ON-LINE MONITORING OF POWER TRANSFORMERS

In the current context of the Brazilian electric system, equipment reliability becomes crucial, bearing in mind that in an interlinked system, failure of part of the grid can, eventually, cascade up into a whole system shut down.

In these circumstances, Power Transformers stand out as one of the most important items of substation equipment (if not the most important), due to several factors like:

- This is indispensable equipment, without which transmission and distribution of electric energy is not feasible.
- This is difficult-to-handle equipment, due to its large-scale dimensions and high mass, which in some cases can reach tens or hundreds of tons in the case of transmission equipment. This means that replacing a defective transformer can take up to several days.
- Average lead-time for a power transformer, after completing the project phase, is of at least three months, with this type of equipment not being held in stock.

In addition to the above-described factors, which expose the need for reliability in power transformers for purely technical and logistics issues, there is also the economic factor that manifests itself for the following reasons:

- Due to the levels of voltage and power involved (from 13.8 to 750kV and from 10 to 800MVA), a few failure types in this sort of equipment have a high destructive potential, which may result in losses on the order of several million Reais.
- With the new regulation of the electrical sector, started in 1996 following the sector's privatization process, any interruption in the supply of energy, or even simple equipment unavailability (planned or not) can result in heavy fines to utility companies.

Bearing in mind the above exposed scenario, the deployment of Online Monitoring Systems for power transformers, given their importance, together with the rest of the substation equipment, with a view to obtaining perfect operation of the electrical system.

Objectives

The following can be mentioned as objectives for this type of monitoring system:

- Diagnosis of current equipment status, in order to offer decision making inputs in terms of whether the equipment should be kept in operation or, or yet in terms of reducing operating loads in order to reduce the risk of severe failure of defective equipment.
- Early prognosis of failure conditions while still in the early stages of evolution, in order to schedule planned stops for equipment corrective actions.
- Monitoring the equipment's operating conditions over the course of its working life, in order to keep the normal aging process under control, accelerated by the tough operating conditions to which the equipment can be subjected by using the electrical system at its limits.
- Using the transformer under emergency overload conditions however with full knowledge and control of the different variables involved, without running excessive risks.

Methodology

The following stages can be mentioned as required for achieving the objectives mentioned:

1. Measuring variables

It is intuitive that in obtaining equipment status diagnosis and prognosis, it is necessary to perform measurements on the equipment, with the appropriate choice of variables to be measured, as well as the level of quality for the measurements, will become a determining factor in achieving the objective proposed to a greater or lesser extent.

2. Storage of readings

Through a history of reading records of the variables, allowing not only prognosis to be made, by evolution trend analysis, but also the deployment of new future analysis methodologies that will certainly appear, bearing in mind the efforts that have been applied in monitoring systems research and development.

3. Information Treatment

So that user relevant information can be obtained from the variables measured and stored, and not just merely create a huge volume of data, often without any apparent meaning, they must be treated. In general, this treatment is comprised of mathematical models that reflect the equipment's physical behavior, in order to generate equipment status diagnosis and prognosis.

4. Information Availability

Once treated the information, the result of this treatment, and even untreated data must be available to system users. Several questions can be conveniently studied and answered, under the liability of having a system with little use simply because of being inaccessible, and consequently the information, unavailable.

Below, details of each one of the stages mentioned are given.

Measurement of Variables

There are basically two types of architecture used in measuring variables for monitoring systems - "centralized" or "decentralized" architecture.

1. Centralized architecture

onsists in using an information concentration element, usually one or more industrial PLCs, equipped with several digital and analog signal inputs. The different sensors and/or measurement equipment are connected to these through their analog outputs and /or dry contacts. These signals are transmitted to one or more computers, usually located in the control room, that will store and treat variables.

This architecture, in spite of at first sight seeming to be simpler and more direct, because of using market standard equipment connected directly to the outputs of the transformer's sensors, it offers a few disadvantages, such as:

- In general, transformer sensor outputs (temperatures, levels, gases, etc.) are already being used by the substation's supervision and/or protection systems, which forces the installation of repeat sensors for the same function or multiplying signals through auxiliary transducers and relays. This leads us to the obvious consequences of:
  - Increase in number of potential failure points;
  - Increased number of equipment for maintenance (when the objective of monitoring systems is exactly to reduce maintenance!);
  - Increase in the number of spare parts, and
  - Risk of different reading values for the same variable;
- Because of being predominantly industrial use equipment, in general PLCs have serious constraints in terms of electrical insulation and operating temperatures. Therefore, ideally these should be in the climate controlled, control room, which would however lead to a large volume of cabling between transformer and control room, making the system even more expensive, with labor intensive installation and maintenance.

2. Decentralized Architecture

A permanent and fast technological development of digital supervision and control equipment in underway, lead in many cases by Brazilian companies. This scenario brings us extremely interesting possibilities in transformer information capture.

Electro-mechanical and/or analog equipment, such as for instance oil and winding thermometers, have been replaced by digital micro-processed equipment. Despite still featuring analog outputs and dry contacts, required for use by the supervision and protection systems, they feature growing connectivity to information systems, in particular through serial communication ports.

