NON INTRUSIVE SOLUTION FOR POWER TRANSFORMERS REAL TIME MONITORING USING AN HYBRID PARK'S VECTOR AND MODEL-BASED APPROACH

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ABSTRACT

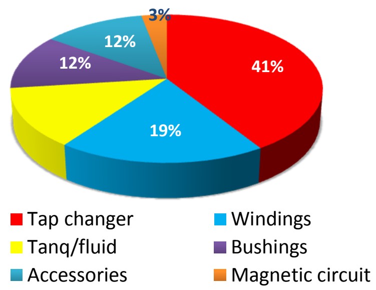
EDP D is testing and implementing solutions to perform online monitoring of a wide variety of assets. The system presented here is intended for the condition monitoring and fault diagnosis of power transformers installed in primary distribution substations. This highly innovative system is able to evaluate the condition of power transformers using two integrated diagnostic approaches that are based on the analysis of electrical variables, namely the primary and secondary currents and voltages of the power transformer. The system is completely non intrusive and does not require the physical installation of any sensor in the power transformer, being entirely installed inside the substation building.
The developed diagnostic system is running in two pilot substations with very promising results, demonstrating its effectiveness in the diagnosis of faults in the transformer windings, magnetic core and OLTC.

INTRODUCTION

Automation and asset management of the 400 HV/MV primary substations supplying the distribution network is of critical importance for the continuity and quality of service. EDP D has been investing in automation equipment and asset management to control and monitor the distribution network to provide the network status information required to support investment, reinforcement and maintenance decisions.
Power transformers HV/MV are the most critical and expensive components in any production, transmission and distribution network. A fault in this component causes a high loss of service and has onerous costs for the utility. Faults in different components of the transformer (
Figure 1) appear typically due to the combination of stress mechanisms of mechanical, thermal and dielectric nature.

STATE-OF-THE-ART

In EDP D, about 70% of the total number of failures that occurred in power transformers over the last 10 years (between 2003 and 2013) had their origin in the windings, on-load tap changer (OLTC), ferromagnetic core and bushings. In its systematic maintenance plan,



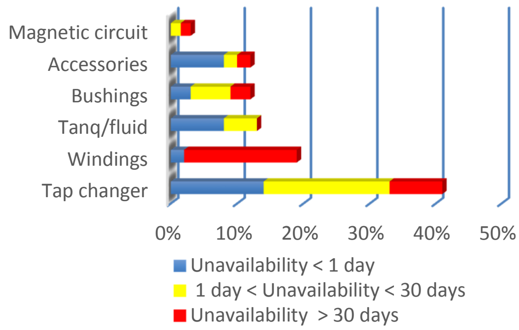


Figure 1: Power transformer failures: component failure rate and transformer unavailability per type of failure [1].

EDP D conducts annual dissolved gas analysis to the oil, physico-chemical tests, search for furanic compounds, detection of hot spots, inspection of OLTCs and electrical tests for screening and detection of anomalies.
These two models of monitoring the power transformers operating condition have advantages and disadvantages, and usually have different costs. So it is important to assess in what circumstances each model should be used, based on the expected benefits and costs involved.

Dissolved gas analysis to the oil

Under the systematic maintenance plan, the following tests are performed:

- Analysis of dissolved gases in oil: allows to identify internal defects in low and high temperature and partial discharge depending on the concentration of gases;

- Physical and Chemical tests: allows to evaluate the aging of insulating oil and how the insulating paper is being affected;
- Furan compounds Search: Allows to evaluate the level of degradation of the insulating paper by identifying the amount of 2FAL component lying in the insulating oil.

Currently, these operations are performed on an annual basis without considering Condition Based and Risk Management (CBRM). If an internal defect is identified, an intensive surveillance plan will be operationalized based in monitoring dissolved gases, which allows following the evolution of the defect identified at intervals of 3 or 6 months depending on the criticality of the defect. Taking in account the SmartLife 2 consortium, only EDP Distribution performs these tests on an annual basis. The consortium advises:

- Chromatographic analysis of gases dissolved in insulating oil must be performed with short intervals of time or even using real time monitoring;
- Physical and Chemical tests and furan compounds may be performed at intervals spaced farther apart, such as 5 in 5 years. The rate of degradation of the oil and insulating paper does not vary significantly from year to year.

So, using a system which allows monitoring the condition of the transformer in real time, it is possible to avoid the cost of dissolved gas chromatographic analysis.

