.

The requirements should be understood in the most important context: faster and more precise assessment of faults and disturbances as well as related equipment operations and performance characteristics. The recent developments in the industry have resulted in creation of new entities and players such as Independent System Operators (ISOs), Transmission Companies (Transco’s), Generation Companies (GenCo's), Distribution Companies (DisCo's) etc. The future trends in utilising advanced technologies for fault and disturbance analysis have to be measured against the needs and related requirements that each of the mentioned entities may impose. This may result in different approaches to the ownership of data recording instruments, subcontracting of data analysis services and wide uses of the results among various entities (internal company departments, regulatory agencies, etc). As a result, some new designs and implementation strategies for fault and disturbance analysis may be needed in the future.

In addition to the mentioned needs that are coming from the industry developments, the technology developments are also very important. The utility industry is known to be technology driven, but some of the existing solutions use rather outdated and archaic technologies. This topic is discussed next.

5.2 Technology

Technological advances and their rapid deployment in the industry have contributed to reshaping the field of disturbance analysis.

One can first observe progress in data acquisition, processing and storage, such as:

- Increasing level of functional integration in the devices, representing a decreasing cost per function (for instance, the DFR becomes a multiple-purpose digital recorder where the triggered as well as system-wide continuous recording features become affordable).
- Availability of precise time sources, making accurate system-wide time stamping and synchronizing of sampling possible.
- Increasing storage capacity, which allows capturing more information.

New communication media and approaches have also had a deep impact. It has become feasible to connect virtually every substation to the utility's WAN, using the most appropriate technology (fibre optics, xDSL, ISDN), thus increasing the available measurements base for disturbance analysis allowing a full coverage of a given voltage level. The data gathering service has become more dependable than with former modem links. Transferring one megabyte of disturbance data has become faster and cheaper; breaking the old speed barrier is certainly an incentive for developing central data storage and analysis, which is simpler to operate and to maintain than a distributed solution.

Finally yet importantly, internetworking all devices and systems has suggested new system architectures and applications, which take advantage of the broader data availability. A part of the disturbance analysis work consists of routine work, such as gathering the data sets, grouping and sorting them, looking for fault-related patterns in analogue and digital signals, measuring amplitudes, phases, time delays, fault locations, and producing some short reports illustrated by disturbance plots.

Fortunately, some progress has been made in the field of automated analysis. As far as digital data are concerned, dedicated software solutions are available nowadays which gather the measurements into a fault database and automatically perform the routine calculations, in particular for the identification and location of high current short-circuit faults based on digital fault recordings [18], [21]. Substation automation systems also increasingly support fault analysis applications by presenting all relevant data to the user.

Some automated disturbance analysis systems may also address some complex ("intelligent") applications, like analysing dynamic system stability, monitoring the performance of switching and protection equipment, detecting high-impedance faults, providing clues concerning the original cause of the fault, assessing impacts on the customers (PQ features).

The fast development of Internet Technology (IT) has a strong and beneficial impact on the way modern disturbance analysis systems are being designed. Formerly, most of the effort needed to be devoted to communication and data management issues. Today, many powerful solutions for building web-based and database-oriented applications are available of-the-shelf. Integrated solutions may be easily deployed in a utility's Intranet or through the Internet, so the designers can integrate functionality in the company's information system and about end-user requirements. From a modern perspective, the whole field of fault and disturbance analysis appears as one of the many interesting functions of a power-network information system.

5.2.1 Consequences of implementing more powerful data processing systems in the recording instruments

Lower cost per recording function, pushing the applications, which are demanding in terms of number of channels, number of measurement nodes or percentage of coverage of the power system. The basic idea is to have multiple recording functions allocated to the single recorder and with this feature one may be able to avoid purchasing yet another IED to perform the additional function. As an example, power quality (PQ) calculations and analysis can be allocated to a standard digital fault recorder (DFR) hence enabling the power quality function to become available at “no cost”. Another example is the decision to put fault location function on a DFR, which eliminates the need to purchase dedicated fault locators. If we assume a fixed cost of a DFR in this case, and we assume that several application functions are allocated to the DFR, it is obvious that the cost per function will be lower than if only the basic recording function was considered.

5.2.2 Consequences of selecting better communication infrastructure

Better reliability and lower costs of data transmission make it possible to automate a part of the analysis of disturbance recordings or messages on a larger scale (all major stations of a utility). This is an important development since the analysis functions can be located closer to the data sources (recorders). In that case, one can take an advantage from very precise recording, which generates much data. Having the analysis function allocated close to the source of data enables a data compression to take place where only the results of analysis may be transmitted instead of transmitting the raw data files. Hence, there are two opportunities for reducing the volume of communications from substations: reduction due to extraction of information, and further reduction through compression of the information file using standard file compression methods.

Faster data transmission (especially when bringing TCP/IP network connections down to substation level) helps to bring condensed summaries from an automatic fault data analyser to the operators in less than 5 minutes, contributing to better and faster system restoration. Having faster transmission increases the overall response time, in particular if local substation processing is not available. Presently, using standard telephone lines, the time required to download data from a DFR may take as long as 10-20 minutes. Taking into account that to get a full assessment of a given event, there may be multiple recorders that need to be polled, the data transmission can be a major impediment in achieving fast response time in both the analysis and restoration. With dedicated high-speed communication networks, and the use of compressed summary files, operators can receive real-time data to be used for immediate subsequent operations.

System integration and maintenance are facilitated in some aspects like (central) power system description data bases, interfaces between several specialised software applications (e.g. recording database, intelligent disturbance analysis engine, maintenance data base, fault statistics…) and self-monitoring of functional components and interfaces. Recent developments in the substation automation IEC standard 61850 will facilitate system integration but we still have to worry about legacy solutions that are not compatible with the new standard but need to be integrated and data files need to be maintained. In this sense, it is very important that retrofitting strategies for interfacing the legacy systems to the new solutions be outlined.

5.2.3 Consequences of employing Artificial Intelligence techniques

Expert systems, invented to describe and preserve through software code the empirical rules used by operators when analysing the events, are a necessary technology if one is considering a major increase in automation of the analysis process. The expert systems come in many different forms such as rule-based, frame-based and eventually object-based allowing structured approach to implementing the automated reasoning part of the analysis procedures. Software solutions designed to facilitate development of expert systems called “shells” can be used to develop user-friendly interface for the rule builders so that the rules can be further upgraded when new rules become available. The main concern with using expert systems is the ability to maintain them. The present practice shows that the rule-based systems consisting of several hundreds rules are still cost effective from the standpoint of maintenance, while the rule-based systems of close to a thousand rules or more are very difficult to maintain and they become far less cost-effective than more simple solutions.

Neural networks have an ability to deal with signal processing in a parallel fashion where multiple features are examined in one complex computation. Typically, neural networks do not use the signals directly but are requiring a feature extraction first. Once the signal features are extracted, neural networks can be used very efficiently to recognize certain data patterns, which in turn can lead to various analysis conclusions. A very good example is the ability of neural networks to detect and classify faults, which is a very important analysis step when trying to decide if the relays have operated correctly. One disadvantage of neural networks is the fact that they need to be trained to recognize certain patterns. The neural network training requires either recorded or simulated data, which imposes a burden of creating and maintaining data needed for training. Moving a neural network solution from one location to another in the power system may require re-training and additional tuning of the solution to be able to make same type of conclusions.

Fuzzy logic is a known analysis tool when dealing with imprecise or incomplete data. The fuzzy variables are introduced to define a “level of belonging” of a certain data set to a given range of the variable. As a result, a fuzzyfication of variables needs to be performed where some empirical studies need to be carried out to determine certain properties of the fuzzy variable. Once the fuzzyfication is done, then an analysis can be performed using the fuzzy logic rules. The final analysis results are obtained by performing defuzzyfication of the variables and associated values into “crisp” representation typically used in the engineering systems.

Other specialised AI techniques, such as genetic algorithms or evolutionary programming, may be used for the analysis purposes as well. By mimicking some decision mechanisms used in the live organisms, an analysis step such as global optimisation can efficiently be performed.

5.2.4 Consequences of relying on Internet technologies

Widespread use of HTTP (web servers and browsers) and SMTP (email) in the corporate networks (Intranets) of the utilities simplify the software architecture and facilitate the dispatching of online information (fault reports etc.) to all interested users.
As a further technological step, the internet may greatly facilitate the communication between recording devices and disturbance analysis servers or between those servers and the end users. However, the dependability, speed and security problems tend to restrict the true internet-based solutions to non-critical applications, like power quality measurement.
The impact of cyber security needs to be addressed when using the internet as medium. The use of secure firewalls and other security measures may be required. If protection relays are to be interrogated, security measures have to be established to ensure that the interrogator is not able to alter the settings of protection relays whilst retrieving records.

5.2.5 Consequences of considering emerging technologies

Other advanced information technologies as applied in the field of disturbance data analysis:
- Search technologies (data mining).
- Pattern recognition.
- Intelligent agents.

5.2.6 Consequences of pursuing standardisation efforts

Favourable effects of data-centric standards (COMTRADE for disturbance records, PQDIF for PS data) can be observed, since they allow to interface devices and software packages from different suppliers and thus to make the "best choice" for every utility.

Ongoing standardisation work which targets functional inter-operability (IEC 61850) [7], including system engineering, will ultimately facilitate the deployment of disturbance analysis solutions, especially when they can benefit from sharing device interfaces, data bases or user interface terminals with other applications (control) [8]. The integration will be possible at a higher level and at lower costs than today’s' disturbance recording and analysis systems which tend to be independent (of protection and control).

5.3 New requirements

5.3.1 Opening of the electricity market, increasing competition

Increasing pressure from regulative bodies is the result of more competitive business environment where the demands for higher reliability and security of operation are ever increasing. The major blackouts, such as the recent one in the Northeast U.S.A., are putting a pressure that the events are recorded in detail so that the analysis and restoration can be performed quickly. This new trend has also been emphasized in some recent national recommendations such as the ones stated in the National Electric Power Grid Study completed in the USA in 2002:
a.) Federal legislation should make compliance with reliability standards mandatory
b.) Penalties for non-compliance with reliability rules should countermeasure with the costs and risks imposed
c.) Routine collection of consistent data and cost of reliability should be ensured to better assess the level and value of reliability.

5.3.2 Disturbance analysis, part of the field of power quality

Conflict between the requirement of controlling power quality and short-term cost savings in the field of network services. Some utilities have engaged in a consistent power quality program and offer PQ contracts while others, who already disposed of experienced personnel or a good measurement base, strongly cut down their power system monitoring programs. (Are quality and price of electricity incompatible goals?)

5.3.3 Less time, more work

Today’s trends show continuous decrease of:

- The number of specialists (usually protection engineers) having the required knowledge to perform disturbance analysis.
- The time the remaining specialists have, and want to take, to inspect single events, due to new duties.

Meanwhile, there is a demand for systematic processing of the disturbances in order to determine power quality levels, be able to answer customers' complaints, and optimise system planning.

So, the methodologies evolve towards an automatic processing of all system data, including at least a reliable sort of the important records, to be complemented by a manual analysis of the most particular or delicate disturbances.

5.3.4 Measurements first, inspection next

The overall tendency is to make the best use of available measurements from any sort of devices (DFRs, DPRs, fault indicators, SCADA alarms) before sending anybody out in the field. Having more detailed recording resulting in more data is in general desirable. Since the communication bottlenecks are a real impediment in the timely transfer of data, earlier discussion of having local substation processing becomes even more relevant. The ability to get information, not necessarily the data itself is an important factor in being able to learn as much as possible about an event without having a need to visit the substations involved in the event and inspect the equipment. If the inspection is still needed, one would go to a substation much more informed about the event and expected trouble, hence could prepare accordingly to deal with the trouble call efficiently.

5.3.5 Cost/benefit assessment, justification approaches

During the last 4 years, there has been a continuously growing interest in developing a statistical and economical model to obtain an overview of the costs (consequences of the disturbances for the company) and to derive some simple, applicable rules to determine which investments and which service activity are economical. Figures for the costs/outage have become more precise, taking voltage levels and power system configuration (grounding mode, interconnections, short-circuit power, protection scheme) into account. The knowledge base obtained through this background work is used to optimise repair and maintenance strategies, define service-level agreements, develop insurance concepts for PQ contracts, etc.

5.3.6 Requirements analysis, implementation strategies

Two major strategies may be considered in implementing the automated analysis: a.) Centralized and/or b.) Distributed architecture. Careful analysis of a given utility situation may suggest that one option has major advantages over the other. Some of the decisions will certainly be impacted by the legacy solution that the utilities already have in place. It should be noted that the requirements might lead to the need to retrofit an existing installation of the recording equipment infrastructure by using third party software. In this case, full understanding of data formats and communication protocols may be needed in order to implement the retrofitting. One example of such an approach is to locate PCs next to the recorder that does not have elaborate data processing capabilities. By transferring the recorded data to the PCs each time the record is made, the new analysis software located on the PC can perform the analysis very quickly. In this case, by purchasing PCs and adding the new software the whole solution becomes much more “open” and efficient.

5.3.7 Operator participation, definition of the analysis goals

Since in most of the utilities the analysis of records captured by recording instruments is still performed manually, the knowledge and expertise of operators is essential in specifying new automated solutions. In this context, it becomes very important that operators do not propagate some personal biases into the requirements specification process. The personal biases may be affected by a fear that once the analysis system is put in place, it may become evident that some of the operators may not be needed in the future since their tasks will be substituted by the automated analysis system. On the other extreme, an approach that attempts to make the entire analysis process fully automated can also meet some difficulties since trying to incorporate too many details in the automated analysis system may result in a too complex solution that is very difficult to maintain. The final balance in the requirements is to try to substitute all the routine operator analysis functions with an automated system and leave more time for the operators to deal with the more complex cases in a less automated fashion.

5.4 Applications

5.4.1 Automatic disturbance analysis

In the power systems, due to various operating conditions, many disturbances occur relatively frequently. Most of these disturbances are not critical to power system operation, but in some instances, such as when permanent faults occur, time-critical actions have to be taken to remedy the situation. The main tasks in the analysis of disturbances are detection, classification and characterization. As a result, it should be necessary to distinguish the disturbance that has occurred from the circumstances in the system leading to the disturbance, and assessment of the importance of its impact. If the disturbance causes some of the equipment to operate, such as is the case with faults causing relays, communication schemes and circuit breakers to act in clearing the fault, then the analysis needs to include performance assessment of the equipment operation as well. If the disturbance only has an impact on the power system operation, then the assessment needs to give a quantitative measure of the impact.

Some systems that perform automatic disturbance analysis are described in the following references [18], [21], [22].

