Aem Elettricità (Ael) forms part of the Aem Spa Group of Companies and operates in the field of electrical distribution in Milan and its neighbouring boroughs. It currently distributes 3200 GWh to approximately 430,000 clients, approx. 50% of the electricity consumers in Milan. In order to ensure the high quality and reliability of its service, Ael has an articulated distribution system that consists of electrical stations, located throughout the city, and an underground cable distribution network.

One of these poles is the Gadio station, located in Milan’s historical centre, which possesses an installed primary transformation power of 180 MVA.

The 220 kV high voltage system of the Gadio station was installed at the beginning of the seventies by the Merlin Gerin company, and consists of a metal enclosed primary generation unit insulated in SF6, with a double system of busbars. Being one of the first metal-enclosed HV plants in SF6 to be built in Europe, the unplanned maintenance on site proves to be particularly problematical and onerous. This is largely because of the difficulty both in getting hold of the necessary spare parts and in obtaining the know-how needed to carry out the maintenance work.

As a result Ael has started to experiment with a different philosophy which consists of equipping the plant with a system to support the maintenance engineer’s decision making. Therefore, the company decided to introduce an Expert System for apparatus on-line diagnostics: the “Insite” diagnostic system, manufactured by Doble Engineering Company. The main determining factor was that it uses a real and proper Expert System rule-base analysis capable of detecting - on its own - the “normal” and “abnormal” working condition of the component being monitored, and capable of sending information, when needed, to the attention of the maintenance engineer or plant asset manager.
Introduction

Aem Elettricità (Ael) forms part of the Aem Spa Group of Companies and operates in the field of electrical distribution in Milan and its neighbouring boroughs. It currently distributes 3200 GWh to approximately 430,000 clients, approx. 50% of the electricity consumers in Milan.

In order to ensure the high quality and reliability of its service, Ael has an articulated distribution system that consists of electrical stations, located throughout the city, and an underground cable distribution network.

In particular, Milan itself is supplied through four high voltage electric substations, which constitute the primary transformation posts (HV/MV), through which the electrical energy is introduced into the medium voltage distribution network.

These primary transformation posts, which play a fundamental strategic role in Ael's distribution logic, are interconnected by means of an oil insulated cable which operates at a voltage of 200 kV and passes through the whole of the city along the North-South axis.

One of these poles is the Gadio station, located in Milan's historical centre, which possesses an installed primary transformation power of 180 MVA.

Gadio Station

Gadio station is situated inside a Liberty building near Sforzesco Castle. As the building is under environmental preservation Aem Elettricità had to choose solutions compatible with the available space. For this reason Aem Elettricità chose metal enclosed units insulated in SF6 to realize 220 kV high voltage plant.

The 220 kV high voltage system of the Gadio station was installed at the beginning of the seventies by the Merlin Gerin company, and consists of a metal enclosed primary generation unit insulated in SF6, with a double system of busbars. It is sized to accommodate an atmospheric lightning impulse voltage on the sectionalised distance of 1050 kV.

In the nineties the plant was expanded by the Society Nuova Magrini Galileo, which added different modules: busbar section module, transformer module and line module.

As the metal enclosed units of the two plant sections have different diameters, the linkage has been realised with a rigid coupling flange designed specially for this purpose.

* Aem Elettricità Spa Italy
** Ampere Spa Italy
*** Doble Engineering Company US
The main electrical characteristics of the 220 kV plant are reported in the following table.

