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Development and implementation of a Condition Monitoring System in a Substation

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Abstract—**Maintenance is a key activity for utilities in order to assure the proper operation of their networks. And it implies a huge amount of human and economic resources. Saving maintenance costs means that it is needed to invest in innovation. In order to improve the effectiveness of the maintenance in the electrical utilities, a transformation from preventive maintenance based on time (TBM) to preventive maintenance based on condition (CBM) is taking place. The core element of the CBM strategy is the implementation of a condition monitoring system. This work treat about the development and implementation of a condition monitoring system in a pilot plant of an electric utility consisting in a 66/25 kV, 30 MVA power transformer and 66 kV and 25 kV circuit breakers. The system was implemented by using the monitoring functions of commercial protection relays equipped with IEC61850 communication capabilities. In this work, first a description of the monitoring system is presented, followed by the description of the pilot plant where the system has been installed and finally, the conclusions and further works are presented.**

Keyword: time based maintenance (TBM), condition based maintenance (CBM), predictive maintenance, substation monitoring, reliability.

I. Introduction

Liberalization and privatization in electrical sector have caused that utilities are continuously under pressure. They must provide power at high reliability while they are looking for maximizing profits. This has resulted in a need for optimizing operation and maintenance costs: doing the most with reduced budgets. Power reliability and final power quality depends mostly on the condition of switchgear and controlgear assets: power lines, transformers, circuit-breakers, etc. This shows that maintenance has always represented a significant part of utilities' financial plans.

The main goals of the maintenance are indicated in [1]:

- reducing maintenance costs;
- reducing catastrophic failures and collateral damage;
- deferring replacement (extend life);
- increasing equipment utilization;
- achieving reliability/availability goals;
- safety and environmental concerns.

Nowadays, outsourcing strategies are prevalent in maintenance activities in order to control its cost. Moreover, maintenance activities have little value added. Maintenance carried out by outsourcing personnel has a risk regarding coordination, complexity and background of workforce. However, reducing operation and maintenance costs does not have to imply a strategy consisting of lack of investments or performing less maintenance. On the other hand, it is necessary to invest in innovation in order to achieve a higher effectiveness.

Furthermore, electricity demand is growing mainly in summer. Such increase implies constraints regarding maintenance of existing electrical networks since traditionally

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maintenance activities were principally performed in summer and now it is difficult to carry them out in such dates.

Therefore, utilities have a central dilemma: keep costs down, increase incomes and improve reliability while the constraints over an ageing network increase.

Current maintenance procedures consist principally on corrective and preventive (time-based). The former is effective for assets that are abundant, non essential and easy to replace, and also for those that have already had a failure, if it is reparable. In other case, a purchasing is needed to replace it. The latter is the most used nowadays. It consists on assess the condition of assets every planned time, according to manufacturer's specifications and utilities' experience. This time depends on asset type and the desired assessment.

Nevertheless, this strategy is no optimum. At the beginning of operation, maintenance is not needed as much as when the asset is closed to the end of the lifetime. Then, over-maintenance is frequently executed in just installed assets and under-maintenance is less than it should be in assets with a long lifetime in operation.

Additionally, electrical grids are ageing. Most of the utilities' facility assets have been in operation for years and are close to the end of their useful lifetime and then, they are more likely to fail. Then, it is needed to know the ageing processes and failures of the assets, moreover when their lifetime is finishing. However, there is no change in maintenance proceedings in order to consider current condition of assets. And moreover, a significant social concern against new power infrastructures that allows replacing ageing infrastructures.

Then, a shift in maintenance strategies is needed: from traditional corrective and time based to condition based. Predictive maintenance is based on condition of assets and then, it is also known as Condition Based Maintenance (CBM). This approach is based on current data of certain key parameters that allow determining the real condition of the assets. Utilities have a lot of data about the condition of their networks. However, it is usually on paper and it is a cumbersome task for technicians to process such huge amount of data. In order to implement such new strategy, a data management tool is largely needed in order to automatically process and analyze the data and help during the decision-making process.