5.4.2 Power quality detection, classification and characterisation

Special type of disturbances is called power quality events. They may be caused by an interruption in service or major deviations of voltage and current signals from the fundamental frequency. Typical power system disturbances are spikes, transients, voltage sags, voltage swells, harmonics, etc. In the case of power quality disturbances, it is very important to have a computational capability to extract a quantitative measure of the disturbance and establish the level of its severity according to a given standard criteria. In modern power quality systems, not only that the mentioned analysis can be performed but also a historical account of the events can be kept. This enables statistical analysis of the events, which in turn may be needed to get a long-term impact of the disturbances.

An example of a modern implementation of automatic power-quality analysis system is described in reference [24].

5.4.3 *Alarm processing*

Traditional alarm processing function is associated with the alarms generated through the SCADA system. All the alarms are brought to the central location and due to an overwhelming number of alarms being associated with a major disturbance; operators have a major difficulty in analysing alarms in real time. Therefore, automated alarm processing systems were developed and implemented by EMS vendors. Today’s intelligent electronic devices will produce a large number of alarms that allow detailed analysis of the events right at the source of the alarms, in the substation. Adding to the alarms additional measurements provided by waveform recording IEDs, the entire analysis may be far more effective than the one provided at the level of the SCADA database. By integrating SCADA data with analysis data coming from different IEDs that have recorded events of interest, alarm processing may be far more effective than the current automated solution used at the EMS level today.

An example of an expert system application to alarm processing in operation in the late 80´s can be found in [25].

5.4.4 *Condition-based maintenance assessment*

Since the monitoring IEDs located in a substation may have access to data reflecting the condition of the power apparatus, a new approach to the analysis of maintenance strategies may be implemented as a result. Many different approaches to assessing the failure rates for various types of power apparatus can be developed using condition-based data recorded by IEDs. Consequently, a new risk-optimised maintenance strategy may be developed. This strategy links the decisions made by operators in running the system and the criticality of various components according to the calculated probability of failure. As a result, if possible, operators will schedule the use of the components whose probability of failure is far smaller than some other components that may also be available, but would be far more risky to use.

5.4.5 *Integrated substation monitoring*

Availability of the IEC standard 61850 for substation integration makes the concept of integrated substation monitoring viable. The local substation database can be easily constructed and automated analysis functions can be implemented to carry out overall substation monitoring tasks. One point of interest has been raised recently: how well defined are the data context descriptions in the IEC 61850. Another important question is related to the ability to correlate outputs of all the different IEDs. In order to do that a clear functional and logical link among various analysis steps needs to be established. It may be observed that future standardization activities are still needed to get a full application understanding of the IED data so that the integrated data can be converted in the required information. Recent standardization efforts in the IEEE Power System Relaying Committee are targeting two distinct areas: more detailed description of the data formats, and clear interfacing definition among various substations and SCADA database. This will allow the results of the overall substation monitoring to be coordinated for larger disturbances involving operation of the equipment in multiple substations

An example of a modern implementation of automatic integrated substation monitoring is described in [23].

5.4.6 *System-wide analysis of cascading events*

The most difficult analysis is the one associated with cascading events. By definition, such events are not expected and when they occur, they may be difficult to control. In such cases, it is most likely that the system will have either to be shut down partially or totally in order to restore it again.

Having a recording and analysis system that will collect data from multiple IEDs and use it all to try to figure out the cause-effect actions is very important if a quick restoration is to be attempted. In such cases, the ability to provide synchronization of the sampling function and accurate time-stamping is critical to the quality of analysis. Needless to say that the communications support to gather the system-wide data in a timely fashion is also an essential feature.

5.5 Conclusions on future trends

An illustration of future trends is depicted in Figure 2 [26]. Several characteristics of the future trends may be observed as follows:

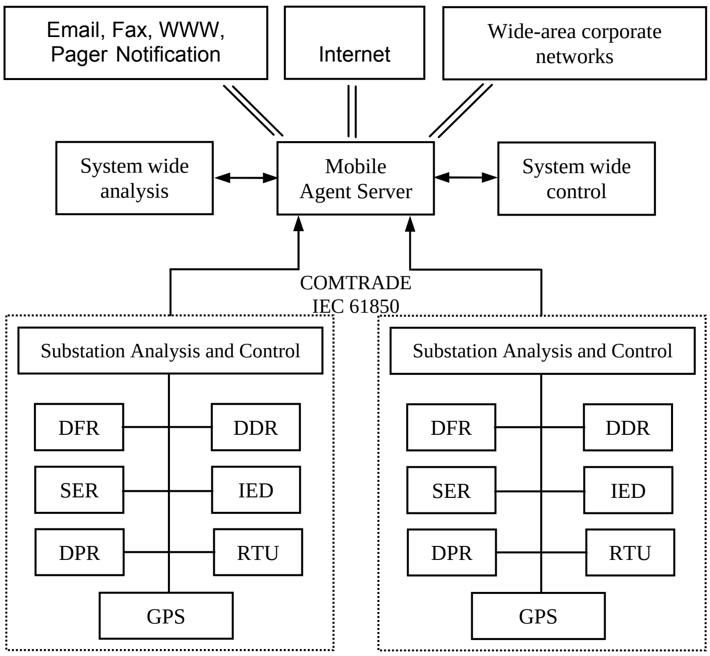

Figure 2: Future trends in the architectures for fault and disturbance analysis implementations.

- Data integration and information exchange will be facilitated by connecting various substation devices such as Digital Fault Recorders (DFRs), Sequence of Events Recorders (SERs), Digital Protective Relays (DPRs), Digital Disturbance Recorders (DDRs), Remote Terminal Units (RTUs) and other monitoring IEDs through a common communication standard such as IEC 61850.
- The analysis will be facilitated if all the recording devices are connected to a Global Positioning Satellite (GPS) time reference.
- Due to a large amount of recorded data, it will be desirable to perform some level of automated analysis at the substation level, close to the data sources while the system level analysis may be performed at the centralised location.
- The utility industry emphasis on performance will require that many different users of data be presented with the result of the analysis, leading to the need to allow both local and wide-area communication facilities and user interfacing tools.
- The data exchange will need to be facilitated by further development of the data format standards including COMTRADE and the IEEE File Naming Convention.
- Some advanced software technologies, such as mobile agent software, may have to be employed to account for the use of diverse processing and data storage environments, which are introduced by various legacy solutions that need to be retrofitted and/or modified to accommodate the new needs.

The main conclusions are as follows:

- Understanding the current business models and related needs of the utility industry is crucial when defining the future trends.
- It is clear that the advanced technology has a lot to offer but some ways of retrofitting the legacy solutions also needs to be addressed since the investments are substantial.
- The required level of performance assessment while there is a shortage of work force has to lead to a much greater level of automation of the data analysis, storage, and retrieval tasks.
- Standardisation of the data formats and application objects has to be pursued if the acceptance of the new solutions is to become a reality.

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“Questionnaire on data recording devices and their applications in fault and disturbance analysis”

WG B5.03 on “Fault and disturbance data analysis including intelligent systems”

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CIGRE - Study Committee B5 – Protection and Automation

Questionnaire on data recording devices and their applications
in fault and disturbance analysis

CIGRE - WG B5.03 - "Fault and disturbance data analysis including intelligent systems"

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1 Introduction

The WG B5.03 "Fault and disturbance analysis including intelligent systems" was created with the following scope:
1. - Identify the characteristics of the existing recording equipment.
2. - Make recommendations to optimise system architectures.
3. - Gather methodologies and experiences for processing information and applications

To undertake its mission this working group prepared a survey covering all the aspects of disturbance analysis from the kind of data and devices used to the main final purposes of the analysis. The survey was delivered in September of 2001 and it has been responded by 25 utilities from 12 countries covering Transmission, Generation and Distribution. This document summarizes the results and conclusions extracted by WG B5.03 from the answers received. The survey structure is shown in Table 1 and consisted of six parts:

Part 1. In the first part of the survey, information about the activity and the size of the responding company was requested. A summary about the group of companies that answered the questionnaire is presented in the chapter 2 of this document.

Part 2. In the second part, information about recording equipment involved in analysis and installation criteria were inquired (models and types of devices, number of units installed, age, and voltage levels where they are installed). The results found out by WG B5.03 from the answers to the survey are presented in the chapter 3 of this summary.

Part 3. In the third part, information about data used for analysis purposes was taken into account (type of signals used, devices that provide them, and triggering methods employed). The results are included in the chapter 4 of this document.

Part 4. In the fourth part, data gathering and storing methods were included (access level, data retrieval approach, communication features and data storage type). Figures and conclusions extracted about these topics are presented in the chapter 5.

Part 5. In the fifth part, questions about the common applications of the information related to the electrical network incidents were made. For this purpose, applications were classified in seven categories: fault analysis, maintenance, power system dynamic performance, power quality, device testing, modelling and other applications. A summary of the answers collected is presented in the chapter 6.

Part 6. In the sixth and last part of the survey, some questions were included to retrieve experts forecast about the future policies of the utilities according to record, management and analysis of incident information, and the reasons that will move to changes in the way to do things. The conclusions about future trends extracted from the answers are presented in the chapter 7.

Table 1. Survey structure

PART 1																	PART 2						PART 3				PART 4										
Utility			Activities				Generation Capacity (MW)						Installations				Devices used																				
																							Data collected				Data gathering, management and processing										
																							Analogue signals				Access level			Data retrieval		Communication				Data storage	
																								Trigger method													
Utility	Address	Country	Generation	Transmission	Distribution	Retailer	Nuclear	Thermal	Hydroelectric	Wind	Sun	Other	kV level (*)	Number of substations	OH lines km	Cables km	Model	Type (**)	Manufacturer	Number of units	Used since year	Used at kV level	Continuous recording	By contact	By threshold or rate	Binary signals	Substation	Regional	Centralised	By request	Automatically	Medium	Speed (Bd)	Standard protocol	Proprietary protocol	Device oriented	Application oriented
1			X	X				7000	1000				**A**				**1**							X		X			X		X				X	X	
													B				**2**							X		X			X		X				X	X	
													C				**..**																				
													D				**n**								X				X	X					X	X	
2			X	X	X		2100	238800	76800				**A**				**1**								X	X			X		X				X	X	
													B				**2**								X	X			X		X				X	X	
													C				**..**																				
													D				**n**						X			X	X				X				X	X	
..													**A**				**1**																				
													B				**2**																				
													C				**..**																				
													D				**n**																				
N				X	X	X		1010				118	**A**				**1**							X	X	X	X			X					X	X	
													B				**2**							X		X	X			X					X	X	
													C				**..**																				
													D				**n**							X	X	X			X		X			X		X	

(*) kV levels: A) higher than 220 kV; B) from 66 to 220 kV; C) from 30 to 66 kV and D) less than 30 kV
(**) Device types: digital protection relays (DPR), remote terminal units (RTU), digital fault recorders (DFR), non-digital protection relays (PR), power quality recorders (PQ), fault locators (FL), multi-purpose digital recorders (DR), sequence of events recorders (SER), substation computers (COM), digital dynamic swing recorders (DSR), electro-mechanical recorders (EMR) and substation automation systems (SA)

2 General information about replying utilities

This chapter summarizes general information about the replying utilities.

2.1 Geographical distribution

Twenty-five companies from 12 different countries and 4 continents responded to the survey.

Table 2. Geographical distribution of answers

Continent	Country	Number of contributions	
Africa	South Africa	1	1 (4%)
Asia	China	1	10 (40%)
	India	2	
	Japan	7	
Europe	Finland	2	11 (44%)
	Ireland	1	
	Netherlands	1	
	Spain	2	
	Sweden	1	
	Switzerland	4	
North America	Canada	1	3 (12%)
	United States	2	
		Total	**25**

2.2 Company activities

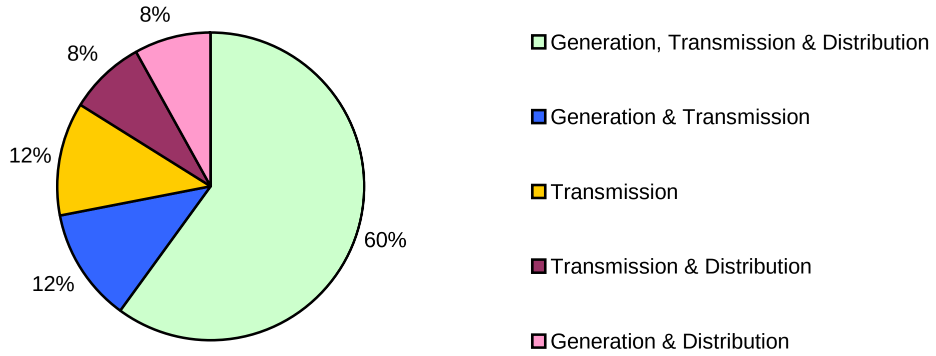
Table 3 summarizes the number and percentages of replying utilities that declared to include each of the three main activities: Generation, Transmission and Distribution in their activities. The mean replying utility is a complete cycle company that generates, transmits and distributes energy.

Table 3. Activity of replying utilities

Activity	Number of companies including each activity in their business	Percentage of companies including each activity in their business
Transmission (≥ 220 kV)	23	92%
Generation	20	80%
Distribution	19	76%

The pie chart in Figure 1 presents the distribution of company activities:

Figure 1. Company activities



- Fifteen companies, representing the 60% of the answers, declare to include all the three activities: Generation, Transmission and Distribution.
- Three companies, representing the 12% of the answers, declare to include Generation and Transmission exclusively.
- Three companies, representing the 12% of the answers, declare to include Transmission exclusively.
- Two companies, representing the 8% of the answers, declare to include Transmission and Distribution.
- Two companies, representing the 8% of the answers, declare to include Generation and Distribution.
- No one company declares to include Distribution exclusively.
- No one company declares to include Generation exclusively.

2.3 Company size

Figure 2 to 7 illustrate the size of the companies that answered to the survey based on different parameters such us: maximum load peak, annual demand of energy, installed generating power, number of substations and length of lines in service. Some of these indexes only apply to a particular segment of the electric power business. In those cases, the figures shown have been built attending only to the companies in which those parameters are applicable and provided necessary data.

2.3.1 All companies

Figure 2 and 3 present the load peak and the energy demand respectively. Load peak is probably the best parameter to compare the size of the companies. Sixteen companies provided their load peak resulting in a mean value of 12,438 MW. Fourteen utilities supplied data about energy demand resulting in a mean value of 58,916 GWh.

