Implementation of new monitoring tools and optimisation of maintenance through the use of Web-based technology

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Abstract**-- Utilities need to reduce costs associated to maintenance of installed equipment. Main ways to achieve this cost reduction are the use of remote access to on-line condition monitoring of equipment, and a shift from preventive maintenance to predictive maintenance. Thanks to the evolution of monitoring systems, maintenance and operation people can concentrate their activity on tasks with high added value. Ethernet can transport the information from the substation to every PC connected to the customer Intranet. This paper describes advanced solutions already implemented covering all type of primary equipment in the substation. Starting from the strict point of view of monitoring it will then proceeds forward with the presentation of diagnostics, prognosis and the challenges posed by the development of such tools. Integration into customer information system will be also discussed. As a last step, we will cast a look on future developments such as complete on-line services.**

Index Terms**-- Communication system software - Expert system - EHV Substation - Maintenance - Monitoring - Predictive control.**

I. INTRODUCTION

MONITORING devices for primary equipment in high voltage substations have been on the market for several decades. Several factors play a key role in the utilities decisions to go for monitored equipment, and sometimes Reliability Centred Maintenance programs. As time goes by some of these factors may become more and more important, as a direct consequence of deregulation policies:

- Ageing equipment, and reduced investment budgets (the latter situation a direct effect of deregulation and the drive for cost savings) makes it mandatory to increase operating life of all substation assets to their limits, possibly beyond. The decision to postpone replacement of primary equipment, and thus save on capital costs, has to be based on a precise assessment of its actual condition, and even better an overview of the whole equipment life history (operating stress, failures, etc.).
- The need to reduce maintenance costs. Reducing frequency of routine inspections where monitoring devices allows for remote assessment of primary equipment condition is an obvious way to reach this goal. Other significant benefits include early detection of incipient faults (through statistical analysis of measurements, trending, etc.), thus avoiding catastrophic failures, increasing the availability of primary equipment, and providing the maintenance teams with the opportunity to program interventions instead of setting urgent and unplanned visits. The move from unplanned maintenance visits to planned intervention is of special interest to large countries with isolated substations, where travel costs adds up to a substantial share of total maintenance costs. Diagnostics tools, giving the most probable cause of failure, makes it possible for maintenance teams to get on site with the relevant spare parts, instead of multiplying travels between site and warehouse.
- The need to know as fast as possible where and when a problem occurred .As a direct consequence of deregulation, penalties for interruption of service tend to increase between utilities, or between utility and regulatory agencies. Access to real time data concerning time and location of failures , and condition of primary equipment on the back –up transmission lines is of utmost importance in order to reduce outage time.
- The needs to operate transmission grids up to their limits, or even beyond, during peak hours or emergencies (see above). For instance real–time monitoring of power transformers thermal stress makes it possible for the operators to manage overload capacity duration safely.
- The need to manage knowledge evens as technically skilled staff retires or is leaving. As maintenance teams are reduced, technical skills are lost (especially on older technologies). Utilities may resort to sophisticated diagnostics tools in order to retain necessary technical knowledge on products which will be kept on service for one or two decades. Detailed measurement and diagnosis files available instantaneously on line speed up the process of failure cause analysis by experts. As the format of information recorded is now standardised, utilities have the opportunity to build up consistent equipment databases, on which to capitalise for optimising use of their assets.
- In some cases, simple technical reasons foster the use of monitoring: for instance early introduction of SF_6 monitoring devices in the US was linked to specific leakage problems in dead tank circuit breakers, which contain large volumes of this potentially harmful green house gas.

First generation monitoring systems could only partially fulfill the needs listed above, a situation that explains why this market remained limited for many years. Such systems usually produced a huge amount of raw data, without any analysis or diagnostics, and could only transmit information (often using proprietary protocol) through point to point communication links, thus restraining access to information. But now evolution of technology had led to a new generation, which can fulfil all these needs, mainly thanks to advances in communication technologies and implementation of expert systems, as shown below, in Fig. 1.