<table>
<thead>
<tr>
<th>Item</th>
<th>Merlin Gerin plant section</th>
<th>Nuova Magrini Galileo plant section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage</td>
<td>245 kV</td>
<td>245 kV</td>
</tr>
<tr>
<td>Rated lightning impulse withstand voltage</td>
<td>1050 kV</td>
<td>1050 kV</td>
</tr>
<tr>
<td>Rated 1 min. power frequency withstand voltage</td>
<td>460 kV</td>
<td>460 kV</td>
</tr>
<tr>
<td>Rated normal current</td>
<td>2000 A</td>
<td>2000 A</td>
</tr>
<tr>
<td>Rated short-time withstand current (1 s)</td>
<td>31.5 kA</td>
<td>50 kA</td>
</tr>
<tr>
<td>Rated peak withstand current</td>
<td>79 kA</td>
<td>125 kA</td>
</tr>
</tbody>
</table>

**Maintenance criteria**

The planning criterion for the maintenance of the Ael installations is a simple time-based scheduled maintenance. This activity is to be carried out on all the installed equipment, at different time intervals depending on both the type of work being carried out and the type of equipment being maintained.

In the case of the Gadio Station, for the part made by Merlin Gerin, the unplanned maintenance that needs to be carried out on the metal-enclosed 220 kV plant has proven to be particularly critical.

In fact, being one of the first metal-enclosed HV plants in SF6 to be built in Europe, the unplanned maintenance on site proves to be particularly problematical and onerous. This is largely because of the difficulty both in getting hold of the necessary spare parts and in obtaining the know-how needed to carry out the maintenance work.

As a result Ael has started to experiment with a different philosophy which consists of equipping the plant with a system to support the maintenance engineer's decision making. This system will help in planning his activity, based on predictive condition-based maintenance criteria. The purpose of this system is to extend the useful life of the plant and to avoid costly work, while still maintaining the necessary safety standards.

To achieve this, the company decided to introduce an Expert System for apparatus on-line diagnostics.

**The expert system diagnostics**

Rule-base Expert-system analysis of the "Insite" diagnostic system, manufactured by Doble Engineering Company, was chosen because of the flexible and modular nature of its architecture, which can easily be expanded to all the station components. The main determining factor, however, was that it uses a real and proper Expert System rule-base analysis capable of detecting - on its own - the "normal" and "abnormal" working condition of the component being monitored.

The system is capable of sending information, when needed, to the attention of the maintenance engineer or plant asset manager, thereby reducing considerably the need to take the plant out of service for inspection and maintenance.

It sends "Alert" messages when it detects any deviation from normal performance, before an actual breakdown or sudden unexpected outage occurs. All this means that the component is being continuously involved in the condition assessment.

The main advantages of the system can be summarised as:

- Maintenance resources are dedicated solely to the equipment that requires repairs
- The Expert System identifies the faulty component
- Reduction of the maintenance costs for carrying out inspections
- The Expert System automatically carries out diagnostic measures while the substation is in operation
- It increases the availability of the system
- The Expert System minimises the need for the substation to be taken out of service for inspection or maintenance
- It extends the working life of the components

The expert system measurements involve the most important substation and power station apparatus: transformers, on load tap changers, bushings, circuit breakers, current transformers, and so forth.

The expert system tracks apparatus performance by measuring the most important parameters of each device. Automatic statistical analysis establishes norms based on actual performance and looks for deviations in order to detect changes in the measured signal.

In this initial experimental stage, it is planned to apply the system to No. 4 220 kV GIS circuit breakers of an older design.

The most important measurements performed on the circuit breakers are: contact operation, motor current, trip and close coil current, trip dc supervision, phase current, drive pressure, SF6 pressure, and other critical factors.

The Expert System Diagnostics will be: mechanism timing, spring tension, dashpot conditions, latch operation, trip and close coil performances, restrike, etc.
## Circuit breaker diagnostics