Figure 2. Load peak

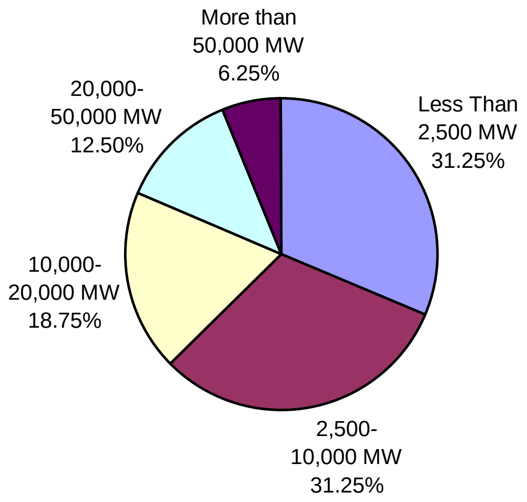
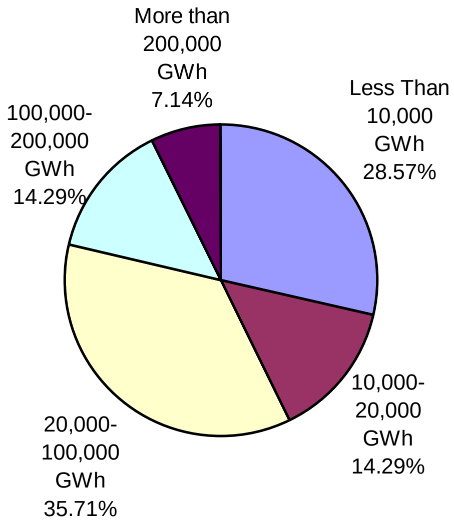


Figure 3. Energy demand



2.3.2 Generation companies

Figure 4 presents the size of the generation companies that responded the survey attending to the installed generation power. Nineteen companies provided their generating capacity resulting in a mean value of 29,534 MW. Figures in the chart represent the percentage of companies with an installed generation power in each power rank.

Figure 5 presents the distribution of the installed generation power, attending to the type of the primary energy. Figures in the chart represent the percentage that represents the installed power of each type from the total of the installed generation power. The chart shows the high presence of power plants based on traditional technologies (thermal, hydroelectric and nuclear) versus the new ones, which represent 0.21% only, being wind energy the most extended.

Figure 4. Generating capacity

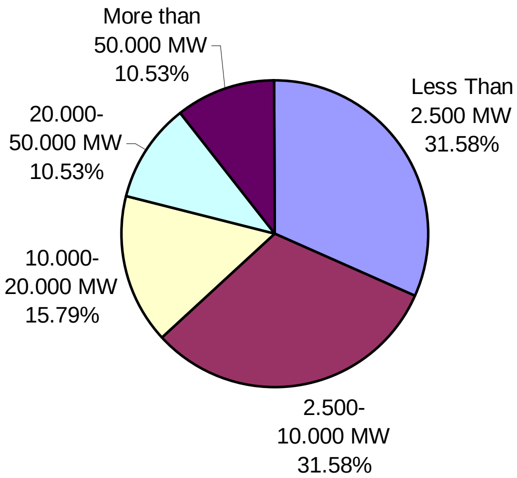
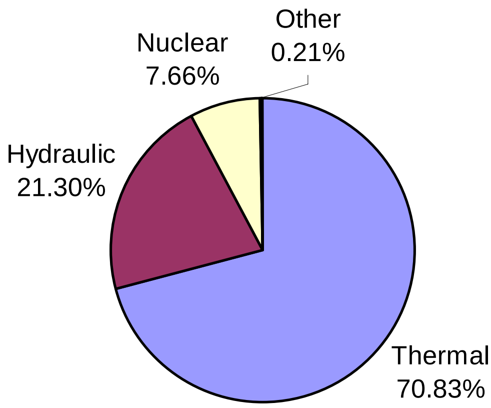


Figure 5. Generation type



Some results from the survey to show up:

- Nuclear: The 44% of generation companies declare to have nuclear power plants, being 3,789 MW the mean value of nuclear power installed.
- Thermal: The 68% of generation companies declare to have thermal power plants, being 22,670 MW the mean value of thermal power installed.
- Hydroelectric: The 64% of generation companies declare to have hydroelectric power plants, being 7,243 MW the mean value of hydroelectric power installed.
- Wind: The 28% of generation companies declare to have wind power plants, being 163 MW the mean value of wind power installed.
- Sun: Only two generation companies declare to have sun power plants, being 543 kW the mean value of sun power installed.
- Other: One company declares to have 3.3 MW of geothermal power installed, and another company declares to have 0.2 MW of phosphate fuel batteries installed.

2.3.3 Transmission and Distribution companies

The next figures provide some reference data about the size of the Transmission and Distribution networks of the companies that answered the survey. The parameters used are the number of substations and the total length of lines. Both are presented classified by voltage level.

Table 4 summarizes, by voltage level, the mean values for the number of substations and kilometres of lines (overhead, underground and total) got from the answers to the survey.

Table 4. Substations and lines

	Voltage	Number of substations	km of overhead power lines	km of underground cables	km of lines
Transmission	$V_n \geq 220$ kV	45	11,368	151	11,428
Distribution	220 kV > $V_n \geq 66$ kV	225	17,963	671	18,467
	66 kV > $V_n \geq 30$ kV	72	1,397	70	1,350
	30 kV > V_n	6,453	5,529	1,553	6,962
	Total: 220 kV > V_n	4,068	21,462	1,837	22,862

Figure 6 presents the percentage of utilities that have in each voltage rank a number of substations lower than the number indicated in X-axis.

Figure 6. Substations by voltage level

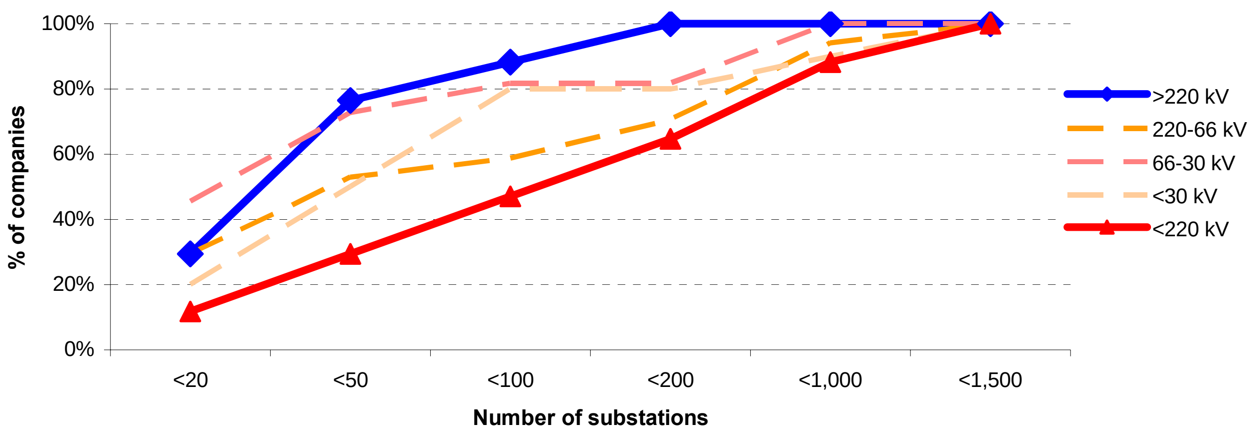
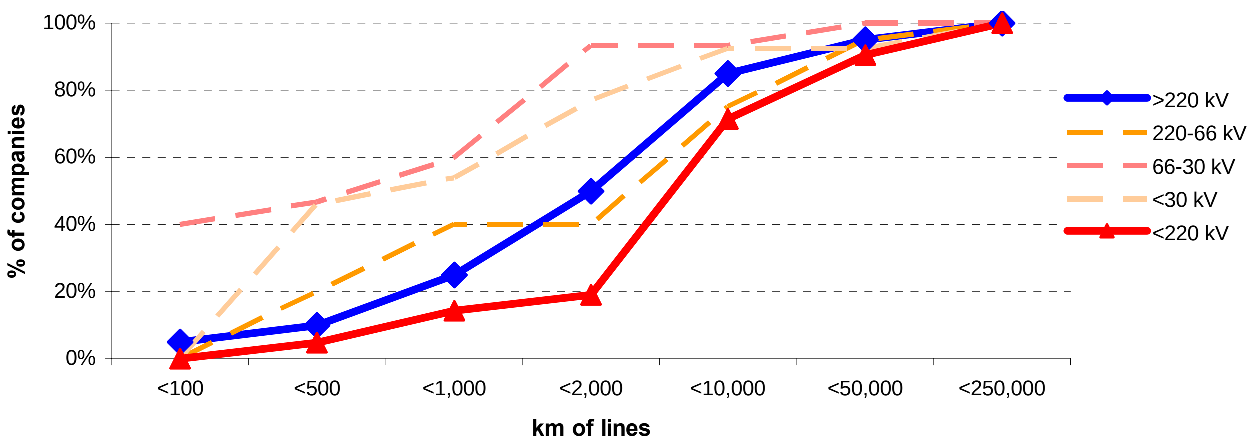


Figure 7 presents the percentage of utilities that have in each voltage rank a length of lines lower than the number indicated in X-axis.

Figure 7. Length of lines by voltage level



3 Equipment

This chapter summarizes information about the recording devices used nowadays by utilities around the world, the installing criteria applied and the recording capacity available.

Recording devices were classified by the working group in the categories listed in Table 5 according to the type of information recorded. Three more types (tape recorder, phasor measurement unit and power plant computer) were initially considered by working group and included in the questionnaire but no company declared to use them so they have not been considered in this report. Utilities were asked about the different devices of each type that they used and their installation criteria (voltage levels where they are installed, year they are used since, number of devices installed of each model …). From the survey responses, a population of 30,839 device units has been considered, resulting in 44.87% of them being non-digital protection relays (PR), 28.22% being digital protection relays (DPR), 10.44% being remote terminal units (RTU) for SCADA, and 7.83% being digital fault recorders (DFR). Non-digital protection relays are the most numerous, and only the 28% of the utilities use them for analysis purposes.

Table 5. Usage of recording devices

Device type		% of units	Used since (% based on the total of each type)		% of utilities that use it	Voltage levels (kV)
			Before 1995	Since 1995 or after		
COM	Substation computer	0.45	21.74	78.26	20.00	From 77
DFR	Digital fault recorder	7.83	90.98	9.02	84.00	From 15
DPR	Digital protection relay	28.22	68.18	31.82	72.00	All
DR	Multi-purpose digital recorder	0.98	30.13	69.87	32.00	From 13.8
DSR	Digital dynamic swing recorder	0.23	95.77	4.23	12.00	400
EMR	Electro-mechanical recorder	0.14	100	0	16.00	All
FL	Fault locator	2.28	86.75	13.25	36.00	From 6
PQ	Power quality recorder	3.96	49.63	50.37	56.00	From 6
PR	Non-digital protection relay	44.87	99.95	0.05	28.00	All
RTU	Remote terminal unit	10.44	99.94	0.06	20.00	From 4
SA	Substation automation system	0.11	55.88	44.12	20.00	From 10 to 220
SER	Sequence of events recorder	0.49	84.51	15.49	24.00	From 10
Total		**100**	-	-	-	-

Figure 8 presents the percentage of utilities that use each type of device for disturbance analysis. Digital fault recorders (DFR) and digital protection relays (DPR) are the most frequently used devices for disturbance recording and analysis purposes, being used by 84% and 72% of the utilities respectively. Power quality recorders (PQ) are used by the 56% of the utilities. Figure 9 presents the mean device-type distribution in a utility. Digital protection relays (DPR) and digital fault recorders (DFR) are, with great difference, the most numerous types of devices, representing 31.87% and 28.64% respectively from the total of recording devices used by a company.

It should be mentioned that there is an increasing tendency in the last few years to replace non-digital devices for digital ones and that the tendency to install digital fault recorders (DFR) is stopping due to the availability of the fault-recording feature in digital protection relays (DPR).

Figure 8. Equipment used for fault analysis

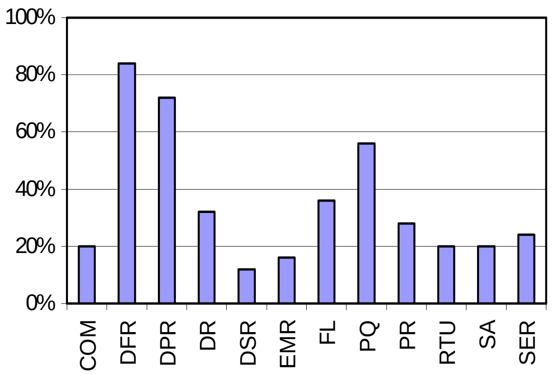
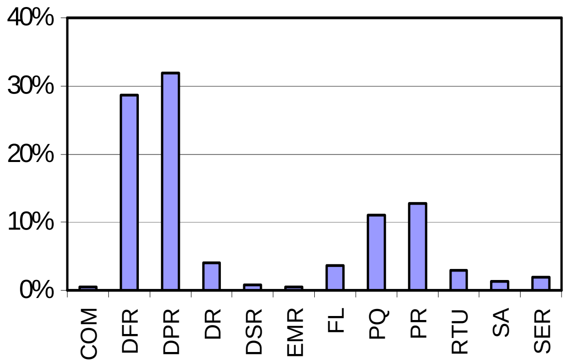
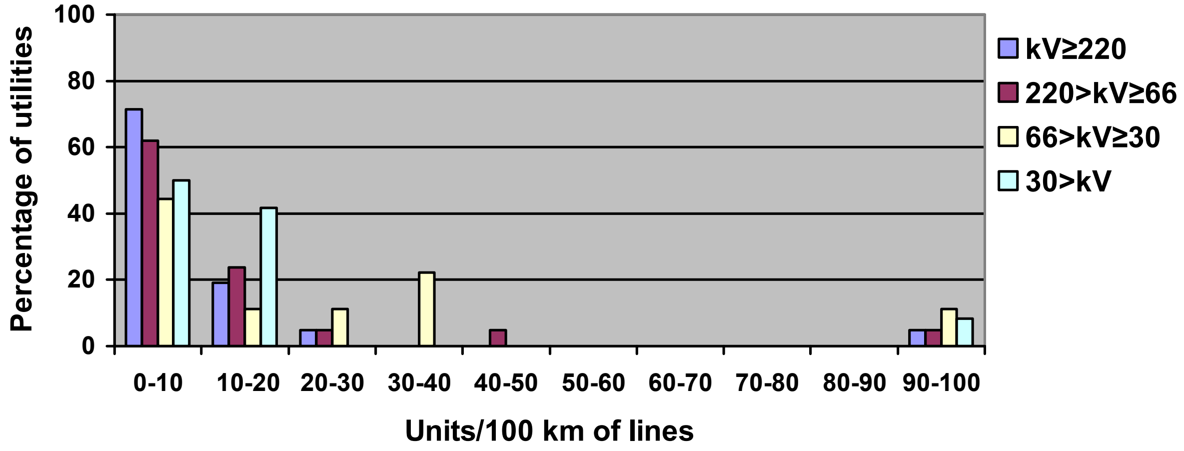


Figure 9. Company recording equipment



Of course, this data is related to the size of the company. Figure 10 compares the number of recording devices installed per 100 km of lines in each voltage level. The mean values are 10 units per 100 km of lines at Transmission voltage levels, 13.41 units per 100 km of lines at Distribution voltage levels over 66 kV, 21.95 units per 100 km of lines at voltage levels under 66 kV and over 30 kV, and 13.62 units per 100 km of lines at voltage levels under 30 kV.