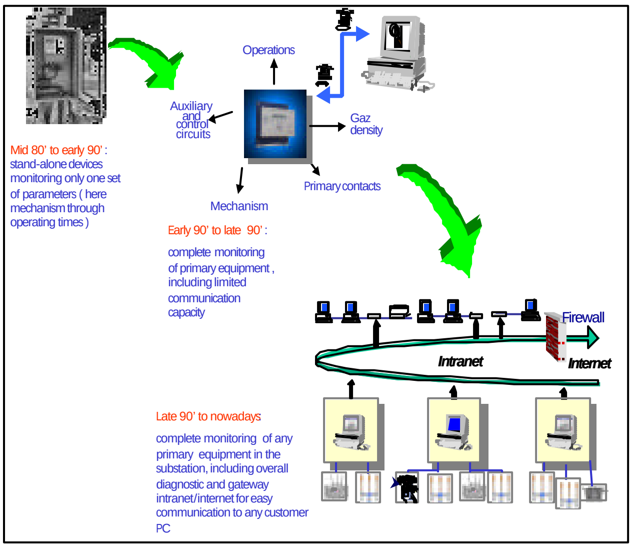

Fig. 1 Evolution of digital monitoring systems for circuit breakers

Let's now describe an example of such complete system , monitoring all strategic primary equipment in the substation , as it is currently implemented within customer's substations.

II. CIRCUIT BREAKER MONITORING

Circuit Breakers are complex mechanisms, of which many parameters can be monitored. Features that have been selected through the years ranged from vibrations within the drive to internal arc location based on pressure waves profile inside GIS enclosure. However, pressure on costs (a significant share of monitoring system overall price is borne by t sensors), need for systems that are altogether comprehensive and simple (for reliability reasons), coupled with experience from field installation led to a limitation of main functions monitored:

- Insulating gas (SF6 or gas mixtures): density, leakage rate
- Operation : monitoring of mechanical parts (operating times , travel curve, velocity , sometimes trip and close coil currents)
- Energy: monitoring of the energy reserve of the breaker (spring reloading time, sometime motor current, or spring position at end of rewinding operation, hydraulic pressure and pump reinflating times, pump efficiency, etc…)
- Primary contacts: electrical wear, arcing time, breaking current
- Auxiliary and control circuits: coil continuity, voltage supply, temperatures, sometimes supervision of current through heating systems
- Self monitoring of the electronic device itself: achieved by means of software watchdogs, hardware watchdog, monitoring of sensors status , of the communication link.

A stand-alone module attached to the breaker performs measurement and first data processing. Further analysis and processing are performed in a server who is common with power transformers and disconnecting switches monitoring systems. In case of breakdown, multiple redundancy is guaranteed between data stored in the local module, in the back up hard disk and in the back up server.

Data are displayed in a synthetic way, since operators don't have much time to analyse figures. Users must have an overview of the status of all the breakers in the substation at a single glance. Visual indicators should tell them quickly if there is a need to go into details of potential problems, or just browse on to next substation.

All event records are stored and instantly displayed on request

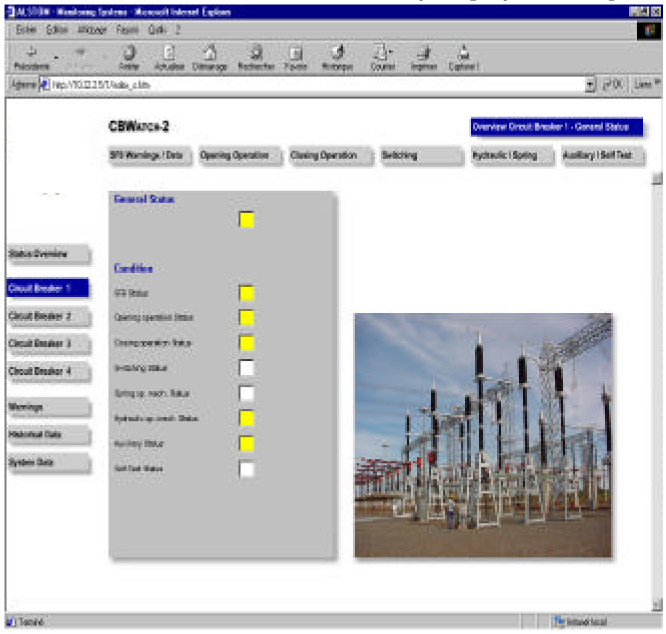

Fig. 2 Visualisation process

For further detailed analysis, users access historical records, displaying different measurements on the same screen in search of some new correlation between parameters , or downloading them for complete statistical analysis.