TRANSFO PROJECT

Introduction

So far, the evolution of Smart Grids has been mostly driven by objectives of both energy efficiency and operational flexibility, especially pursuing the ability to manage over energy flows across networks with smart metering and several automation mechanisms and tools. In this process of distributing intelligence throughout the infra-structure, the logical 'counterpoint' to such operational goals consists in the ability to manage the relevant capabilities of scattered physical assets, with criteria and tools of the Asset Management scope, from investment decision support and, thereafter, throughout the entire life cycle exploitation. In recent years, in fact, significant advances in different technological areas – sensors, microsystems, wireless networks, and web service programming – have made it feasible to bring industrial maintenance to higher levels, by bringing together maintenance, operation and engineering, through the whole life cycle of assets. The key to this policy lies in the ability to monitor, in real time, a number of variables that describe the operating status and condition of equipments that, being critical to the respective process operation, should be subject to more sophisticated maintenance criteria: Condition-Based Maintenance (CBM) and, in the long-term, other forms of Predictive Maintenance, namely those based on Risk Management criteria, as preferred by most utilities.
To minimize the impact of this asset failure, utilities have been systematically developing efforts to adopt technical innovative solutions to foresee those potential failures as soon as possible.
EDP D is currently running a pioneer and innovative project with a Portuguese academic institution (University of Coimbra) to develop and test a diagnostic system that monitors the electric currents and voltages in a power transformer in order to detect incipient faults occurring in its windings or magnetic core, through Park's Vector analysis. This technology has been successfully applied to electric motors and drives for the past 20 years and is now being applied at an industrial level to static machines like power transformers [2-5].
The developed diagnostic system is a hybrid system, which combines the analysis of the Park's Vector of the on-load excitation currents of the transformer with a new model-based diagnostic approach, thus allowing the detection, identification and location of faults in the power transformer with high sensitivity.
Two pilot projects have been running for several months, demonstrating the feasibility and applicability of this real time diagnostic system.
The main benefits of the TRANSFO solution are:

- Remote monitoring in real time;
- Intermittent fault detection;
- Easy to correlate the faults with network events;
- Discrimination between faults in the electrical circuit and in the magnetic circuit;
- Detection of potential faults in diverter switch (increased contact resistance);
- Self-learning algorithm;
- Applicability to any power transformer, regardless of its type, age or other characteristic;
- No need for physical access to the power transformer.

Diagnostic approaches

The TRANSFO solution has two diagnostic approaches built-in. One is based on the analysis of the on-load excitation current Park's Vector of the power transformer, and the second one is a model-based approach, which calculates several electrical parameters of a per-phase mathematical model of the power transformer, which are continuously monitored and compared against reference values stored during the commissioning phase of the diagnostic system.

On-load excitation current Park's Vector

The on-load excitation current of a power transformer is defined as the current i_{exc} shown in Figure 2.

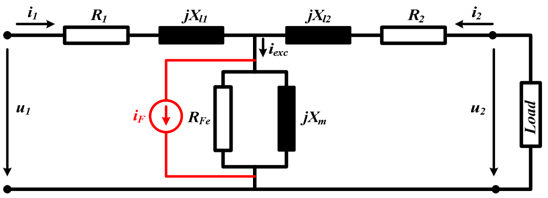


Figure 2: Per-phase equivalent circuit of a power transformer with a fault in its core or windings.

In case a fault appears in the core of the transformer (a hot spot for instance) or in the windings (inter-turn short-circuits), an additional current i_F will be added to the original on-load excitation current. Hence, the detection of the current i_F can be used for the diagnosis of faults in the core or windings of the transformer.

The three on-load excitation currents, one associated to each phase, can be calculated by the measurement of the primary and secondary line currents, and correlating those data with the vector group and transformation ratio of the transformer. The Park transformation is then applied to these currents thus obtaining two components $i_{d,exc}$, $i_{q,exc}$ and a complex quantity given by $\underline{i}_{exc} = i_{d,exc} + j i_{q,exc}$ [3, 4]. A Fast Fourier Transform is finally applied to this complex quantity, thus allowing to detect eventual faults in the windings or core of the transformer. This technique, although allowing to detect faults in the windings and core, is not able to discriminate them. That task is accomplished with the aid of the second diagnostic strategy, based on a mathematical model of the transformer which also has the role of detecting the increase of the contact resistance in the OLTC.

Model-based diagnostic approach

A per-phase mathematical model of the transformer is built during the commissioning phase of the diagnostic system. During this phase, different electric parameters are calculated, such as the iron losses of the transformer, magnetizing reactance, total resistance per phase, among many others. All these values depend on the load level of the transformer and as such a 48 hours period is chosen for storing the calculated values in lookup tables that will serve later on as reference values. After this initial period, called calibration mode, the system will enter into the typical diagnostic mode, where the parameters mentioned above will be recalculated and compared with the ones stored in the lookup tables. In case of a discrepancy between the two, a fault is detected and identified. This method is adequate for the detection of the increase of the contact resistance in the OLTC. In parallel, it allows to discriminate eventual faults detected in the core or windings of the power transformer.