New advances in sensors, electronics and information and telecommunication technologies have increased the use of Intelligent Electronic Devices (IEDs) into the electrical systems. Nowadays, these IEDs make possible to know more operation data. Moreover, they are able to interchange information, acquire and process it, as well as remote reading. This evolution improves network operation and, at the same time, it represents an opportunity towards the change of the maintenance philosophies in the electrical systems.

This paper presents a monitoring pilot plant in a substation in service with the aim of implementing a Condition Monitoring System. The pilot plant comprise a 66/25 kV power transformer of 30 MVA; a 66 kV oil circuit-breaker and a 25 kV SF6 circuit-breaker. The methodology to develop this idea has followed the guidelines depicted in [2]: identify prevalent failures, determine detection methods and data management, which include data collection, analysis, decision-making and work execution.

This project is a first step towards a more cost-effective maintenance where it is also included the criticity and the significance of assets in the whole system, besides the asset condition. This is known as Reliability Centered Maintenance (RCM) strategy.

Following chapters describe the implementation of a monitoring system in the pilot plant before mentioned. At first, a description of the monitoring system is presented and then, an implementation of the system in the pilot plant is discussed.

II. Substation Monitoring System

Monitoring is the first step towards the implementation of the CBM strategy. Monitoring consists basically on acquiring significant parameters from the assess of interest, normally power transformers and circuit breakers for being those assess of major importance and with higher impact on the performance of the system. The collected data allow carrying out analyses and diagnose the condition of the assets which is of great use as a support to the decision-making maintenance schedule and then, reducing failures and breakdowns.

During the development of the project, the following three key factors were defined: first, the selection of equipment parameters to be monitored; second, selection of equipment to be monitored; and third, selection of substation to implement monitoring system. These factors were defined by mean of literature revision and surveys with maintenance and operation personal of the utility.

At the same time, the model for the implementation of maintenance strategies, first CBM and later RCM, have been also considered within the scope of the project. The whole system was conceptually structured in three levels:

- Level 1: data acquisition from each asset through appropriated sensors.
- Level 2: data storage and processing at substation level.
- Level 3: integration of the data from different substations into the general maintenance management system of the utility.

The scope of this project was limited up to the level 2, but it is worth to mention that the real benefit from the system will be obtained in the level 3, since it is the stage where the system will be able to provide maintenance decision-making information by mean of well defined models, which is in fact what utilities really cares about.

Substation monitoring is complex because the huge amount of special features to consider. It can be whether continuous (on-line) or no (off-line), depending on the asset and the diagnosis to perform. It is also needed a combination of correct sensors to monitor assets according to their technology, and data acquisition and software to process them.

Moreover, the system must be able to be implemented in any type of substation both new and in service. Obviously, there is a technologic gap between these two types in favour of the former ones. It is easier to implement a monitoring system since design stage or using installed IED's capabilities. However, the interest is focus on in service substations since their assets have consumed part of their lifetime and their failure probability has increased. Then, it is more important to predict possible failures in this kind of facilities.

Utilities build their facilities with assets from different manufacturers. Then, there is a variety of communication protocols. To be able to integrate such diversity, a new standard has been developed for communications within a substation: IEC 61850.

A. IEC 61850

The IEC61850 standard defines communications between IEDs in an electrical substation. It has been developed by TC57 of the International Electrotechnical Commission (IEC), and the objective was the development of an international standard for communications in an automated electric substation.

Until the new standard appeared, several proprietary communication protocols coexist in a substation depending on the quantity of different vendors used. This makes the integration of devices from different vendors in the same substation a hard task. One of the main objectives of the new standard is the interoperability of IEDs from different manufacturers.