<table>
<thead>
<tr>
<th>Component</th>
<th>Defect</th>
<th>Behaviour of Diagnostic Parameter</th>
<th>Signals Measured</th>
</tr>
</thead>
</table>
| Control Circuit      | Control Circuit Failure  
Faulty Command Coil (Trip-Close)  
Faulty Auxiliary Contacts  
Latch Mechanism Failure  
Degraded Latch Lubrication  
Loss of Stored Energy Operating  
Mechanism/Linkage Failure  
Degraded Operating Mechanism/Linkage Lubrication | Trip Timing: Too Slow/Fast  
Close Timing: Too Slow/Fast  
Incorrect Sequence          | Trip Coil Current  
Close Coil Current  
52-a Aux Contact  
52-b Aux Contact                                    |
| Main Contacts        | Operating Mechanism/Linkage Failure  
Worn/Misaligned Contacts                                                                 | Fail to Interrupt Current  
Fails to Conduct Current  
Increasing Contact Erosion  
Restrike Observed         | Trip Coil Current  
Close Coil Current  
Phase Currents                                          |
| Heater               | Failure to provide heat,  
Continuity of Heater Circuit, Faulty Power Source  
Leaks  
Liquefaction                                                                 | Inadequate Heating  
Change in Heater Current or Status                      | Heater Temperature  
Ambient Temperature  
Heater Current                            |
| SF6 System           | Excessive operations,  
Motor insulation problem  
Unloader valve problems  
Continuous motor operation  
Lack of lubricant  
On/Off pressure transducers  
Interface Problems                                         | Transients on the motor current waveform  
Motor operation count  
Incomplete motor operation  
Motor not turning off  
High motor current  
Motor turning off or on at the wrong pressure | SF6 Pressure  
SF6 Temperature                                          |
| Energy Storage       |                                                                                         |                                                                                                      | Motor Current  
Pneumatic Pressure.  
Hydraulic Pressure  
SF6 Pressure                                 |

### Table 2. Diagnostic Capabilities for Circuit Breakers

The essential circuit breaker analysis covers basic circuit breaker timing fundamentals. This analysis correlates circuit breaker timing with respect to the control coil signal(s) and auxiliary contact(s) (52a and 52b). This package is designed to analyze circuit breaker timing on both TRIP and CLOSE operations including inter-pole timing for iterated phases where applicable. The Phase Current Trip analysis is a limit driven analysis using limits that correspond to Contact Wear, Interrupting Time and Inter-Pole Synchronization, the Phase Current Close analysis including limits for Current Ignition Time and Inter-Pole Synchronization. These limits will be determined by the manufacturer’s specifications or by user's experiences. The SF₆ analysis features two algorithms used to determine the number of hours until a low-pressure alarm occurs using current and historical data.

### Defect detection

The On-Line Diagnostic system is the tool to keep user appraised of apparatus condition at all times. The expert system is a rule-based artificial intelligence software designed to examine recordings gathered by the hardware components. Normally functioning equipment and some apparatus data are the only input requirements. This analysis software, based on proven field-tested techniques, is a diagnostic program that employs a database, a knowledge base and parametric models. The database stores both historical waveform data, in COMTRADE compatible file format, and single-point data. INSITE extracts critical
performance attributes, called features from the data recordings. The EXPERT SYSTEM algorithms analyze combinations of the extracted features and effectively identify degraded operation and incipient apparatus failure with its rules and statistical rich knowledge base. These prioritized maintenance messages, provided in a plain text format, called the “Alerts” communicated via fax or pager, indicate the severity and probable cause of incipient problems. This method of communication helps managers avoid the data flood typically associated with simple monitoring devices.

System configuration

Server: The server program manages the Data Acquisition Units (DAU), the database and is the data and communications server. The server facilitates Doble’s continuous Expert System Diagnostics. It contains the basic platform for data acquisition and storage and the Expert System diagnostics engine. The server hardware can be located in the substation (Local Server), or remotely either at Doble or at a user designated location (Remote Server).

The Client program runs either on the server hardware or remotely on a Windows 95/98 or NT machine. The remote connection is made over a modem or via LAN/WAN provided by the user.

Case study

We are going to show one interesting case study in order to provide the analysis description. On New Year’s Eve, December 31, 1997, at 4:27 p.m., INSITE recorded a Breaker TRIP operation and issued an ALERT!, which warranted concern. What follows is an explanation of the findings.