System architecture and deployment

The developed diagnostic system relies solely on the measurement of electrical signals, namely the primary and secondary currents and voltages of the power transformer being monitored, as shown in Figure 3.

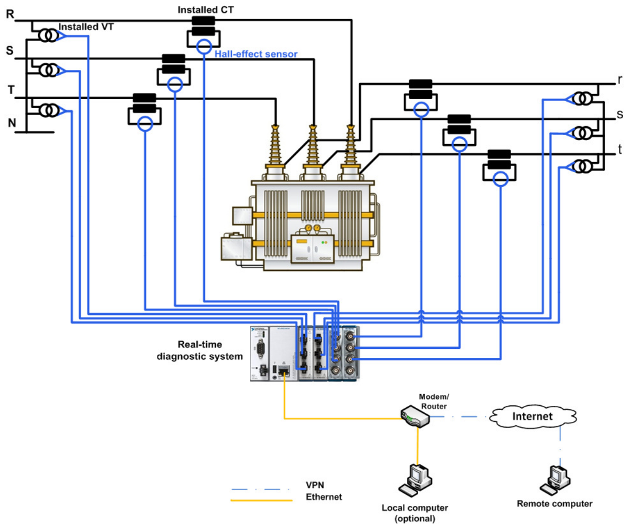


Figure 3: Architecture of the EDP Distribution's real time diagnostic system for power transformers.

The current transformers (CTs) and voltage transformers (VTs) already installed in the substation are used to collect the physical currents and voltages of each power transformer. Inside the substation building, signal conditioning boxes containing high-precision hall-effect sensors collect the secondary currents of the CTs (Figure 4) which are then fed to a modular and reconfigurable embedded data acquisition and processing system (cRIO). The cRIO platform includes analog and digital I/O modules, which allow the direct measurement of the secondary voltages of the VTs. The cRIO platform has a reconfigurable FPGA chassis and an embedded controller where the diagnostic routines run in real time, giving the user a diagnostic result about the condition of the different components of the power transformer every 3 seconds. The cRIO communicates the diagnostic results to a server through Ethernet, although other interfaces can be used such as RS-232, RS-485 or fiber optics.

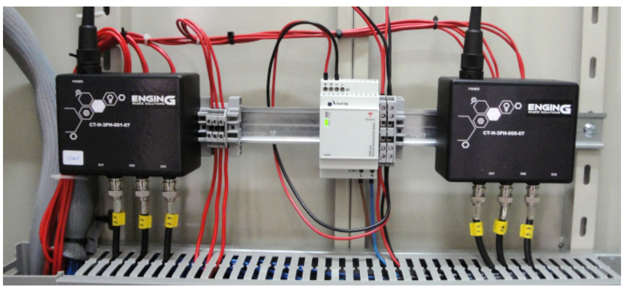


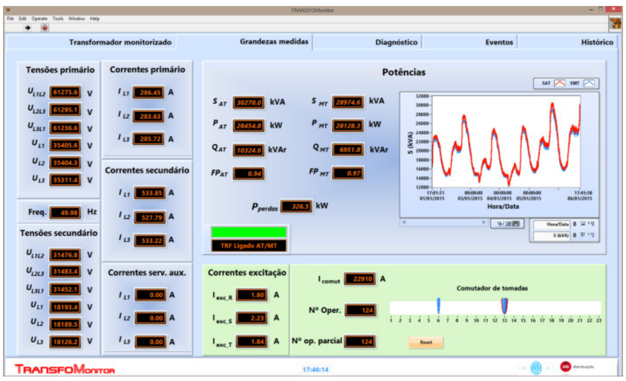
Figure 4: High-precision and non invasive current measurement boxes installed in one pilot substation.

User interface (HMI)

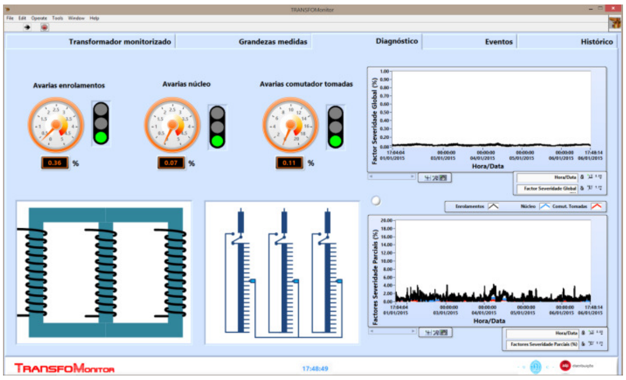
One of the aims of this project was to develop a diagnostic system with a very simple and intuitive interface, so that non expert users can easily start using the diagnostic system and interpret the information it provides.