In addition to the new standardized communication protocol, the IEC61850 standard also defines unified system configuration language, standardized information models, environmental and electric conditions, and specifies standard techniques for testing of conformance of implementations. It also provides self-description of the elements of the substation system. This self-description reduces the cost of data management and configuration, and reduces down time due to configuration errors.

Despite its recent publication, the IEC61850 standard is consolidating as the future international standard for communications in electric substations. In addition, several extensions and actualizations of the standard are under way regarding not only substations but also almost the whole electrical energy supply chain as well. Activities are being done to adapt IEC61850 standard to wind power plants (IEC 61400-25), hydro power plants, distributed energy resources (IEC 61850-7-420), and also in power transmission and distribution as well as power quality monitoring.

III. Pilot Plant

The pilot plant is an Endesa's substation located in surrounding area of Barcelona. It consists on the monitoring of a 66/25 kV transformer, its upstream circuit-breakers (66 kV) and a 25 kV circuit breaker. A scheme of such pilot plant is shown in Figure 1.

The plant comprises the two first levels quoted in former section: level 1, which acquires and concentrates data for each asset; and level 2, which concentrates and process data from the whole substation.

A. Level 1

1) Power transformer monitoring

The monitoring of the power transformer mainly consists in the evaluation of the oil condition (dielectric and refrigerant), to estimate the state of the cellulose (dielectric), of the active part (core and windings). Likewise, the power transformer is constituted by a voltage regulator from which the contacts state, oil (dielectric) and mechanism are evaluated.

For this purpose, available signals in the substation are used, like the voltage signal from the high voltage transformer side, the transformer load current signal from the current transformers, the refrigeration fans group current and failure signals and the tap-changer position and the current of its motor. To complete these signals, new sensors have been installed for the oil and ambient temperature monitoring, the oil moisture and the oil gases in solution.

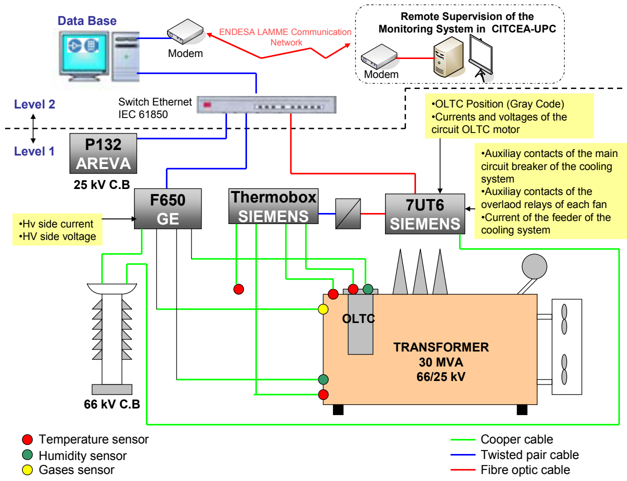

Figure 1. Arquitechture of the monitoring system.

The temperature is read in four different points by using Pt100 sensors. Two of them have been installed in the same power transformer, in the oil superior layer and in the oil inferior layer. A third one has been installed in diverter switch compartment of the OLTC, and the last one is located off of the transformer to read the ambient temperature. Oil moisture is measured through Vaisala MMT318 sensors in two different points: oil inferior layer and tap-changer cubicle. There is also available a Hydran M2 sensor, from the GE, installed in the upper part of the oil circuit. Hydran M2 analyzes the oil gases in solution and gives the concentration in ppm of a patron compounded by hydrogen (H_2), carbon monoxide (CO), acetylene (C_2H_2) and ethylene (C_2H_4).

Table 1 presents a summary of the parameters and sensors installed in the power transformer to monitor it.

2) Circuit-breakers monitoring

The finality of the circuit breaker monitoring is to know the number of operations, the contact wear and the state of the breaker mechanism. The impossibility of manipulating the switch to install new sensors has only allowed achieving available signals in the substation. Table 2 shows these parameters.