Figure 10. Recording devices installed



Talking about the number of recording devices installed per substation, we can point out that the mean values are: 5.45 at Transmission voltage levels, 5.72 at Distribution voltage levels over 66 kV, 8.32 at voltage levels under 66 kV and over 30 kV, and 6 at voltage levels less than 30 kV.

Regarding the different types of recording devices, Table 6 shows the mean number of devices of each type installed per 100 km of lines at each voltage level. The empty cells correspond to those cases about which responses to the questionnaire did not provide data.

Table 6. Number of recording devices/100 km of line

Device type		Transmission	Distribution		
			220>kV>66	66>kV>30	30>kV
COM	Substation computer with storage, communication and processing functions	0.32	0.11	0.10	0.12
DFR	Digital fault recorder	1.40	1.64	2.01	2.50
DPR	Digital protection relay	3.17	6.68	9.05	6.83
DR	Multiple-purpose digital recorder	0.77	0.70	3.59	0.60
DSR	Digital dynamic swing recorder	0.20	0.50	-	0.50
EMR	Electro-mechanical (paper) recorder	0.25	0.30	0.15	0.15
FL	Dedicated fault locator	0.49	0.93	0.89	0.80
PQ	Power quality recorder	0.44	0.96	3.04	1.37
PR	Non-digital protection relay	22.94	21.06	27.52	26.92
RTU	Remote terminal unit	2.08	2.18	1.64	1.39
SA	Substation automation system	0.58	0.45	-	0.17
SER	Sequence of events recorder	0.36	0.55	0.41	0.64
Total		**10.00**	**13.41**	**21.95**	**13.62**

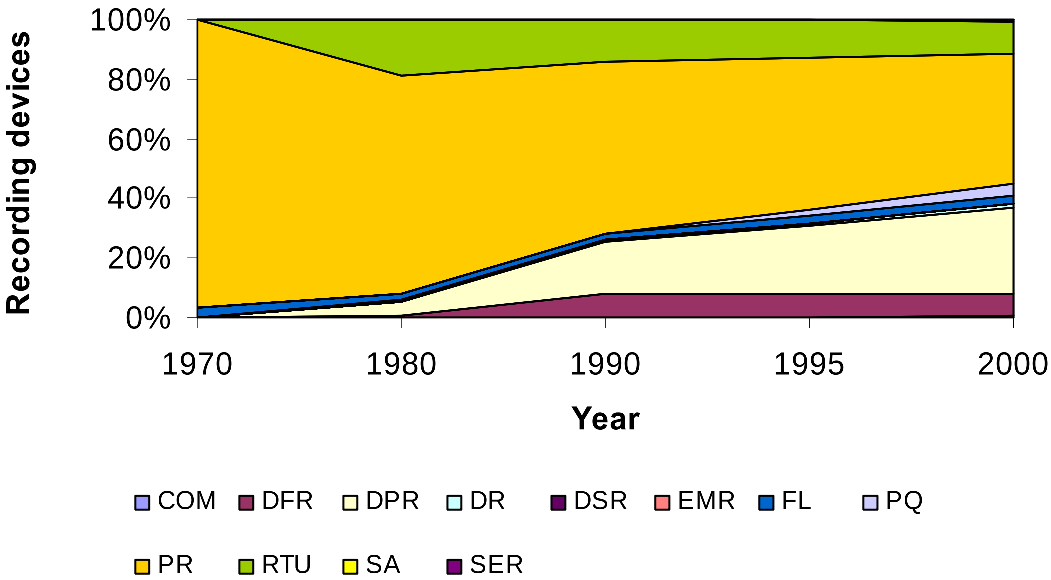
Table 7 shows the mean number of devices of each type installed per substation at each voltage level. The empty cells correspond to those cases about which responses to the questionnaire did not provide data.

Table 7. Number of recording devices/substation

Device type		Transmission	Distribution		
			220>kV>66	66>kV>30	30>kV
COM	Substation computer with storage, communication and processing functions	0.24	0.04	-	-
DFR	Digital fault recorder	0.73	0.56	0.80	-
DPR	Digital protection relay	1.40	2.23	2.44	1.69
DR	Multiple-purpose digital recorder	0.27	0.24	1.04	1.13
DSR	Digital dynamic swing recorder	0.12	-	-	-
EMR	Electro-mechanical (paper) recorder	0.17	0.19	0.08	0.08
FL	Dedicated fault locator	0.30	0.44	0.12	0.11
PQ	Power quality recorder	0.40	0.23	0.07	0.18
PR	Non-digital protection relay	11.01	8.85	10.92	12.46
RTU	Remote terminal unit	0.54	0.50	0.22	0.24
SA	Substation automation system	0.20	0.24	-	0.18
SER	Sequence of events recorder	0.22	0.24	0.21	0.25
Total		**5.45**	**5.72**	**8.32**	**6.00**

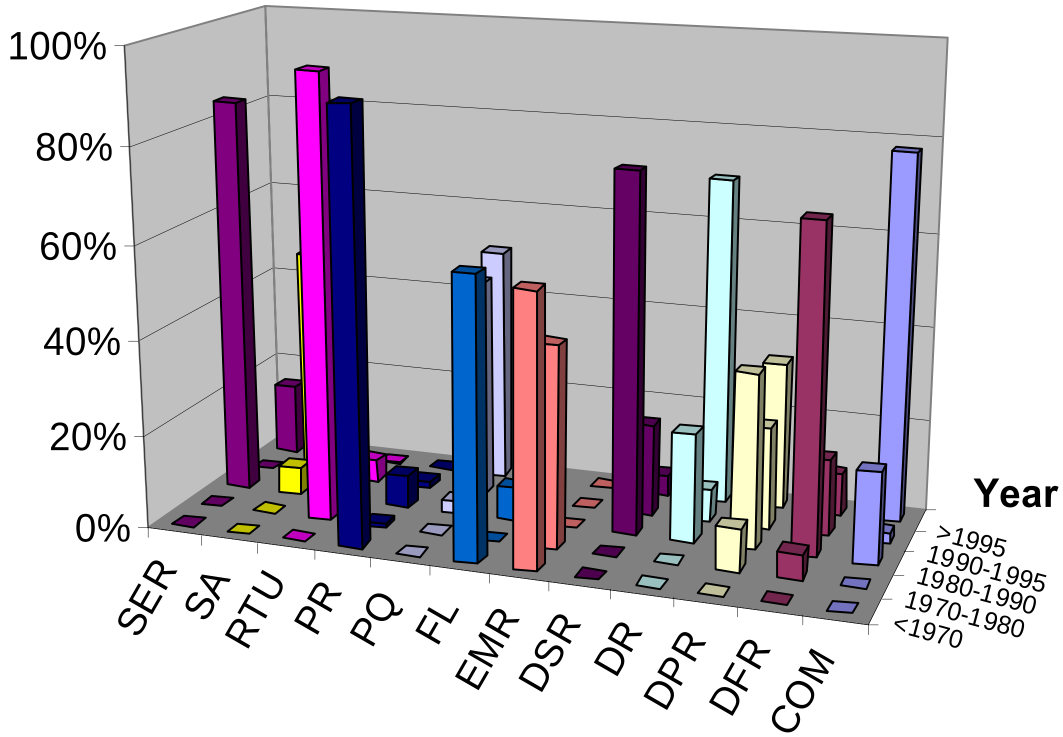
Another interesting variable is the age of the equipment. Figure 11 presents the evolution in time observed in the distribution of the recording devices installed. Until 1970, non-digital protection relays (PR) were practically the only source of information for disturbance analysis purposes with a few fault locators (FL) and electro-mechanical recorders (EMR). The seventies saw the SCADA development and the arrival of the numerical technology with the application of the first digital protection relays (DPR) and digital fault recorders (DFR), but it was in the eighties when digital protection relays (DPR) and digital fault recorders (DFR) experienced a strong growth reaching respectively the 17.9% and the 7.6% of the recording devices installed. Nineties attended to the consolidation of the tendency to replace non-digital protection relays (PR) for digital ones (DPR), reaching the 31.8% of the total recording devices although the 44% of them are still non-digital. However, a stop in the tendency to install digital fault recorders (DFR) was observed due to the improvement of the fault-recording feature of digital protection relays (DPR). Also in the nineties new devices like the power quality recorders (PQ) and multi-purpose digital recorders (DR), come to the recording device family and will probably have a big development in next future.

Figure 11. Distribution of recording devices. Evolution in time



Device type		<1970	1970-1980	1980-1990	1990-1995	>1995
COM	Substation computer	0.00%	0.00%	0.12%	0.12%	0.46%
DFR	Digital fault recorder	0.00%	0.77%	7.61%	8.08%	7.69%
DPR	Digital protection relay	0.00%	4.87%	17.86%	22.86%	29.01%
DR	Multi-purpose digital recorder	0.00%	0.00%	0.31%	0.35%	1.01%
DSR	Digital dynamic swing recorder	0.00%	0.00%	0.24%	0.26%	0.24%
EMR	Electro-mechanical recorder	0.06%	0.09%	0.06%	0.05%	0.05%
FL	Fault locator	3.37%	2.53%	2.07%	2.36%	2.35%
PQ	Power quality recorder	0.00%	0.00%	0.15%	2.34%	4.09%
PR	Non-digital protection relay	96.57%	73.24%	57.66%	50.81%	43.98%
RTU	Remote terminal unit	0.00%	18.50%	13.63%	12.45%	10.78%
SA	Substation automation system	0.00%	0.00%	0.01%	0.07%	0.11%
SER	Sequence of events recorder	0.00%	0.00%	0.27%	0.23%	0.24%
Total		**100%**	**100%**	**100%**	**100%**	**100%**

Figure 12. Devices age



Device type		<1970	1970-1980	1980-1990	1990-1995	>1995
COM	Substation computer	0.00%	0.00%	19.57%	2.17%	78.26%
DFR	Digital fault recorder	0.00%	5.49%	69.03%	16.46%	9.02%
DPR	Digital protection relay	0.00%	9.23%	37.09%	21.85%	31.82%
DR	Multi-purpose digital recorder	0.00%	0.00%	23.18%	6.95%	69.87%
DSR	Digital dynamic swing recorder	0.00%	0.00%	76.06%	19.72%	4.23%
EMR	Electro-mechanical recorder	57.14%	42.86%	0.00%	0.00%	0.00%
FL	Fault locator	59.26%	0.00%	7.12%	20.37%	13.25%
PQ	Power quality recorder	0.00%	0.00%	2.78%	46.85%	50.37%
PR	Non-digital protection relay	90.76%	0.83%	7.06%	1.29%	0.05%
RTU	Remote terminal unit	0.00%	94.38%	0.78%	4.78%	0.06%
SA	Substation automation system	0.00%	0.00%	5.88%	50.00%	44.12%
SER	Sequence of events recorder	0.00%	0.00%	84.51%	0.00%	15.49%

Figure 12 presents the age distribution of the recording devices installed nowadays. Can be showed up that:

- Most of sequence of events recorders (SER), the 84.5% of them, are 20 to 25 years old. The new substation automation systems include this functionality so they are replacing the sequence of events recorders (SER).
- The 94.1% of substation automation systems (SA) were installed in the nineties.
- Most of remote terminal units (RTU), the 94.4% of them, are 30 to 35 years old. The tendency nowadays is to change the classic RTU by substation automation system that includes the functionality to communicate with SCADA.
- Most of non-digital protection relays (PR), the 96.6% of them, are more than 35 years old, and the rest are more than 15 years old. Clearly, the tendency is to replace these relays by digital protection relays.

- The power quality recorders (PQ) are new devices installed from nineties until now. It is a clear tendency to increase the number of units installed in the future.
- The 59.6% of fault locators (FL) are old devices with more than 35 years, but the 33.6% of them are less than 15 years old. The tendency is not to install special devices for fault location and to include this functionality in digital protection relays.
- Electro-mechanical recorders (EMR) that are still in service are more than 25 years old. Digital fault recorders replaced them in the eighties and afterwards this functionality was included in digital protection relays.
- Digital dynamic swing recorders (DSR) started in the eighties and 85.5% of them are 10 to 25 years old. In nineties, a reduction in the number of units installed was observed, probably due to the appearance of the multi-purpose digital recorders.
- Multi-purpose digital recorders (DR) started in the eighties also and 69.9% are less than 10 years old. The present tendency is to increase their number.
- Digital protection relays (DPR) started in the seventies, the 9.2% of them are more than 25 years old, the 37.1% are 15 to 25 years old, the 21.9% are 10 to 15 years old and the rest 31.8% are less than 10 years old. The present tendency is to increase their functionality: fault location, fault recording, events recording, monitoring, bay control… and use them instead of other devices like fault locators, fault recorders and sequence of events recorders.
- Digital fault recorders (DFR) started in the seventies, the 5.5% of them are 25 to 35 years old, but most of them, the 69% were installed in the eighties. The resting 25.5% are less than 15 years old. Nowadays the trend is to replace digital fault recorders including their functionality in digital protection relays.
- The installation of substation computers (COM) has experienced an increase in the last 10 years due to substation automation systems boom and the development of monitoring technology and maintenance management based on it.

4 Data

This chapter summarizes information about data collected by recording devices used nowadays by utilities around the world. Data are classified in three types: analogue signals, binary signals and other signals.