Most monitoring devices compare measured values with fixed limits to detect occurrence of an abnormal condition. These limits usually correspond to acceptance criteria of the breaker, during routine tests on factory or at site. Typically the same set of limits apply to all individual breakers of a particular type. This method, though quite well adapted to brand new breakers, may prove difficult to adapt in case of retrofitting of monitoring systems on breakers already installed on site for many years, and close to their end of life (25 to 30 years). For these breakers, for which extension of service life is considered, a closer kind of monitoring might be recommended, to keep a close eye on any potential drift.

In this case, the system records a few operations on site and then, according to a maximum percentage of deviation from the actual measurements defined by the user, computes limits by itself. This kind of set up, called "fingerprint ", makes it possible to get quickly the set of monitoring limits for any kind of installed breaker and proves particularly useful for retrofit application.

III. MONITORING OF POWER TRANSFORMERS

A multitude of different measurable variables can be collected for on-line monitoring of power transformers. However, it is very rarely useful to use the entire spectrum. Therefore, sensor technology must be adjusted to the specific requirements of a particular transformer or transformer bank, depending on their age and condition. From the experience of more than 120 monitoring systems the following general set-up of sensors for example is proposed for the use at a 400 kV power transformer:

- PT100 for measurement of top oil temperature
- PT100 for measurement of ambient temperature
- C.T. for measurement of load current (single phase)
- Measurement of voltage at measurement tap of bushing (three phase)
- Measurement of oil pressure of bushing
- Sensor for measurement of oil humidity
- Sensor for measurement of gas-in-oil content
- Tap changer position
- Power consumption of motor drive
- Digital inputs for switching status of fans and pumps.

For early error detection, the monitoring of the active part is of particular importance. It is fundamental to either measure the electrical variables load current and operating voltage directly at the transformer. Bushing-type current transformers are used for load current measurement. The load current is an important starting variable for calculation of hot-spot temperature according to IEC 60354 [2,3] and thus presents ageing of active part insulation. This enables the evaluation not only of information regarding the temporary overload capacity of the transformer but also of the lifetime consumption.

The voltage applied to the transformer is acquired at the measurement tap of the capacitor bushing by means of a voltage sensor. By this way a change of the capacitance of the bushing which is the start of deterioration of the bushing can be detected. Overvoltages represent an essential risk potential for the insulation of transformer windings. These voltage peaks can be detected through a peak value sampler. In connection with the volume of noxious gases, which are dissolved in oil, one can draw deductions regarding possible damage to the insulation of the active part after the occurrence of voltage surges.

For the gas-in-oil detection a Hydran sensor is used which reads a composite value of gases in ppm (H_2 (100%), CO (18%), C_2H_2 (8%), C_2H_4 (1,5%)). As hydrogen is a key gas for problems in the active part, an increase in the output signal of the sensor is an indication for irregularities such as for example partial discharge or thermal overload. The evaluation of this measuring signal, together with the dependency on the temperature of the oil and the load current, provides a reliable basis for the continued operation of the transformer. In the event of an increase of gas-in-oil content, an immediate reaction can be effected via an off-line gas analysis to determine the concentration of the other components dissolved in the oil in order to limit the cause of the damage.

A capacitive thin film sensor is used for the detection of moisture in oil. There are several causes for an increase of water-in-oil content. Due to the fact that water is a result and also an origin of oil/paper insulation degradation the water-in-oil content is an important indicator for the condition of winding insulation, in particular for already aged transformers.