The main user interface panel has different tabs, each one showing different information. The first tab contains the main characteristics of the power transformer being monitored, like its nameplate data. The second tab contains the measured and calculated variables like the phase voltages, currents and power of the transformer, load level profile, tap changer position (which is automatically estimated by the diagnostic system), number of operations of the tap changer, among other information (Figure 5(a)). The third tab, shown in Figure 5(b), contains the results provided by the diagnostic system about the working condition of the different components of the transformer: three semaphores, one for each type of fault the system is able to detect, which can assume three different colours: green (good condition); yellow (incipient fault) and red (major fault). In addition to the qualitative information provided for each type of fault, the diagnostic system also indicates the values of the severity factor defined for each fault, expressed in percentage. These numbers represent a measure of how serious a fault is (being 0% an ideal and never reachable value for a power transformer without any fault). In addition to this information, when a fault is detected, the corresponding transformer component is highlighted in red in the illustrations shown in the window.

The user interface is complemented with another tab where warnings and alerts are issued, stating clearly if some fault is detected, how serious it is and some recommendations for the operator of the system. A final tab allows the user to check the historic values saved by the system in its main database.



(a)



(b)

Figure 5: TRANSFO user interface: (a) measured quantities; (b) diagnostic results.

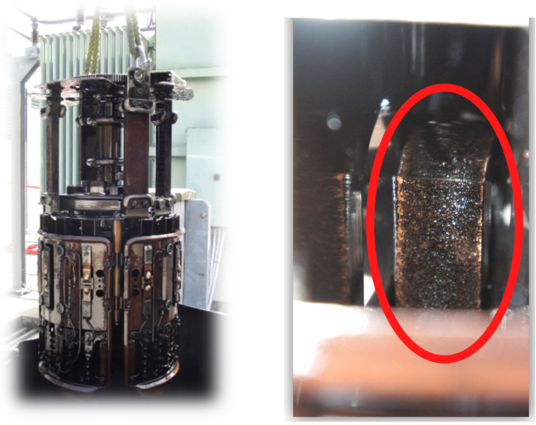
OBTAINED RESULTS

To verify the applicability and effectiveness of this innovative diagnostic solution, two power transformers in two different pilot substations were selected for monitoring. A 31.5 MVA 60/30 kV transformer (Figure 6) and a 20 MVA 60/15 kV transformer were selected, being the first located in a primary substation of a city (substation A) while the second one is installed in a rural area (substation B). Both transformers are equipped with on-load tap changers. The first transformer was manufactured in 2005 and the second one in 1976.

During the commissioning phase of the diagnostic system, some preliminary testing is done, especially to evaluate the condition of the OLTC. When the diagnostic system was installed in substation A, everything was considered normal and the system is running up to this date, indicating that the core, windings and OLTC of the power transformer installed in that substation are in good conditions.

However, during the commissioning phase of the diagnostic system in substation B, the obtained results indicated a potential problem in the contacts of the diverter switch of the OLTC. Following these results, a decision was made to stop the power transformer in order to inspect that component. The inspection of the diverter switch revealed some degradation of the arcing contacts, as shown in Figure 7.

Figure 6: Monitored power transformer in one of the pilot substations.



(a) (b)

Figure 7: (a) OLTC being removed for inspection; (b) degradation of the arcing contacts of the diverter switch.

With regard to the core and windings of this second power transformer, the system is indicating that they are in good conditions.
From the results obtained during the several months that the diagnostic systems have been running in the two pilot substations, it can be concluded that the diagnostic system proved its usefulness in characterizing the operation of the power transformers and the condition of their most critical components.

CONCLUSIONS

The TRANSFO Project presents unique characteristics that allow, in a predictive way, to perform monitoring, diagnosis and assessment of the technical condition of power transformers, which allows to maximize the life of these important assets of EDP Distribution and in addition, contribute to the reduction of risk associated with power transformers faults, which, to occur, would have a very negative impact in EDP Distribution business.
This system also allows to optimize short- and long-term investment plan for renovation and rehabilitation of the HV/MV power transformers park.
Even without considering the costs associated with any faults (e.g. repair, mitigation measures for a rapid replacement of the power supply, quality of service impact, reputation / image and environmental damage), this project presents a payback of approximately 13 years.
By the exposed, EDP Distribuição decided to adopt this solution starting to upgrade the pilot to more 5 substations.

Acknowledgment

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