4.1 Analogue signals

Mainly, analogue signals recorded are phases and neutral currents, and phases to ground and neutral to ground voltages, although other analogue signals are occasionally recorded like current and voltage phasors, active power, reactive power, generator excitation…

Figure 13 presents the percentage of devices of each type that provide analogue signal recordings that are used for disturbance analysis purposes. Obviously, all digital fault recorders (DFR) and electro-mechanical recorders (EMR), and the 100% of multi-purpose digital recorders provide analogue signal recordings for disturbance analysis purposes. In addition, the 95.77% of digital dynamic swing recorders (DSR), the 96.48% of power quality recorders (PQ), and the 83.93% of digital protection relays (DPR) provide analogue signal recordings that are used for disturbance analysis purposes. As has been mentioned in the previous chapter, digital protection relays (DPR) are replacing digital fault recorders (DFR) and electro-mechanical recorders (EMR) in this function. Neither non-digital relays (PR) nor sequence of events recorders (SER) provides analogue signal recordings. Remote terminal units (RTU), substation automation systems (SA) and substation computers (COM) are occasionally providers of analogue signal recordings, although their sampling rates are very much lower than those corresponding to fault recorders and digital protection relays.

Figure 13. Devices recording analogue signals for disturbance analysis

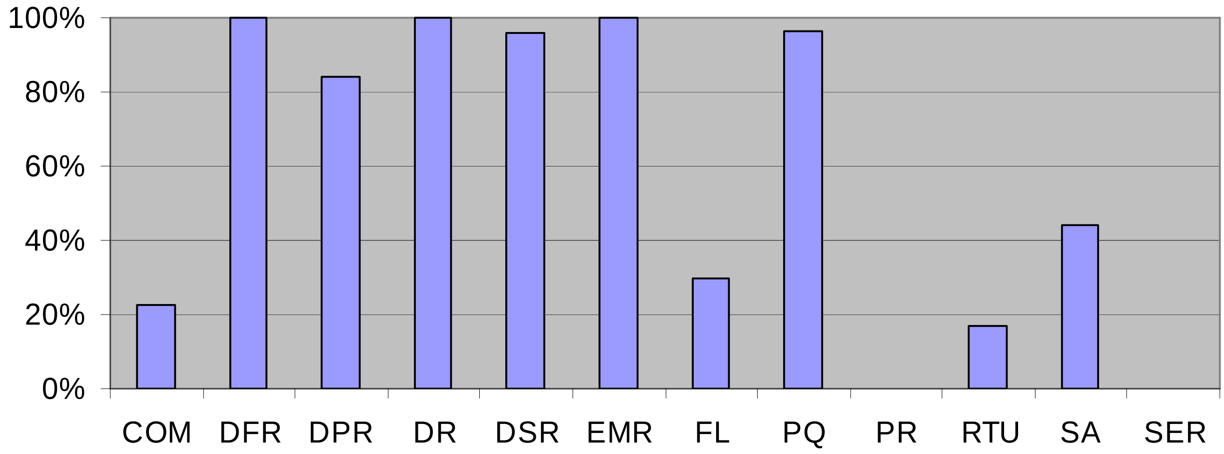
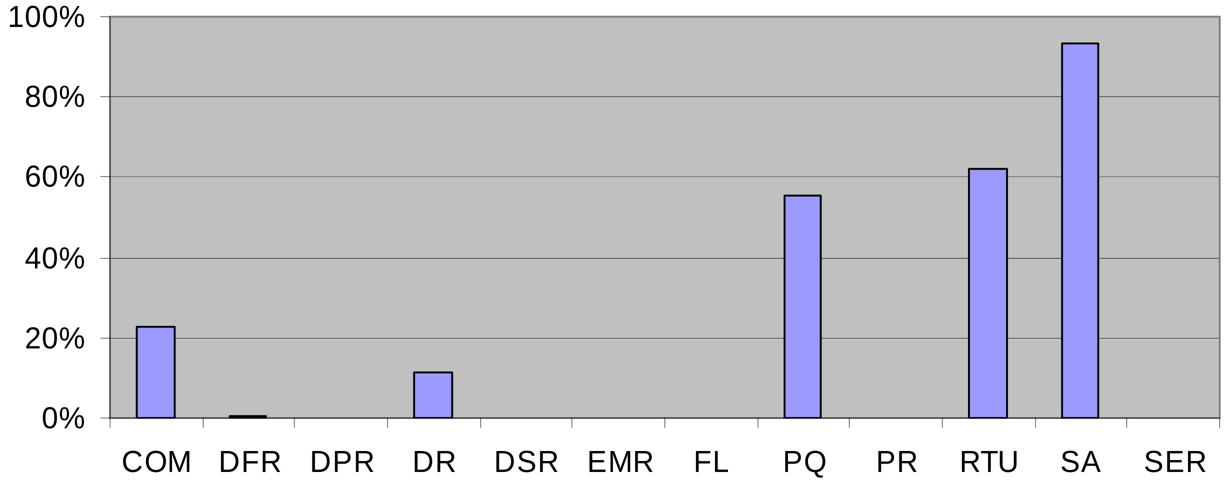


Figure 14 presents the percentage of devices of each type that provide permanent analogue signal recording that is used for analysis purposes. All recording devices have a limited storage capacity. Consequently, in order to avoid significant data losses, two solutions are possible:

- To extract the information frequently to a massive storage device (in this case all data are permanently stored although only those related to the events analysed will be used).
- To retrieve useful data immediately after an interesting event occurs (in this case all data are temporarily stored in the recording device and only those data related to the events to analyse are retrieved and permanently stored).

Substation automation systems (SA) in the 93.33% of the cases, remote terminal units (RTU) in the 62.29% of the cases, power quality recorders (PQ) in the 55.60% of the cases, and occasionally, in the 22.58% of the cases, substation computers (COM) and multi-purpose digital recorders (DR) in the 11.59% of the cases, use continuous recording of analogue signals.

Figure 14. Continuous analogue signals recording



The instantaneous values of the magnitudes measured are sampled at a frequency that depends on the recording features of each device and the number of records and their length depend on the storage capacity of each device. Usually, recorders measuring several analogue signals will generate large files. In these cases, using a long recording time causes fast run out of memory. To manage these restrictions, most of devices are programmed to trigger their recording facilities under certain conditions or events like a relay tripping, a magnitude surpassing certain value, or a certain rate of change in a magnitude. Figure 15 presents the percentage of devices of each type that provide triggered analogue signal recording for analysis purposes. It must be mentioned that the 100% of digital fault recorders (DFR), digital protection relays (DPR), digital dynamic swing recorders (DSR), electro-mechanical recorders (EMR) and fault locators (FL), the 88.41% of multi-purpose digital recorders (DR), the 77.42% of substation computers (COM) and the 47.03% of power quality recorders (PQ) are configured to record analogue magnitudes under tripping conditions. Remote terminal units (RTU) in the 37.71% of the cases only, and occasionally substation automation systems (SA), in the 6.67% of the cases resort to triggered recording.

Figure 15. Triggered analogue signals recording

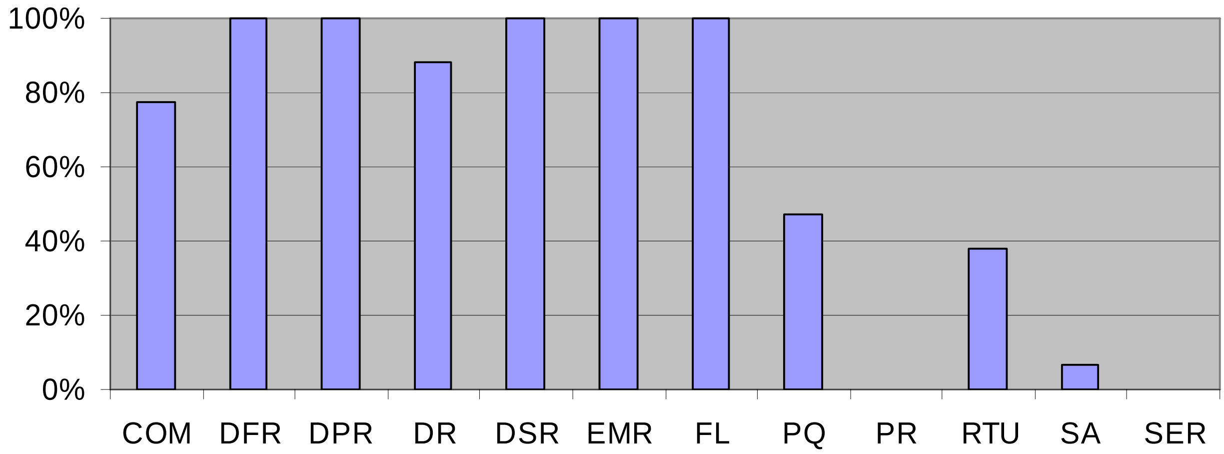
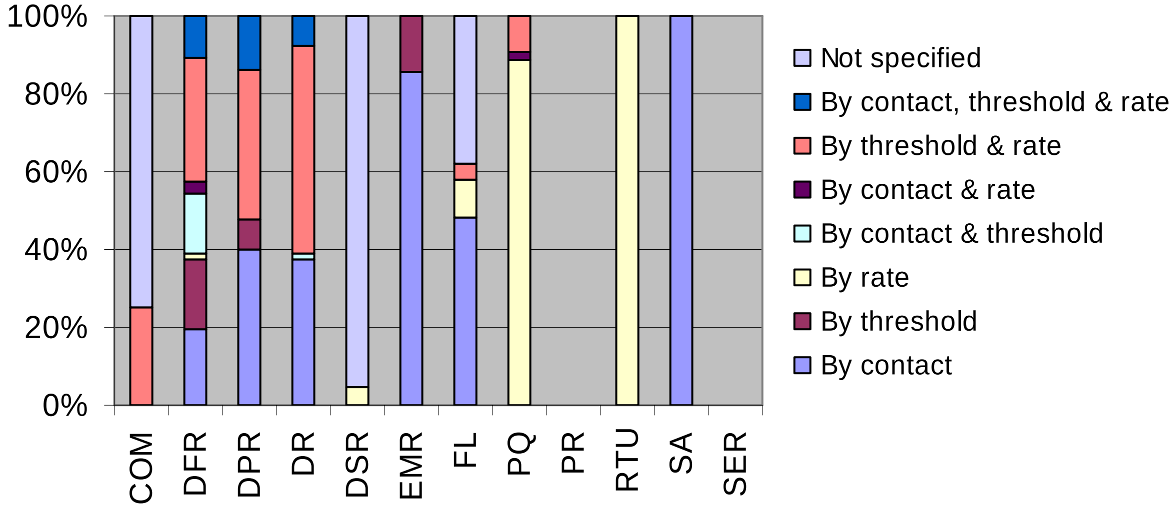


Figure 16 summarizes the modes of triggering analogue signal recording used. Three triggering methods are considered:

- By contact. It means that recording starts when an event occurs that cause a change in the status of a contact. It can be a trip order from a protection relay, a breaker opening, a breaker closure…
- By threshold. It implies that recording starts when a measured magnitude either surpasses certain value or goes underneath certain value.
- By rate. It means that recording starts when a measured magnitude rises or decreases in time over a certain rate.

The triggering method used depends on the type of device and mainly on the analysis purpose. Those devices whose recordings are used for power quality analysis or dynamic performance analysis like power quality recorders (PQ), digital swing recorders (DSR) are mainly triggered by threshold or rate, because it is not possible to guarantee that an event like a breaker opening or a relay tripping will occur in the substation associated to the studied phenomena. On the other hand, those devices whose recordings are used mainly for fault analysis such as electro-mechanical recorders (EMR), digital fault recorders (DFR), digital protection relays (DPR) or fault locators (FL), are triggered by contact (under tripping conditions usually) in a high percentage of the cases, close to 50% or higher. However, it is common practise that this method coexists with triggering by threshold or rate in order to get recordings in those cases when a failure trip occurs in fault condition. In the figure it can be seen that except in the cases of electro-mechanical recorders (EMR), fault locators (FL) and substation automation systems (SA), the percentage of devices programmed to trigger analogue signals recording exclusively by contact is under 40%. It means that, except in these three types mentioned (EMR, FL & SA) more than 60% of the recording devices installed are programmed to trigger analogue signals recording by threshold or rate, and especially by threshold.

Figure 16. Modes of triggering analogue signals recording

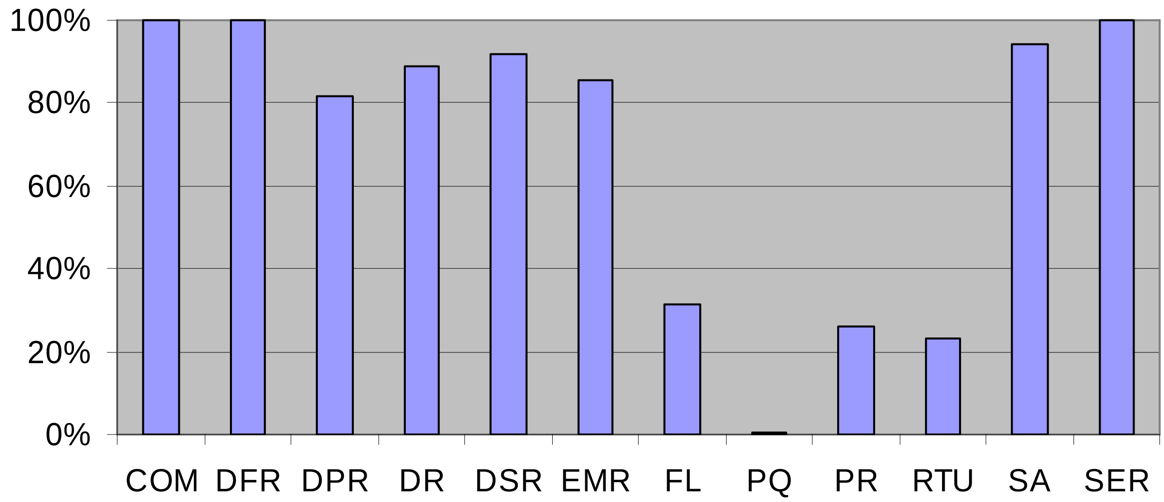


4.2 Binary signals

A binary signal means a status variable like circuit breaker status (open/close), protection relay status (tripped/not tripped), auxiliary contact status (open/close), protection function status (started/not started)…

Figure 17 presents the percentage of each type of device that provides binary signal time tagged recordings that are used by utilities for analysis purposes.

Figure 17. Devices recording binary signals for analysis



4.3 Other signals

From all the answers to the questionnaire collected, we can say that moreover analogue signals (currents and voltages) and binary signals, utilities commonly use other information provided by recording devices in the analysis of electrical network disturbances. Among this additional information, we can find the next records, reports, measurements or indications: energy, active power, reactive power, harmonics rates, voltage dip, fault location, flicker, frequency, air temperature, negative and zero sequence components of voltages and currents, impedance, phasors of voltages, currents and impedances and targets. Figure 19 in the next page presents the percentage of devices of each type that provide these data according to the responses received.