In the cooling unit, not only the switching state of the oil pumps and the ventilators is monitored but also the temperature values. For this purpose, the input and output oil PT100 probes measure temperatures. The intention is to make selective statements regarding the state of the entire cooling plant from the measured values.

Recordings of the tap changer position and the operating current help determine the number of switching operations of the tap changer and the total switched current, which gives information abut the burning of diverter switch contacts. If the limiting value, pre-set in accordance with the maintenance instructions, is exceeded a message is generated.

Oil temperature difference between the OLTC and main tank can relate to the severity of LTC contact wear. Heat in the OLTC compartment can be caused by abnormal conditions like contact arcing, misalignment of contacts, loose terminations, locked rotor current of internal tap changer motors and overloading of contact.

Due to the fact that serious damage to the transformer can be expected in the event of the failure of the tap changer, the monitoring of this mechanically and electrically highly stressed element is of great importance. In order to be able to obtain information regarding the mechanical state of the switch the power consumption of the tap changer drive mechanism is recorded.

The outputs of the above mentioned sensors are wired onto field bus terminals in the monitoring module installed at the transformer. Within these data acquisition units the analogue signals are digitised and send via a field bus to the monitoring server. By means of this industrial proven technology it is possible to monitor all transformers in one substation with a single system which is extremely cost effective. The erection of the server in an operating building offers the advantage that the ambient conditions (e.g. temperature, vibrations) are much more suitable for a PC. The connection to the protection and control system can be done either by dry relay contacts or a digital protocol according to IEC 60870-5-101.

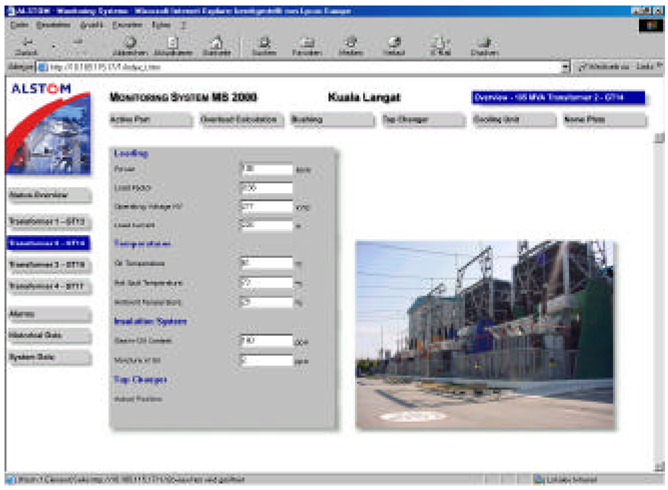

Fig. 3 Web based-based visualisation of transformer condition

During the last years the AREVA monitoring system MS 2000 was installed world-wide at power transformers of all major manufacturers. In the beginning utilities started to test the system with grid-coupling transformers of minor importance. Due to the good experience it is now operating at such strategic important points as nuclear power stations, pumped storage power stations, coal power stations and aluminia industry. Most of these installations were retrofitted on-site at already aged transformers. Normally the installation of sensors requires no welding at the transformer and takes about two days. The transformer has to be taken out of operation only for half a day to install the voltage sensors and the tap changer monitoring module.

An additional module installed on the MS 2000 monitoring server generates HTML-based web pages, which show the on-line and historical data, as in Fig. 3.

IV. MONITORING OF DISCONNECTING SWITCHES

In order to be able to obtain information on the mechanical state of the disconnector, the drive power consumption is recorded during operation. This power consumption is proportional to the torque of the drive. The operation of each disconnector has a specific signature which is monitored by the MS 2000, as in Fig.4.