In this way, a large part of the connectivity features of the sensors and equipment, that would normally be used on the transformer, regardless of the existence of a monitoring system, is used in obtaining the necessary measures for the system.

The advantages of this architecture are:

- Analog outputs and dry contacts of Supervision equipment and sensors remain free for use by the substation supervision and/or protection systems
- No need for repeat sensors or multiplication of signals, reducing the number of equipment installed, with consequent reduction in costs of installing, maintenance and spare equipment or parts, as well as potential failure points.
- No risk of discrepant readings for the same variable;
- Increased variable reading accuracy by the monitoring system, bearing in mind that digital data transmission technologies eliminate one stage of analog information transmission, with its intrinsic errors.
- The best transformer supervision and control equipment were developed specifically for use in power transformers, taking into account the extreme temperature and electromagnetic interference conditions found in the environment they are installed in.

In this architecture, the physical information transmission medium can be, for example, a twisted pair operating in standard RS485 (simplicity and low installation cost, practically no special care requirements, good interference immunity) or optical fiber cables (installation requires specialist labor, special care in installing and handling, relatively high cost, total interference immunity). For both physical media, there are examples of several monitoring systems in operation, with fully satisfactory results.

The quality of the information collected is, as previously mentioned, a determining factor in the quality of the diagnosis and prognosis obtained, with this being the reason for the emphasis paced here in the possible measurement architectures.

Measurement Storage

Readings for the measurements taken by transformer supervision equipment are sent to a computer, in the substation control room or other remote locality (for example, the Company Maintenance Center), where they are stored in information history databases and conveniently treated.

The current state of information technology offers a wide range of possibilities for this part of the system, both in terms of hardware and software.

In general, relatively long recording intervals can be used, on the order of a few minutes, since the main variables usually measured on transformers have relatively long time constants (see item "Treatment of Information").

Information storage is carried out in hard disk databases, using whatever means are deemed necessary to ensure information availability (backup copies, disk mirroring, etc.). It is possible to store many years of data, due to the recording interval used and the appearance on the market of devices with increasing volumes of available space.

Treatment of Information

It is desirable to obtain from monitoring systems information going beyond the "raw" data captured by the measuring equipment. At times, just the untreated data can be enough and valuable for maintenance engineers in obtaining equipment diagnosis.

However, on other occasions, "human" interpretation of the data can be extremely difficult or even impossible. In this case, taking advantage of the processing capacity of a digital computer becomes necessary, by way of mathematical and logical modeling for their treatment.

Another important aspect that deserves to be highlighted is that these mathematical and logical models constitute, by their very nature, Specialist Systems, i.e., translation of the knowledge that engineering has about the machine in software capable of emulating certain aspects of its behavior. In this way, monitoring systems contribute to preserving knowledge, which no longer depends exclusively on the human agents involved.

Below, a few examples of possible mathematical models are given, as well as the variables used in creating them. A few of the models suggested work with data obtained off line, whether due to the lack (or prohibitive cost) of on line measuring equipment for the variables involved (as is the case for chromatography and physical-chemical property tests), or because creating the model involves and depends on forming a database comprised of information obtained manually (as is the case of the contact wear model for OLTC due to interrupted current).

- Calculation of estimated insulation life cycle loss, due to thermal aging of cellulose, corresponding to the load conditions to which the transformer was subjected.
- Monitoring of future oil/winding temperature gradient forecast, with alarm in case of detection of trend that will lead to reaching alarm levels and shut down due to winding temperature, as well as indication of time remaining before alarm and/or shut down temperatures are reached.
- Monitoring of transformer natural and forced cooling, based on comparison between the temperature measured at the top of the oil and the value for this temperature calculated based on ambient temperature and load current data, with alarm in case of detection of yield drop for the cooling system, i.e. , temperature measures higher than calculated, discounted the tolerance margin.
- Monitoring of transformer and commuter under load oil temperature differential, with alarm in case of detection of change in this differential behavior pattern.
- On line monitoring of gases in oil levels, with alarm both when critical levels are reached, as in the case of detected growth trend that will in future reach these critical levels.
- On line monitoring of oil moisture levels and calculation of estimated insulation moisture as a function of oil moisture and temperature, with alarm both in case critical levels are reached and in case of detected growth trend that in future will culminate in these critical levels.
- Calculation of the bubble formation in oil due to moisture, with alarm in case of winding temperature close to bubble formation or in case of detection of load conditions that will lead to this temperature, with an indication of the approximate time required to reach close to critical temperature.
- Calculation of water in oil condensation temperature (formation of free water), with alarm in case of lower oil temperature reaching condensation temperature or in case of detection of loading conditions that will lead to reaching this temperature, with an indication of the approximate time required to reach close to critical temperature.
- Monitoring of currents and torques developed by fan and cooling pump motors (torque calculated based on measured voltage and currents), with warning of possible abnormal conditions such as torque and/or current above expected values or detection of rise trend for torque and/or current indicating evolution of possible problems in motors.
- Monitoring of currents and torques developed by the commuter motor (torque calculated based on measured voltage and currents), with warning of possible abnormal conditions

such as torque and/or current above expected values or detection of rise trend for torque and/or current indicating evolution of possible problems in motors and;/or devices associated to them.