Figure 18 presents the installation criteria followed by utilities to install the fault location functionality in the network attending to the voltage level. The number of units per 100 km of lines installed at Transmission and Distribution voltage levels over 66 kV is almost twice the number of units per 100 km of lines installed at Distribution voltage levels below 66 kV.

Figure 18. Fault locators/100 km of lines

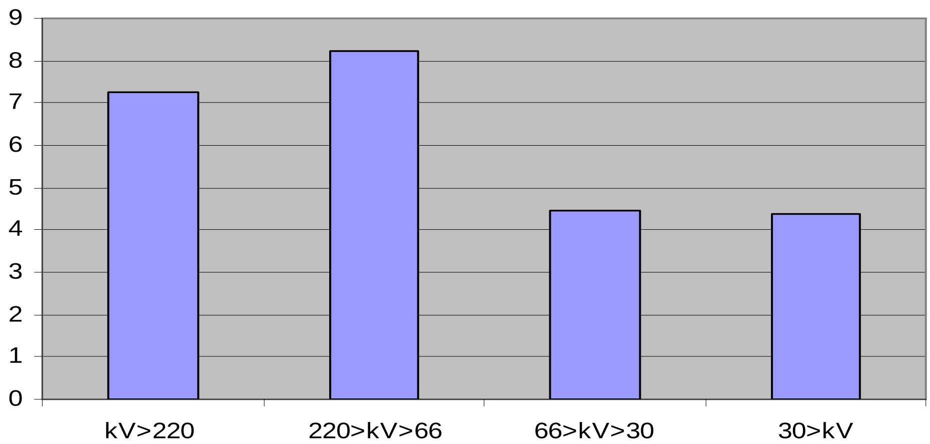
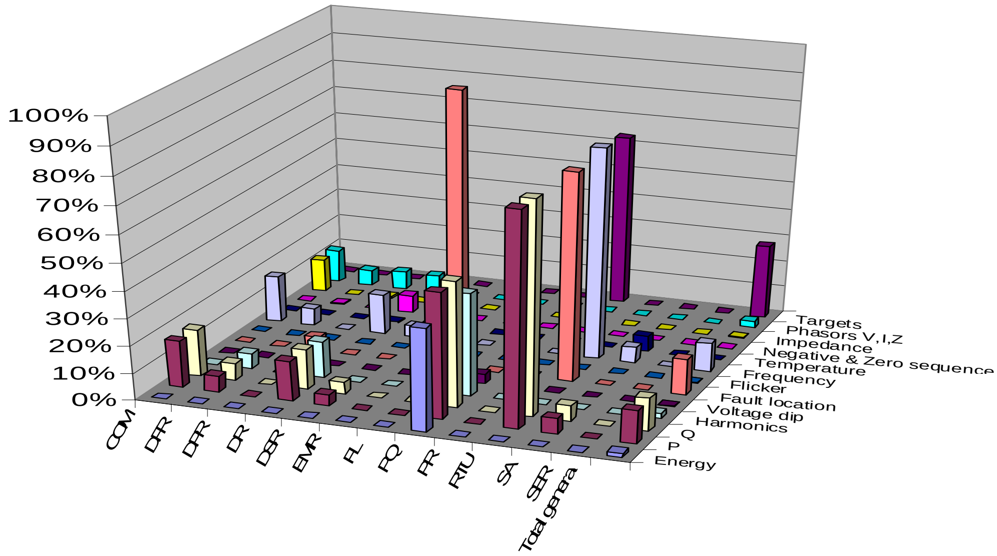


Figure 19. Devices recording other signals for disturbance analysis



Device type		Energy	P	Q	Harmonics	Voltage dip	Fault location	Flicker	Frequency	Air temperature	Neg. & Zero sequence	Impedance	Phasors: V, I, Z	Targets
COM	Substation computer	0	17.4	17.4	0	0	0	0	17.4	0	0	12.3	12.3	0
DFR	Digital fault recorder	0	6.1	6.5	5.8	0	0	0	6.5	0	0.4	0	5.8	0
DPR	Digital protection relay	0	0	0	0	0	5.3	0	0	0	0	0.8	6.8	0
DR	Multi-purpose digital recorder	0	14.9	14.9	13.6	0	0	0	14.9	0.33	6.6	0	6.6	0
DSR	Digital dynamic swing recorder	0	4.2	4.2	0	0	0	0	4.2	0	0	0	0	0
EMR	Electro-mechanical recorder	0	0	0	0	0	0	0	0	0	0	0	0	0
FL	Fault locator	0	0	0	0	0	100	0	0	0	0	0	0	0
PQ	Power quality recorder	37.8	46.2	46.2	37.8	3.52	0	0.08	5.3	0	0	0	0	0
PR	Non-digital protection relay	0	0	0	0	0	0	0	0	0	0	0	0	63.2
RTU	Remote terminal unit	0	77.5	77.5	0	0	75.9	0	77.5	0	0	0	0	0
SA	Substation automation system	0	5.9	5.9	0	0	0	0	5.9	5.9	0	0	0	0
SER	Sequence of events recorder	0	0	0	0	0	0	0	0	0	0	0	0	0

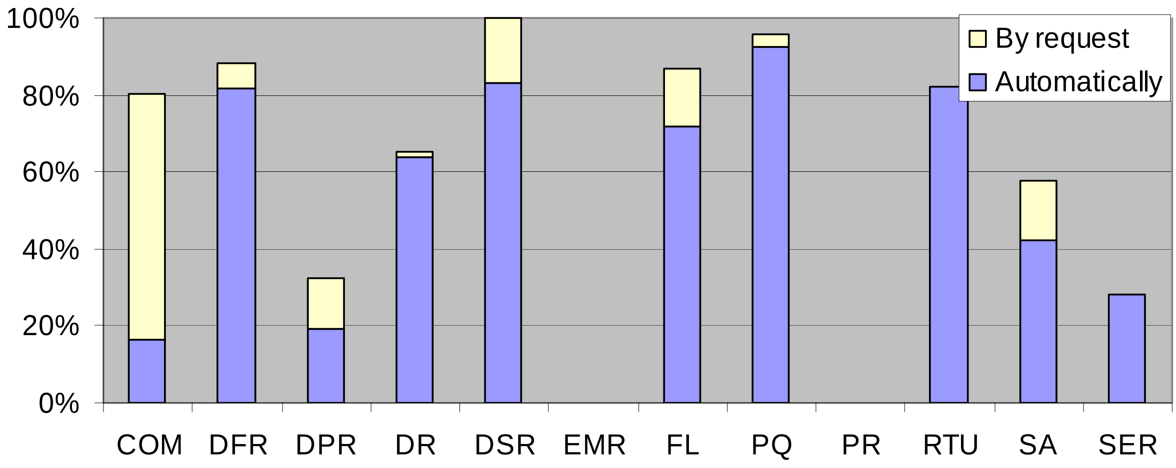
From data presented in Figure 19 can be shown that:

- The recognized use for disturbance analysis of additional information provided by digital protection relays (DPR) as fault location, phasors and impedance measured by the relay, is very limited being under 7%.
- Information about fault location is provided to operator by SCADA in the 76% of the cases.
- Information about targets of non-digital protection relays (PR) is still used in the 63% of the cases.
- Electro-mechanical recorders (EMR) and sequence of events recorders (SER) do not provide additional information but analogue and/or binary signals.

5 Data gathering, management and processing

Most of the devices have a limited memory that usually has a circular structure. It means that once the memory is full the new records are written over the oldest ones. In order to download to a central database all the interesting records before they be overwritten it is necessary to access frequently to the records in each device. To reduce time and costs to access to this information is a common practise to provide communications infrastructure to connect remotely with digital devices as digital fault recorders and digital protection relays. Figure 20 provides for each type of device the percentage of the installed units accessed remotely, distinguishing those accessed automatically from those that requires human intervention to retrieve data from the devices.

Figure 20. Remote data retrieval



It should be noticed that:

- The 33% of all the devices that provide information useful for disturbance analysis purposes are accessed remotely.
- The 59% of all the digital devices that provide information useful for disturbance analysis purposes are accessed remotely.
- Information from the most of the devices accessed remotely, the 85% of them, is automatically retrieved, and on the other hand only the 15% of them is requested with human intervention. Therefore, the utilities have developed in cooperation with their suppliers of digital devices, applications to retrieve data automatically.
- In practice, almost all digital fault recorders (DFR), multi-purpose digital recorders (DR), power quality recorders (PQ), remote terminal units (RTU) and sequence of events recorders (SER) that are accessed remotely, they are accessed automatically.
- On the other hand, only the 17% of the substation computers (COM) that are accessed remotely, they are accessed automatically.
- Only the 32% of the digital protection relays (DPR) are accessed remotely, and the 59% of them are accessed automatically.

Figure 21 summarizes the modes used to collect all data available for disturbance analysis. Most of information (70%) is collected at substation, and only 35.5% is collected remotely, (8.3% at regional level from regional offices, and 27.2% at central level from a central office). Percentages do not summarize 100% because some utilities follow the practice of collecting the same data at different levels.

Figure 21. Modes of data retrieval

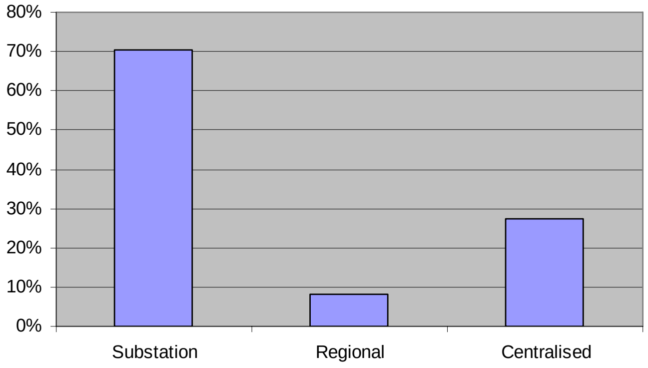
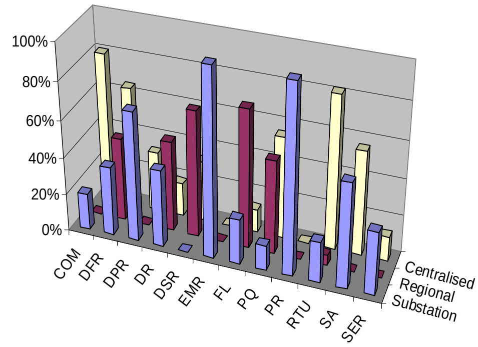


Figure 22. Modes of data retrieval by type of device



Device type		Substation	Regional	Centralised	Total
COM	Substation computer	19.57	0	80.43	100
DFR	Digital fault recorder	37.14	44.51	64.64	146.29
DPR	Digital protection relay	69.28	0	32.11	101.39
DR	Multi-purpose digital recorder	41.39	48.68	17.88	107.95
DSR	Digital dynamic swing recorder	0	67.61	32.39	100
EMR	Electro-mechanical recorder	100	0	0	100
FL	Fault locator	24.07	74.22	12.39	110.68
PQ	Power quality recorder	13.27	50.12	54.95	118.35
PR	Non-digital protection relay	100	0	0	100
RTU	Remote terminal unit	21.84	5.47	82.06	109.36
SA	Substation automation system	55.88	0	55.88	111.76
SER	Sequence of events recorder	33.77	0	13.25	47.02

Figure 22 shows figures about the modes used to collect data from different types of devices. Again, in some cases the percentages do not summarize 100% because some utilities follow the practice of collecting the same data at different levels. It can be shown that:

- Data from electro-mechanical recorders (EMR) and non-digital protection relays (PR) has to be collected locally at substation level and this contributes significantly to the high percentage of information retrieved at substation level.
- Around the 46% of the information from digital fault recorders (DFR) is collected at two levels. Most of utilities analyse these recordings at a central office but in no few cases these recordings are analysed at regional offices too.
- A high percentage (69.28%) of information from digital protection relays (DPR) is collected at substation level and only around the 32% is collected remotely and centralised.
- From figures can be deduced that utilities consider that information about fault location is more useful at regional level probably where maintenance crews are located, and this is the reason because data from fault locators is collected from regional offices in the 74.22% of the cases.
- From figures can be deduced that data from power quality recorders (PQ) are analysed at regional offices or at a central office being both possibilities equally preferred by utilities.
- In around the 22% of the cases the information from RTU for analysis purposes is collected locally at substation.
- Information from substation automation systems (SA) is collected fifty-fifty locally at substation and from a central office.
- In the case of sequence of events recorders (SER), the percentage of them accessed is very low (47.02%) due a utility that declared to have many units installed did not indicate in the survey the mode used to access them. Therefore, the only thing that we can conclude is that it

seems that the most of the information from sequence of events recorders is collected locally at substation in a rate of 3:1 respect to those accessed remotely.

Figures 23 and 24 offer information about the communication media adopted by utilities to access remotely to the data stored in recording devices. Figure 23 shows the percentage of utilities using each medium, and figure 24 shows the percentage of recording devices connected to each medium.

Figure 23. Communication media. Percentage of utilities

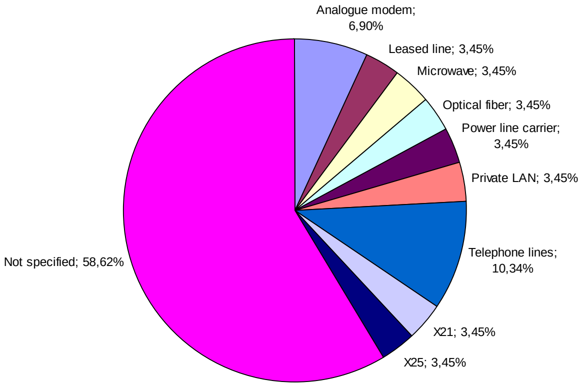
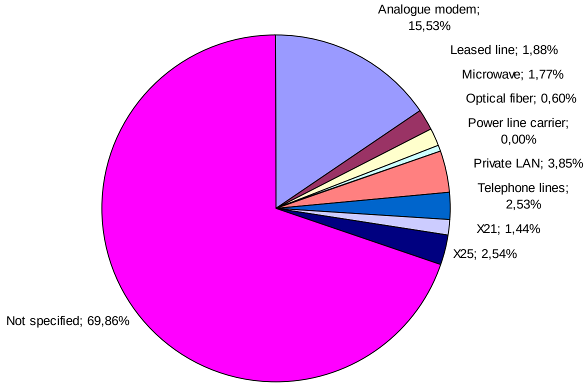


Figure 24. Communication media. Percentage of devices



The data transmission speed used varies a lot depending on the physical medium, from 200 bauds in power-line-carrier solutions to 64000 bauds in X21 solutions. Data transmission rates from 1200 to 9600 bauds are the most usual. Figure 25 shows the distribution of the number of recording devices communicating at each rate.