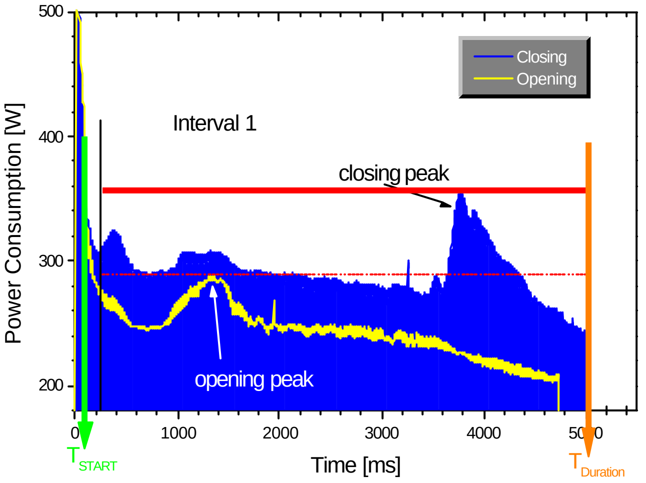

Fig. 4 Monitoring of mechanical state of disconector

Some characteristic properties can be seen immediately. Considering the closing, the force of the entering contacts produces the characteristic peak at the end of the operation. During the opening-process the leaving contacts produce a characteristic peak at the beginning of the operation that is smaller compared to the closing peak. If the measurement is repeated, the curves that are observed are identical.

The characteristics of the opening- and the closing-process can be easily examined.

The monitoring system MS 2000 - DISCONNECTOR will examine in this case the following parameters of the torque: transformer:

- Duration of motor start-up
- Max. power consummation
- Duration of the operation
- Total energy used for each disconnector operation

The position of the disconnector is obtained from the status of the open/close contacts. The respective auxiliary contacts are wired onto digital inputs. Furthermore the number of operations and the time since last operation are evaluated.

V. EXPERT AND DIAGNOSIS TOOLS VERSUS MONITORING TOOLS

Monitoring refers to the measurement and storage of raw data, their compensation with relevant influence factors (temperature, pressure, operation voltage, etc.), and finally the comparison of these final values with rated limits. If compensated measurements don't fill inside rated limits, alarms and warnings are sent.

Diagnostics tools or expert system refer to software products that transform the output of monitoring systems (through statistical analyse, rule-based or neural-network based programs) into diagnosis indicating the reason of observed alarms , the sub-components most likely to be the cause of current problems , and even the recommended procedures to follow in order to get primary equipment back into service . These systems also give prognosis (advance warnings that a problem is developing now and a failure is likely to happen in some pre-determined period in the future), and an estimation of remaining lifetime before end of service based on all the records building up the life history of primary equipment. This last figure is based on actual condition of primary equipment, not on theoretical life span. Therefore it is a precious tool for the asset manager when time comes to discuss refurbishment or replacement of equipment in service.

Diagnostics and prognostics are a tricky subject, because pieces of primary equipment in the substation are complex devices, made out of several hundreds pieces. Defining the component, which causes abnormal behaviour, is often difficult, because many failures could lead to the same symptoms. Thanks to their intimate knowledge of their products, manufacturers of equipment can nonetheless propose a certain number of diagnostics and prognostics. Levels of confidence for these diagnostics will of course increase as return on experience gets larger, but they depend also on the type of primary equipment monitored: equipment that operates continuously (i.e.: power transformer) tend to develop slow, continuous degradation of their performances, thus allowing early diagnosis of incipient failures. Equipment that do not operate continuously (i.e.: circuits breakers and disconnecting switches) would sometimes show few, even no degradation of performances before failure during an operation. This may be the case when the coil plunger gets stuck or some mechanical part breaks. Another point is that manufacturer's failure databases are much restricted to factory and site commissioning problems. Problems occurring while the breaker is in service on site are much less known because

- in the absence of any monitoring system, symptoms that announced the incoming problem were not detected, not recorded and thus never transmitted to the manufacturer
- 2) utilities usually don't share their failure database with the manufacturers.

As a consequence, achieving a truly comprehensive expert system is a matter of time and co-operation: first step consists in installing monitoring devices on a large pool of primary equipment, building up a standardised event records database. Then as time goes by and failure database grows, manufacturer and utility joined determining efforts result in further diagnostics and prognosis being added to the initial system, in a continuous progress.