- Record of operating hours for fans, with preventive maintenance event warnings.
- Record of the number of operations performed by the OLTC, with estimate of time remaining before next inspection of contacts and/or preventive maintenance, as well s warnings that the number of operations for the inspection and/or maintenance actions has been or will shortly be reached.
- Calculation of OLTC arc contact wear, based on the load current at the moment of tap operation. Implementing this calculation depends on:

  Option 1 – knowledge of the mathematical model for contact wear, usually a trade secret by OLTC manufacturers, or,

  Option 2 – experience acquired by system monitoring in the relation between variables measured and those supplied manually by users.
- Calculation of OLTC operation forecast where the minimum contact thickness will be reached for the equipments arc contacts, as well as the time foreseen for the remaining life cycle of these contacts.
- Diagnosis of the probable internal transformer conditions, determined according to the guidelines of the different chromatography data analysis methods, with alarms discriminating the type of abnormality probably occurring.
- Diagnosis of the insulation oil's physical-chemical conditions, determined in accordance with the guidelines of the rules in force, with alarms in case of values outside the previously defined limits.

The trend is for the above suggested list to continually grow, whether through research work carried out all over the world (including in Brazil, in companies and research institutions) to this end, whether through the experience accumulated by users in deploying monitoring systems, and increasingly more often used.

Information availability

For monitoring systems to be effective and achieve their end objectives, the result of data treatment, as well as untreated data, must be available to system users.

Different questions, such as the ones listed below, must be studied and answered, under the liability of ending up with a system with little practical use, simply for being inaccessible, and consequently, the information unavailable.

- Who, or what departments, need access to monitoring systems?
- From where must the system be available for querying? Only from the substation, in a specific department or from anywhere in the company?

Note that in the case of unmanned substations, systems offering only local access, from the computer in the control room, can be of very little use, since using them would depend on users going to the substation site. On the other hand, in the case of industrial plant substation, with maintenance engineering always close by, systems with access from any computer on the company Intranet can be unnecessarily expensive.

Below, several alternatives currently implemented arte given for access to monitoring systems, with choice of the most convenient depending largely on each one's application, as shown by the examples above.

1. Local access

Access to the monitoring system is performed from the same computer where the data is stored and treated, which can be installed in the substation control room (most common option) or remotely, for example in the company's Maintenance Center. Using this latter option depends on a good and reliable data link between the Center and the substation.

2. Local and simple remote access

Access to monitoring systems can be performed on the same computer where the data is stored and treated, as in the preceding option, and also from a remote computer, which connects to the local computer when required, by way of modems, dedicated data link, etc. Frequently, remote access software must be installed on the access computer, which implies in usually accessing the system always from the same computer.

3. Local and remote access via Intranet

Access to monitoring systems can be performed on the same computer where the data is stored and treated, as in the preceding options, and also from any remote computer connected to the company Intranet. The local computer is also permanently connected to the Intranet, in a few cases through a firewall.

The information made available by the monitoring system comes in Internet page format, so that it does not require any specific software to be installed on remote computers, withy the system being accessed through a commercial Internet browser (Internet Explorer, Netscape Navigator, etc.).

This option features the advantage of allowing access to the system from any company site or even outside the company, wherever there is an Intranet connection to the Internet and authorization for external access (that can be purpose specific). This does not exclude the possibility of limiting access only to authorized staff, by way of passwords or firewall, if there is one.

One case where these features can be useful is where it is desirable for the system to Grant access not only to Maintenance Engineering, but also to the operations department. As can be observed in the mathematical models mentioned as examples, some of these items of information can be extremely useful for this sector.

This type of access has been quite used in Brazil by different utility companies, being part of the specification for monitoring systems, like Furnas, Eletrosul and Escelsa.

Conclusion

This paper presented the general objectives of using monitoring systems on power transformers. The logical sequence for the stages, equipment and software required for achieving these objectives have also been shown.

Different alternatives available on the market for implementing the different portions of the system were emphasized, showing, as the case warranted, their advantages and disadvantages, ot the applicability or non-applicability of certain solutions, dependent on each user's needs.

Several examples of possible mathematical models were given, that help users in interpreting the readings for the variables.

There is still much to evolve in automating system diagnosis and prognosis, whether through developing new mathematical models, or by deploying other AI tools, in addition to Specialist Systems, like Neural Metworks, Fuzzy Logic, Genetic Algorhythms, etc.

In this improvement process, through the implementation of new calculations and tools, the role of users is essential in monitoring systems, notably in electricity utility services, in the sense of making available knowledge from maintenance engineering accumulated over many years, and creation of equipment failure data databases. This means that a higher level of consistence will be reached for monitoring systems, making them more effective for being based on the reality of maintenance engineering

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