Figure 25. Data transmission speed (Bauds)

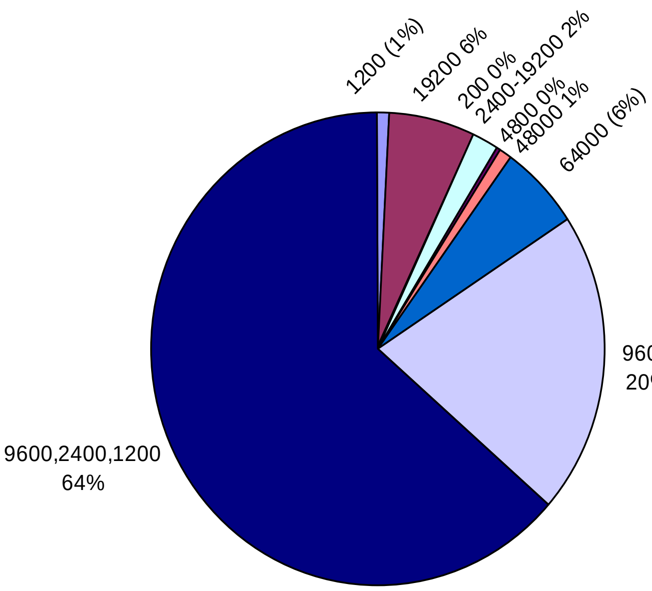


Figure 26 shows data about the types of protocols used. The number of recording devices accessed using proprietary protocols is higher than the ones using standard protocols (53.25% and 30.41% respectively). The remaining 16.34% has not been specified. The figure shows the proportion for each type of device.

Figure 26. Communication protocols

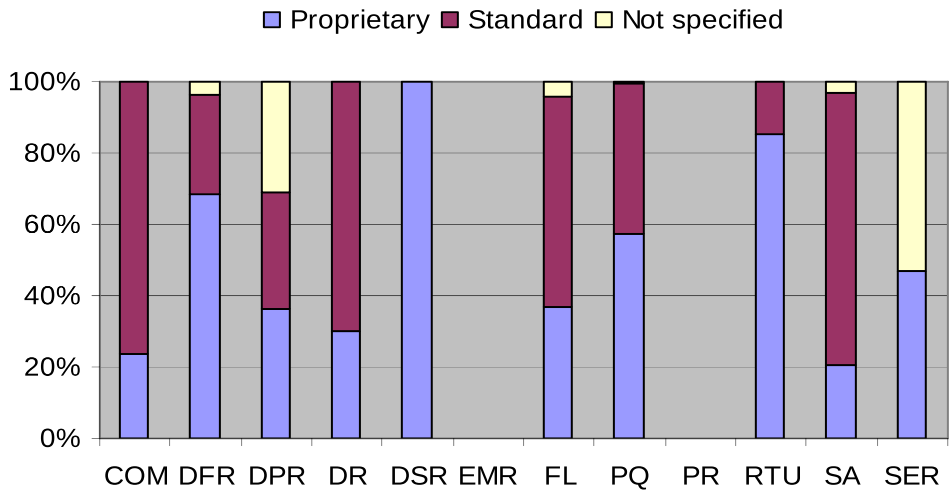


Figure 27. Data storage format. Percentage of devices

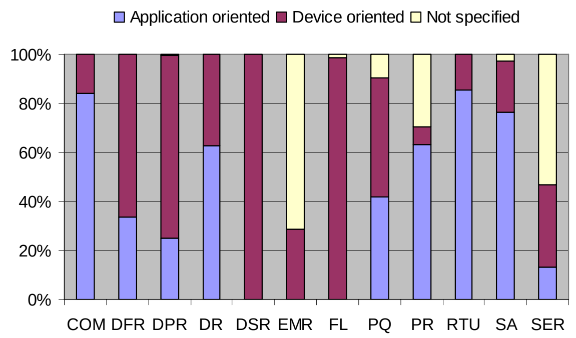
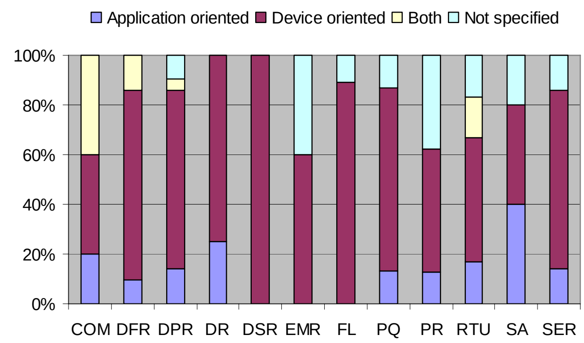


Figure 28. Data storage format. Percentage of utilities



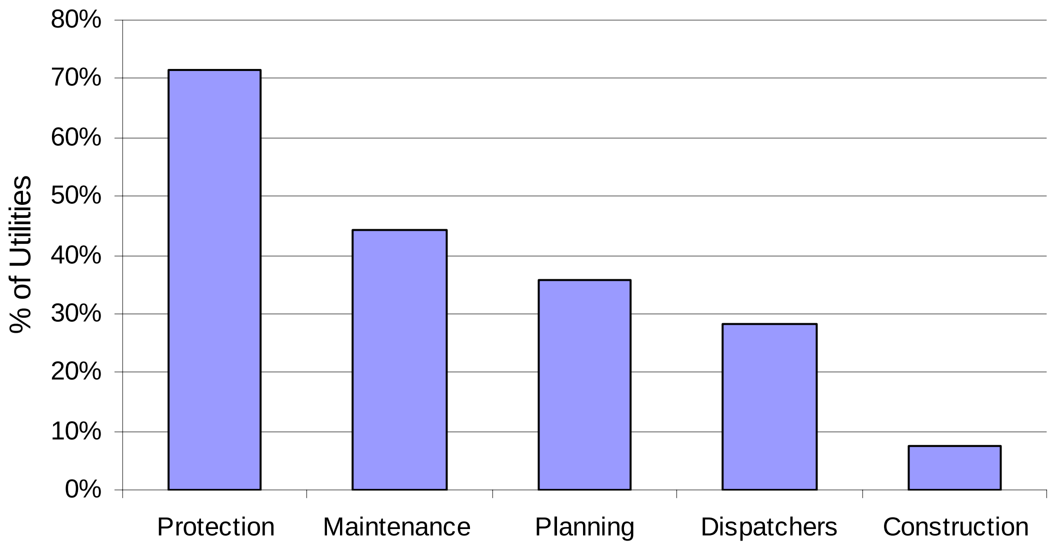
Figures 27 and 28 present information about the format used for data storage indicating if it is oriented to the application needs or is oriented to the device needs (usually conditioned by storage capacity limits and communication band-with restrictions). Figure 27 presents the percentage of devices whose data is stored in each of these formats. Figure 28 presents the percentage of utilities using each of these data formats by each type of recording device.

6 Applications

This chapter describes the main applications and uses of recorded data indicated nowadays by utilities, according to the survey responses collected. Applications have been classified in the following categories: fault analysis, maintenance, power system dynamic performance, power quality, device testing, modelling and others. In each category were studied the type of events or disturbances considered in the analysis, the equipment whose performance is checked, the list of users of the analysis results and how they use it, and finally, the data sources.

Talking about data users, figure 29 shows the percentage of companies that declare that data analysis concerns each of their departments (Protection, Maintenance, Planning, Dispatching and Construction) considering all possible applications.

Figure 29. Users



6.1 Fault analysis

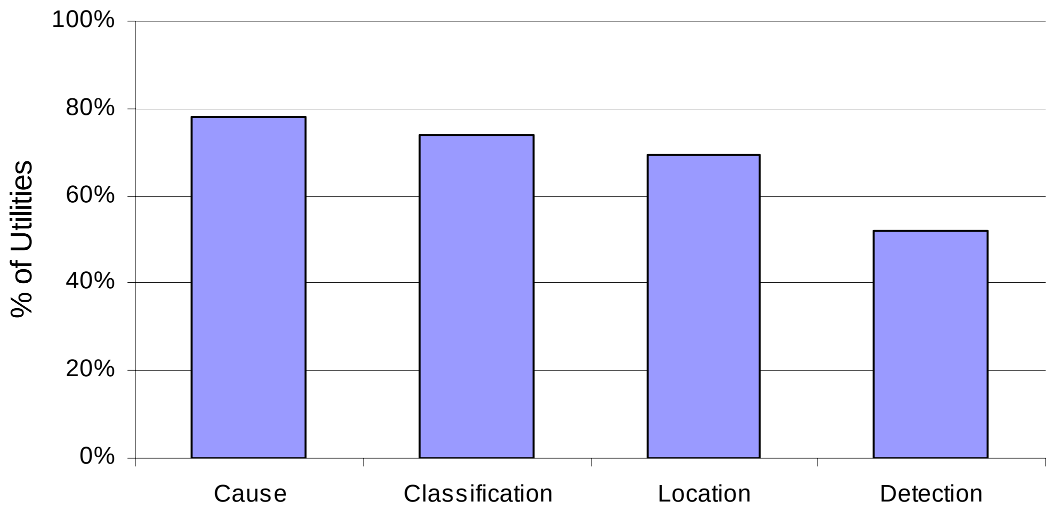
Among all the answers to the questionnaire received, 22 of them provided information about fault analysis practices. Table 8 summarizes them.

Table 8. Fault analysis applications

Topic	Practices
Event analysis	In most cases, the objectives are to determine cause, location and type of the fault. In some cases, current level and duration are included in the objectives.
Equipment performance evaluation	The performance of relays and breakers is evaluated.
Users	Protection and maintenance engineers. Dispatchers.
Data sources	All available information is used. Signals evaluated are voltage, current and frequency. No utility declares to use data from power quality recorders (PQ) and non-digital protection relays (PR) for fault analysis purpose.

As shown in figure 30, utilities use fault data mainly to determine the cause of disturbances. Special interest is given to the fault location to either know where to repair or to determine if the fault occurred in a customer plant or in external network. Special attention is given also to the type of fault in order to help maintenance people in fault location activities and to identify possible design failures. Recording devices help to determine the sequence of events and analyse the current levels and duration. The study of the network equipment performances is very important and the survey has shown that the most of the observed devices are protection relays and circuit breakers, which are exposed to a high level of stress conditions. Reliability of fault clearing and operating time are the parameters usually considered.

Figure 30. Uses of fault data



Usually, protection engineers analyse fault data and send their conclusions to the maintenance staff if repair is necessary or to dispatching engineers in order to minimise fault effects in the future. In some cases, all the information is managed and analysed by a central office, and the results of the analysis are distributed from there, but in other cases, actions analysis are made at regional level. As far as possible, all available data are used for fault analysis. In most cases, the observed signals are voltages, currents and frequency.

6.2 Maintenance

Among all the answers to the questionnaire received, 17 of them provided information about practices related to maintenance application of disturbance analysis. Table 9 summarizes them.

Table 9. Maintenance applications

Topic	Practices
Events considered	All faults. System monitoring.
Equipment performance evaluation	Relays and breakers are the most evaluated equipment. The importance of control is close to relays and breakers.
Users	Protection and maintenance engineers. Dispatchers.
Data sources	Mainly digital protection relays (DPR) and digital fault recorders (DFR)

The study of faults is important for maintenance, in fact 44% of utilities declare that maintenance people are involved in disturbance analysis as it is shown in figure 29. In the majority of disturbances, certain protection equipment is supposed to operate and the analysis of the available records allows one to observe the performance not only of the protection devices but the protected equipment as a whole.

Most of utilities check relays and breakers operation. Thanks to the analysis of the voltage and current records and the sequence of events list, it is possible to determine the operating time and the opened poles. Possible changes in relay settings or configuration are also monitored. The predictive maintenance must be promoted.

Maintenance personnel need this information, but also protection and planning engineers, who analyse and enhance equipment performance, and improve its reliability. The data sources for this application are mainly digital protection relays (DPR) and digital fault recorders (DFR).

6.3 Power system dynamic performance

Among all the answers to the questionnaire received, 18 of them provided information about practices related to the analysis of power system dynamic performance. Table 10 summarizes them.

Table 10. Analysis of power system dynamic performance

Topic	Practices
Events considered	Large disturbances involving power, voltage or frequency oscillations. Faults located in other networks.
Equipment performance evaluation	Protection system. Power plant control. Automatic voltage regulators (AVR). Power system stabilizer (PSS). Primary and secondary regulation performance evaluation.
Users	Planning engineers. Protection and maintenance engineers.
Data sources	Mainly digital protection relays (DPR), digital fault recorders (DFR) and power quality recorders (PQ). The signals studied are mainly active power, reactive power, voltage and frequency.

Only disturbances involving major power, voltage or frequency deviations are of special interest for dynamic analysis. Faults located in neighbouring networks are studied to analyse the response of the electrical system against an external disturbance. The analysis covers the working of the protection system (relays and breakers) and the power plants. The study of the performance of devices such as automatic voltage regulators (AVRs) or power system stabiliser (PSS) gives information on the system stability.

Planning engineers carry out stability and frequency analysis, as well as primary and secondary regulation performance while the protection engineers study the protection dynamic response and performance. The signals studied are mainly active and reactive power, voltage and frequency. They are obtained from different sources like digital protection relays (DPR), digital fault recorders (DFR) and power quality recorders (PQ).

6.4 Power quality

Among all the answers to the questionnaire received, 18 of them provided information about practices related to power quality applications. Table 11 summarizes them.

Table 11. Power quality applications

Topic	Practices
Events considered	Faults resulting in voltage dips. Faults with effects to the customers. Harmonics.
Equipment performance evaluation	Transformer tap changers. Instrument transformers.
Users	Dispatchers. Planning engineers. Protection engineers.
Data sources	Mainly digital fault recorders (DFR), digital protection relays (DPR), multi-purpose digital recorders (DR) and power quality recorders (PQ). Mainly the signal studied is voltage.

Different international standards, such as European Normative EN50160, require electrical companies to assure and to check the power system quality. Every time voltage variations or harmonics are recorded, and principally when a customer complains, the disturbance must be analysed in order to clarify the causes and to eliminate them in the future. Transformer and tap changer performances are studied in relation to power quality.

The users are mainly planning engineers and dispatchers. The parameter most commonly used to evaluate the power quality is the voltage that is recorded principally by digital fault recorders (DFR), digital protection relays (DPR), multi-purpose digital recorders (DR) and power quality recorders (PQ).