IPO Circuit Breaker Pole Disagreement

The site is a substation in Canada with the following equipment:
- 12 –230 kV Air Blast Breakers Brown Boveri
- 1 –230 kV Oil Circuit Breaker CGE pneumatic operated.
- 1- 230/28/28 kV, 125 MVA step down Transformer

Circuit Breaker Information

This breaker is a BBC Air-blast Type DMVF-250-NC8. The breaker consists of ten series contacts, eight interrupting contacts and two isolating contacts. The eight interrupting contacts are separated into two groups of four contacts, and are located on each side of the isolating contacts, which are in the center of the contact scheme. The contact layout is illustrated below:

![Figure 2. Type DMVF-250-NC8 Circuit Breaker contact layout per phase](image)

Two trip coils wired in series control the interrupting contacts (or stacks). Once the interrupting contacts have tripped, a pneumatic signal is sent to the isolating contacts 50 ms later by just one of the interrupting contact stacks. This means the isolation contacts are controlled by only one set of interrupting contacts. Once the isolating contacts are opened then all of the interrupting contacts will then return to the CLOSED position. The cycle time for the interrupting contacts during a TRIP operation is roughly 86ms.

On December 31, 1997, the substation maintenance group of this utility received the following ALERT!: This caused this utility to look at the signal recordings to find out what caused this ALERT! to be issued. The investigation commenced.

Investigation

The phase current recordings are shown in figure 3. Phase B re-establishes load current roughly 85 - 90 ms after the intended TRIP. However, Phase B finally completed the TRIP cycle 250 ms after the original TRIP command.

![Figure 3. Unintended Reclosure of One Circuit Breaker Pole](image)

The TRIP coil currents clearly indicate a malfunction with the breaker’s TRIP operation, as per figure 4. There was a repeat of the Phase B TRIP coil current, indicating that the breaker never latched. The 52-A
relay never changed state and the isolating contacts never completely opened.

Figure 4. Comparison of trip coil currents on all three phases

The breaker resides in Canada, and the utility believes that extreme weather conditions caused the breaker to operate poorly during New Year’s Eve. The diagnostic system recorded the ambient air temperature to be -56°C. This cold temperature was also accompanied by high winds.

It appears that only one side of the breaker operated initially, and it was the stack of four interrupting contacts that did not pneumatically control the isolating contacts. It was concluded that the cold temperatures must have contributed to slowing down and binding the other set of four interrupting contacts. Finally, after 250 ms, the breaker’s air and mechanical system was able to overcome any impeding forces and the breaker cleared any load current still flowing through Phase B.

Two main factors help validate this theory. First, is the momentary interruption time of Phase B. As seen in the phase current recordings, the momentary interruption time is between 85 and 90 ms. This correlates with the predicted time of 86 ms for the interrupting contacts’ cycle time. The second factor is the pressure traces. Shown on figure 5 are the pressure recordings for Phase A and Phase B. The Phase A trace shows both stacks utilizing air simultaneously, thus creating an exponential decrease in pressure. Phase B depletes the air slower and in two stages which are synchronized with the Phase B line current and coil current. The malfunction of Phase B caused just one half of the breaker’s interrupting capabilities to be used not once, but twice during this TRIP operation. This situation created two undesired opportunities for the breaker to possibly fail during the TRIP on Phase B. There was no immediate concern with the operating condition of this breaker, but they will be looking at it in the near future.

Figure 5. Change in air pressure vs. time

Conclusion

This example shows the importance of on-line expert system diagnostics, not just on-line recordings. If this incipient failure is a rapidly deteriorating condition, the only hope of catching the problem without an expert system would be continuous evaluation by personnel.

In a large installation of on line monitoring equipment this is not possible. Taken together, continuous measurement and expert system analysis in a communications environment will provide apparatus asset owners with three totally new dimensions of security which are:

A. Apparatus condition is always known.
B. Early warning of emerging problems provides lead-time to plan and implement corrective action.
C. If the decision to delay action, continuous diagnostics automatically watches for further signs of trouble.

Each of these is an important contribution. However, Doble’s early customers have stated that the ability to “live with” a known potentially serious problem is the greatest benefit of all. Now these systems can be economically justified.