On the other hand, a 25 kV circuit breaker is controlled trough an Areva P132 IED, which also allows the equipment monitoring. It will be considered the same parameters shown in table 2, although the IED allows to monitor more parameters of this circuit breaker Additionally, for the integration of the P132 to the pilot plant an actualisation to the IEC 61850 has been needed.

3) Acquisition and concentration of data

The devices destined to acquisition and concentration of data at level 1 are: Thermo-Box, SIPROTEC 7UT635 and F650. These last two devices are IED's and have been installed in the control room. Both work at the same time as communication interface between level 1 and level 2, using fibre optics or shielded twisted pair connections. This communication is based in IEC 61850 protocol. However, connection between sensors and the equipment is done using copper cable.

TABLE I. POWER TRANSFORMER MONITORING PARAMENTERS AND SENSORS

Monitoring parameter	Sensor
Upper oil temperature	Pt100
Gases disolved in oil	Hydran M2
Oil humidity	Vaisala MMT318
Coger oil temperature	Pt100
Ambient temperature	Pt100
High-voltage 3-phase currents	Current transformer
High-voltage 3-phase voltages	Voltage transformer
Oil humidity of OLTC	Vaisala MMT318
OLTC oil temperature	Pt100
OLTC position	Gray code
OLTC motor 3-phase currents	Current transformer
OLTC motor 3-phase voltages	Voltage transformer
Fan-cooling system relays	
Fan-cooling system 3-phase currents	Current transformer

TABLE II. 66 KV CIRCUIT BREAKER MONITORING PARAMENTERS AND SENSORS

Monitoring parameter	Sensor
Line voltage	Voltage transformer
Load current	Current transformer
Switch opened or closed	Circuit breaker auxiliary contacts

Thermo-Box is a Siemens temperature transducer that is located in the transformer adjacent box. This device receives signals that come from Pt100 sensors and it sends measurements through RS-485 to the SIPROTEC 7UT635 device that will centralize all data. The distance between the power transformer and the control room is quite long so there is electromagnetic noise risk. To assure the correct communication between Thermo-Box and 7UT635 a RS-485 to fibre optic converter has been used, also from the manufacturer Siemens.

SIPROTEC 7UT635 device is a Siemens differential protection relay used for the fast and selective short circuit elimination in any voltage level in transformers, but also rotative machines, short-lines and buses. But the main finality of this device in this project is making use of its monitoring capabilities and, in that case, to concentrate temperature measurements and calculate the hot-spot. Using I/O boards it is possible the monitoring of more power transformer parameters.

General Electric F650 device provides fast protection, control and monitoring, including over-current protection, directional elements, voltage and frequency protection, circuit breaker failure, etc. This device uses analogical inputs for moisture and oil gases in solution measurements in the transformer, as well as all parameters related with the circuit breaker, taking account to the multiple possibilities of the monitoring functions. These parameters are circuit breaker operation, trip failure and total arcing current among others. Besides, it is also possible to get the oscillography when the circuit breaker trip,.

B. Level 2

1) Communications and Data Base

Communication between both levels of monitoring system is made trough 3SWT switch provided by μSysCom. This managed switch is designed to achieve reliable performance in hazardous environmental and EMI conditions and it is especially destined to Ethernet communications networks in electrical substations following the IEC61850 standard.

Data acquired in level 1 is stored in a database located in the substation Control Room computer. This computer is also connected to a second network that form part of the utility's proprietary network, which allow remote visualization of the database using a web server. Considering the huge quantity of data involved in the monitoring system, only the most important data, such as maximum, minimum and average, is stored once every 15 minutes in the data base to reduce capacity storage problems.