VI. BENEFITS OF WEB-BASED TECHNOLOGY

New communication technologies have solved several imperfections of first generation systems.

- Distribution of information to all departments of a utility has become a smooth and easy process. Before, the user had to get to the information, using proprietary protocols on a point to point link. Now information comes up to the user, thanks to standardised field buses in the switchyard (Modbus , Profibus, DNP), and Ethernet TCP/IP at station level. Interchangeability of devices between major players in the market is now a reality .All PC and routers have native Ethernet communication capabilities. HTML protocol is the obvious protocol for fast and easy visualisation of data, FTP for easy download. Use of these natives PC capabilities and installed intranets means low-cost integration and set-up of monitoring systems
- Maintenance .of HMI and diagnostic software has become transparent to utilities. Huge savings on computers associated maintenance costs are possible because there is no more need to install dedicated HMI software (and manage compatibility of PC operating systems, conflicts between different applications, new releases, etc.). Access to all system‘s functions is achieved with a standard PC, equipped with off the shelves WEB-browsers thanks to user friendly HTML pages and java applets located within the server.

  If further analysis is needed , any set of data can be downloaded from the server via FTP protocol in ASCII format, which can be read by any kind of mathematical or statistical tool.

  Should any restricted access be mandatory, password protection, restraining the access of some users to certain data is embedded as native components of Internet technology. For instance access to configuration parameters of monitoring devices should not be available to everyone.

  A key point of tools using java-enabled browsers is their inherent simplicity and user friendly interface. This makes it very easy for the operators to use it, thereby significantly shortening learning curves and training costs associated with any new tool. Experience from installed devices and past failures can quickly benefit the system because developing new visualisation and diagnostic pages is a simple process. Once the release is ready, simultaneously downloading it on all installed servers through internet/intranet reduce the costs traditionally associated with the management of different releases of the same software.
- Integration into the customer's information systems is straightforward: monitoring system provides the user with SQL-type databases, which can be accessed via ODBC protocol. An example of complete integration of on-line monitoring and power systems control software is described in our reference [4].

VII. FUTURE TRENDS: INTEGRATED ONLINE SERVICES

Ongoing integration of services and information pushes already existing systems described above towards global experts and asset management systems (Computerized Maintenance and Management System – CMMS), which handle all processes involved with primary equipment (training, maintenance, repairs , refurbishment , replacement , upgrades, etc.).

Let's take an example to illustrate the process: a user in the field or in the control room receives an alarm from the breaker ID# 1DL0249 showing 'spring motor – spring rewinding time'. He then clicks on the "diagnostics" features and finds out the real cause of the problem. Once he has made up his mind whether to can fix the breaker or put it out of service for late repair, he has to take appropriate actions.

This is where the CMMS gives him further support. It provides a structured way of organising the information in the customer language. From the original tag "ID# 1DL0249", via a graphic environment, the user is able to find its equipment and the correspondence with manufacturer references, after which he will be able to look for general information on original order, manufacturer and technical data.

To prepare actual repair operation, it is necessary to access all kinds of information related to the problem. A well-structured set of document will permit to do so. Not only general documents but also specific documents related to the equipment serial number will be available. It means that users will be able to trace all kind of events (Expertise, refurbishment, repair) that happened with this specific piece of equipment because all reports are traced and stored.

Then each broken part has to be identified by its number. This is possible because the CMMS stores the Bill of Material as built in factory. This task is usually painful and time consuming due to lack of information with conventional methods. Another difficulty is to confirm that the part in the field corresponds to the part registered in the system. To clear all doubts, a photo or diagram is provided with by the system. Emergency spare parts orders are processed quickly and without any mistakes.

The user in the field has two choices when it comes to finally repair the breaker:

- either repair it on its own if possible (with the repair manual included in the system)
- or send an emergency work order to the nearest manufacturer's facility able to perform such tasks, using Internet or e-mail addresses given by the CMMS.

Adding to these functions, the CMMS should procure parts tractability, local contact, training available on equipment and much more.