6.5 Device testing

Among all the answers to the questionnaire received, 14 of them provided information about practices related to device testing applications. Table 12 summarizes them.

Table 12. Device testing applications

Topic	Practices
Events considered	Events involving unexpected equipment behaviour or dysfunction.
Equipment performance evaluation	Relays and breakers are the most evaluated equipment.
Users	Maintenance staff. Protection engineers.
Data sources	Digital protection relays (DPR), fault recorders (DFR & EMR), and sequence of events recorders (SER).

Unexpected equipment behaviour or failures in operation of devices such as relays and breakers lead to analyse the recorded events. Maintenance staff uses data for performing spare parts management and scheduling equipment replacements. Protection engineers analyse, for instance, high resistance faults or failures of equipment. Data used are obtained from digital protection relays (DPR), fault recorders (DFR & EMR), and sequence of events recorders (SER).

6.6 Modelling

Among all the answers to the questionnaire received, 15 of them provided information about practices related to modelling applications. Table 13 summarizes them.

Table 13. Modelling applications

Topic	Practices
Events considered	Short-circuit events and all located faults. Large disturbances and instabilities.
Equipment performance evaluation	Results of computer network models are compared with disturbance recordings.
Users	Planning engineers. Protection engineers. Researchers.
Data sources	Digital fault recorders (DFR) and digital protection relays (DPR).

For modelling purposes, the records of permanent faults whose location is perfectly known are used. Large disturbances and instabilities are events of interest too. In general, the most interesting disturbances are those that can be precisely reproduced using computer models of the network. Also long records are used to evaluate the response in a long timeframe, in order to calibrate not only the immediate response of the network model, but also the long-term time response including restoration. The performance of the network model is evaluated by reproducing a fault whose record is available in a database. Afterwards, a comparison is made between the results of the computer network model and the fault record. This work is usually done by planning and protection engineers. The records used in these comparisons are obtained mainly from digital fault recorders (DFR) and digital protection relays (DPR).

6.7 Other applications

Table 14 summarizes the answers to the questionnaire received providing information about other applications.

Table 14. Other applications

Topic	Practices
Events considered	Representative or otherwise interesting faults.
Equipment performance evaluation	-
Users	Education staff.
Data sources	All the available recording devices.

Educational applications of recording device data are the most frequently mentioned in the survey responses. Education staff takes benefits of the representative or otherwise interesting faults for personnel education. Records for this purpose are retrieved from all the available recording devices.

7 Future trends

Every year, devices with new features appear in the market, improving the recording features of the existing devices. What is the policy followed by utilities to apply technology improvements? This chapter shows some of the trends related to fault recording extracted from the answers to the survey.

7.1 Recording devices

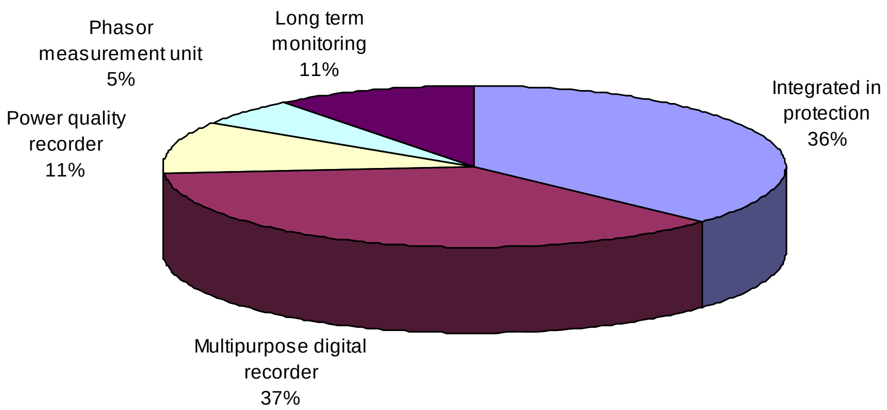
As could be expected, the trend is that traditional (not numerical) recording devices, such as electro-mechanical recorders (EMR), and non-digital protection relays (PR) are disappearing. Generally, the enquired companies trend to quit using non-digital devices as has been illustrated in figure 11 (actually, 64% of them declare to follow this practise). Some of the older devices are still in use only because the cost of replacement is too high and this kind of investment does not have a high priority).

Another observed trend is that some types of digital recording devices like sequence of events recorders (SER) and digital fault recorders (DFR) will disappear in the next future. The reason is that many utilities do not install dedicated fault recorders any more; using instead this functionality included in other devices like digital protection relays (DPR), multi-purpose digital recorders (DR), or substation automation systems (SA). Actually, the 45% of the utilities declare themselves to have left installing sequence of events recorders (SER), and the 36% declare to have left installing digital fault recorders (DFR).

Some utilities are considering to install multipurpose digital recorders (DR) with longer timeframe of continuous recording capacity, in the range from several minutes to hours in order to monitor the evolution of the system response following a disturbance till the complete restoration of the pre-fault values of the main parameters (voltage and frequency).

There is a high and increasing tendency to install power quality recorders (PQ) mainly in distribution networks at voltages levels from 6 to 110 kV (15% of companies declare themselves to follow this practise).

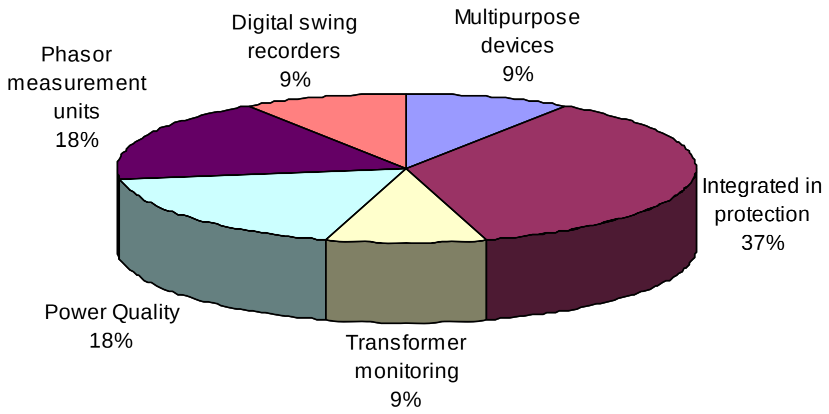
Figure 31. Recording devices increasing



Regarding future devices, integration of recording functionality in the protection and automation systems seems to be the trend as has been mentioned before. Power quality monitoring will be extensively used at distribution voltages under 220 kV and will be introduced at transmission voltages over 220 kV. Phasor measurement units (PMU) will provide easier disturbance analysis of the power system. New desired features will be included like direct interface with optical current transformers and optical voltage transformers, and longer timeframe recording capacity from several minutes to hours, or even more.

Figure 32 summarizes the new devices that will come in next future according with the prediction of the utilities that answered the survey. Percentages represent the supporting degree of each device according to their frequency among the survey responses.

Figure 32. New devices coming in the future



Recording and protection devices will be equipped with optical sensors and will integrate GPS time signal for angle measurement purposes.

7.2 Data uses

Most of utilities declare to expect that monitoring of the network and the use of disturbance-recorded data will let them to reduce maintenance cost via risk management. For example, recording devices provide data about the number of operations of each breaker, the fault current interrupted and the time inverted in each operation, so maintenance frequency could de defined according to the fault duty (mentioned by the 25% of the utilities that answered the survey).

Among the predicted advances in the use of recorded data are:
- Monitoring of power system performance in aspects such as stability, dynamic performance, active power control and reactive power control.
- Network model verification.
- Dispatching assistance.
- Planning assistance.

7.3 Data gathering

There is a trend to enhance data gathering features of the recording devices and, of course, of the communication infrastructures. The 50% of the utilities that answered the survey bet for future quicker and automatic data gathering systems via web or network based applications. The use of standard communication protocols is increasing too. Many companies (the 38% of the utilities that answered the survey) tend to build a centralized database to store all disturbance data from all the different possible sources.

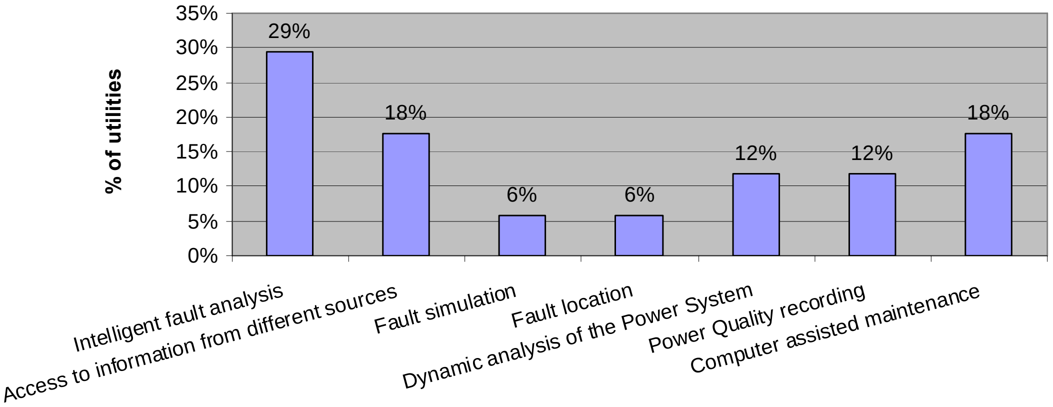
7.4 Applications

Regarding applications, the trend is toward more powerful fault analysis systems. Intelligent and expert systems will carry automatic fault and disturbance analysis. A desired feature is the access to data from different devices and sources.

Other applications include dynamic analysis of the power system, fault location and power quality monitoring and recording.

Figure 33 summarizes the future applications mentioned by the utilities that answered the survey indicating the percentage of them that support each application.

Figure 33. Applications



7.5 Reasons for a change

Change in policies of recording devices is mainly related to technology. New communication links and the increasing use of numerical relays integrating protection and control functionalities, and substation automation systems offer new application opportunities. What are the reasons that justify the necessary investments to get the benefits offered by these new technologies?

Figure 34 summarizes the main reasons given by the utilities that answered the survey indicating the percentage of them that support each reason.

Figure 34. Reasons for a change

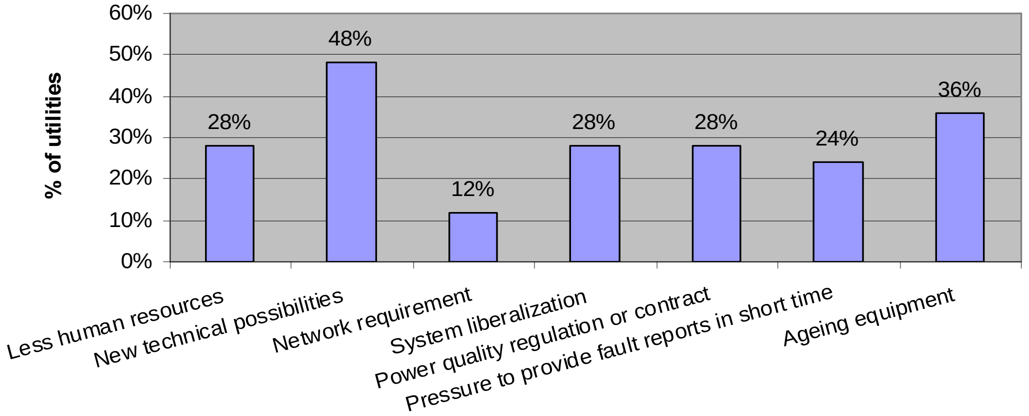
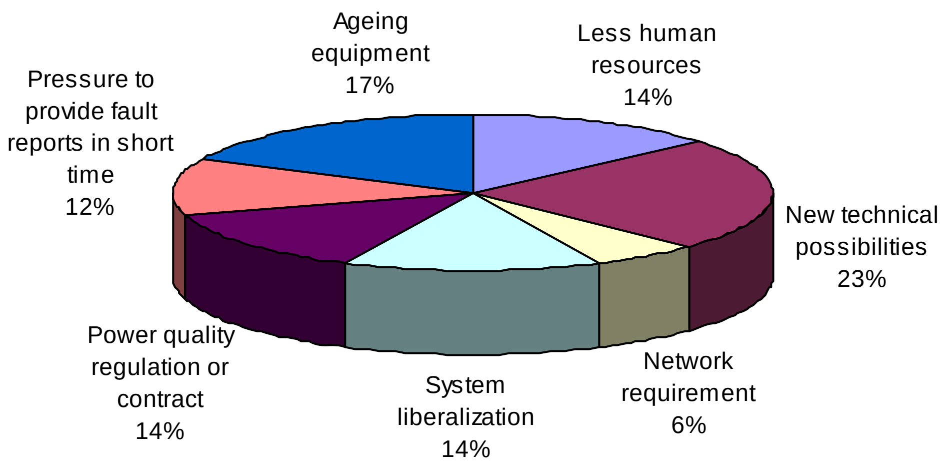


Figure 35 shows the weight distribution among all these reasons according to their frequency in the answers to the survey.

Figure 35. Reasons for a change



8 Conclusions

The recording devices are apparatus that help not only to describe faults and other disturbances, but also to predict the future behaviour of the system. In fact, to understand the faults which occurred in the past is the only way to avoid their reproduction in the future. Moreover, it is possible, with the aid of the records given by these devices to calibrate models used to simulate future systems and predict new threats before they occur.

The trend in the last decade is to substitute classical devices by digital ones, due to the higher number of features they have, as well as the multiple communication systems today’s world offers, most of them based in digital means. This trend is not only maintained, but also increased for the next years.

Concerning to infrastructure the following conclusions can be pointed out:
- The devices mainly used for disturbance analysis are protection relays and fault recorders.
- There is an increasing tendency in last years to replace non-digital devices with digital ones.
- There is a general tendency to use records from digital protection relays instead of those from digital fault recorders.
- Analogue signal changes are used for triggering to allow for selected rather than continuous recording.
- Most of utilities (70%) still collect the information needed for disturbance-analysis purposes locally at substation.
- Records from digital fault recorders are retrieved mainly from a remote central office, but in no few cases (around 46%), these recordings are retrieved and analysed at regional offices too.
- Remote data retrieval is preferably made automatically.

Concerning to the applications the following conclusions can be pointed out:
- Disturbance analysis mainly concerns to protection engineers.
- In near 50% of utilities, maintenance people are concerned with fault analysis.
- Causes and fault location are the main outcomes of disturbance analysis.
- Utilities consider that information about fault location is more useful at regional level where maintenance crews are located.
- Pressed by regulations, utilities are increasing their vigilance regarding power quality. More than 50% of utilities use power quality recorders.
- At present, personnel education and validation of network models are usual applications for disturbance data analysis.