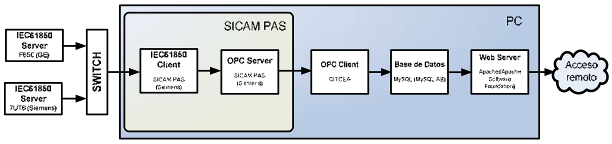

Figure 2. Monitoring system data flow

In Figure 2 is shown the data flow in level 2. Data flow starts in IEDs that concentrate data from field sensors and send data using their IEC61850. Data from IED's servers in IEC61850 protocol are acquired by a computer using IEC61850 client of the software SICAM PAS developed by Siemens. At the same time, this software also has an OPC server that supplies the data received in OPC format. An especially developed OPC client is then who makes a basic data processing and inserts them to a database. Finally, a web server makes possible remote visualization of the database.

2) OPC: OLE for COntrol Process

OPC is a series of open specifications created by the OPC Foundation that ensures standard connectivity in industrial automation based on OLE, COM and DCOM technologies developed by Microsoft [3]. The OPC Foundation was created in 1995 (in collaboration with/promoted by Microsoft,) and it is dedicated to standardize communication and ensure interoperability in multi-vendor control and monitoring systems in a Windows environment.

The OPC specifications define objects, interfaces, and methods to facilitate interoperability in process control and manufacturing automation applications. Before OPC appears, each device used to have their custom interface or driver, what makes the integration of devices from different vendors a difficult and laborious task. OPC solved this problem defining a standard interface regardless of the type and source of data. For that reason, the appearance of OPC has caused great benefits in the development of Human Machine Interface (HMI) or SCADA systems

3) Data analysis

The data stored into the data base allow carrying out an assessment of the condition of both the transformer and the circuit breaker and by means of this diagnosis, the scheduling of the maintenance activities can be achieved. In order words, the data is transformed into useful information as a support to the decision making process.

Through international standards such as ANSI-IEEE and IEC, which have already issued mathematical models that represent the thermal behaviour of the transformer, is possible to obtain information such as the hot-spot temperature, aging index, remaining useful life, etc. Then, all this information can be properly used for assessing the actual condition of the transformer.

By measuring the temperature of the upper layer of oil and the ambient temperature, is possible to calculate the hot-spot temperature of the winding. Then, based on the hot-spot temperature, the aging index is calculated. Additionally, by measuring the moisture of and the gas dissolved in oil, is possible to obtain a good idea about the ageing of the solid and liquid insulation of the transformer.

For example, by mean of the procedure indicated by the standard IEC 60354 [4], the hot-spot temperature of the winding can be calculated by the expression (1):

$$\Theta_h = \Theta_o + H_{gr} \cdot k^Y; \quad (1)$$

where:

Θ_h: hot-spot temperature
Θ_0: top oil temperature
H_{gr}: hot-spot to top-oil gradient
k: load factor I/IN (measured)
Y: winding exponent

In the same way, the IEEE C57.91-1995 states a similar equation for calculating the hot-spot temperature [5]. It is worth to mention that as part of the project, the calculation of both hot-spot temperature and aging rate was carried out by means of the IEC and IEEE standards in order to compare the results.

In the case of the circuit breakers, by measuring the accumulated energy during breaking as well as the number of operations is possible to determine the wear out of the main contacts. As a result, maintenance activities can be schedule only when they are really required. On other hand, by means of the auxiliary contacts of the circuit breaker is possible to determine indirectly the operation time of the circuit breaker both during opening and during closing. By comparing the values of operation time measured to a fingerprint is possible to detect possible damages in the mechanism.

IV. Conclusions and Further Work

A condition monitoring system in a substation has been introduced. It is an open system that can be implemented in any kind of substations, both new and in service, independently of the manufacturer assets. And capabilities of IEDs and new standard IEC 61850 regards to monitoring have been pointed out.

Monitoring systems will do maintenance more effective since it will be performed according to current condition of assets. Furthermore, it will increase the reliability of power infrastructure and then, the power quality that customers get.

Further work on data managing is needed in order to achieve a general maintenance management system. Monitoring is the first step towards a CBM first, and RCM later on.

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