Of course such CMMS system has to work on highly reliable and up-to-date database if it is to give out accurate information. This will only be possible if utilities and manufacturers work together to maintain these databases. Both parts will have an interest in so doing: utilities will benefit from a powerful tool which will optimise their asset maintenance and management, and manufacturers will use them in order to optimise activity of their engineering and maintenance teams.

Development of such commercially available CMMS is now finished, and first implementations are on the way.

VIII. CONCLUSION

Web-based technology have given monitoring systems a significant boost because they greatly increased access to information on operating condition of primary equipment. Furthers steps to enhance their potential to drastically shorten response times and larger diffusion of information are under way. Such tools are now able to provide utilities with a global and real time knowledge of their whole transmission system, complete expert system to diagnose and prevent failures, a global installed pool of all kind of equipment installed all over the country and direct links to manufacturers spare parts resources and maintenance teams. Besides these tools integrate all the information into a single system with the same interface for all users. They ideally support the drive for efficiency of utilities that need to increase the performances and availability of power grids.

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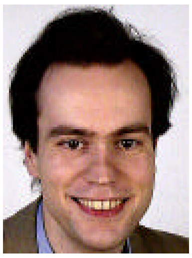
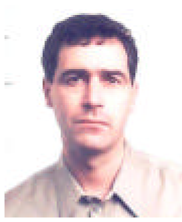
X. BIOGRAPHIES



Thierry Jung was born in Sarreguemines , France on April 29, 1969. He graduated from the Ecole Nationale Supérieure d'Ingénieur of Caen (ENSI Caen) in 1993 in Opto-electronic and Micro-electronic Engineering. In 1995 he obtained a DESS in management from IAE-Strasbourg. He joined Alstom Research Center in 1996. Since 2000 he is responsible for development , application and industrialization of electronics dedicated to Air – insulated High Voltage Switchgear . He is member of IEC and Cigré working groups .

Stefan Tenbohlen received his Diploma and Dr.-Ing. degrees from the Technical University of Aachen, Germany, in 1992 and 1997, respectively. 1997 he joined AREVA Schorch Transformatoren GmbH, Mönchengladbach, Germany, where he was responsible for basic research and product development and in this function working in the field of on-line monitoring of power transformers. Since 2002 he is the head of the electrical and mechanical design department. He is member of the German committee of CIGRE A2 (power transformers) and the German Power Engineering Society VDE-ETG FB Q2 (Materials, Electrical Insulations and Diagnostics).

Jean Altwegg graduated in 1971 from the Ecole d'Ingénieurs from Genève, Switzerland, as EUR ING by FEANI in Paris in 1997 and as Master of Business Administration, in 2003, by the Federal University of Itajubá in Brazil. In 1986, he joins AREVA, São Paulo and today he is manager of the technical and the commercial departments of the circuit breakers, disconnectors and surge arresters plant in Itajubá, Brazil. He is menber of the CIGRE's Brazilian CE13 comity.



Philippe ROUSSEL: Graduated as Mechanical Engineer from Ecole Centrale de Lyon in 1990. Started as a research engineer at ALSTOM (formerly Gec Alsthom) for GIS in 1991 : design and testing of GIS circuit-breaker and complete bays. In 1997, became Strategic Marketing Manager for high voltage AIS equipment (circuit breakers, surge arresters and generator circuit breaker). In 2000, became product manager for high voltage disconnectors and compact substations. He is a member of SEE (the French electrical engineering society) and former member of Cigré WG23-01 on 'Substation concepts'.

Carl Harfouch received his Diploma B.Ing. from Polytechnique of Montreal, Canada, in 1994. He first did test engineer for a period of two years in high voltage apparatus. Then he joined the switchgear R&D team in Lyon, France for 3 years to develop 245kV breaker and monitoring system. In 1998, he was responsible for breaker and low voltage for the High Voltage unit in Montreal. In 2000, he joined the services teams as manager to develop computerise maintenance and management system (CMMS), monitoring services, retrofit and refurbishment solution.