SMART GRIDS: ASSET MANAGEMENT IN PRIMARY DISTRIBUTION SUBSTATIONS, WITH SMART SENSOR NETWORKS

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ABSTRACT

The system presented here addresses the condition monitoring and diagnosis of critical assets in distribution substations, namely HV and MV automatic circuit breakers, HV disconnect switches, and some variables and devices in power transformers. For this purpose, a highly distributed systems platform is presented here, which, having the capability to integrate a number of deeply embedded devices that pass information among themselves and act as a single system, allow people in charge to intelligently and timely react to both trends and events found in those pieces of equipment under observation and subject to Asset Management criteria.

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.

In this line of approach, EDP Distribuição (EDP Group),– the main Distribution System Operator (DSO) in Portugal, where it operates over 400 HV/MV Substations – approached both the University of Coimbra and Eneida, S.A., given their expertise and industrial background on smart sensors and the respective integration over both cabled and wireless communication networks, in order to devise, specify, and demonstrate an innovative smart sensors platform for the real-time monitoring of a number of new variables of critical assets in power substations.

SCOPE

Currently, fourteen new variables are being monitored in three power substations, within the framework of a successful pilot trial. The operation status of each of the different substation components under observation can be assessed based on information generating at smart devices that are spread throughout the premises, as follows:

- Automatic circuit breakers – both HV and MV –, monitoring the transient electrical currents during shutdown (the line ac currents, plus the dc current through the command coil), and the vibration signature of a breaker's operation, thus anticipating electric and mechanical malfunction with trend analysis against standard patterns;
- Manually/Remotely-operated HV-input disconnect switches, by measuring both the degree of alignment of moving parts and the respective temperature, whenever closed, so as to immediately detect and, therefore, avoid persistent hot-spots;
- Power transformers, where vibration signature and temperature can be recorded and evaluated against standard patterns previously established, and the operating condition of motors and power transmission gears used to modulate the Transformer Turns Ratio (TTR) can be monitored through current and vibration sensors.

Our approach to the architecture and some of the underlying technologies of a highly distributed systems platform is presented next, which, having the capability to integrate a number of deeply embedded devices that pass information among themselves and act as a single system, allow people in charge to intelligently and timely react to both trends and events found in those pieces of equipment under observation.

SYSTEM ARCHITECTURE AND DEPLOYMENT

The whole system was designed conceptually as a set of inter-communicating tasks, which are logically grouped into functional sub-systems that are mapped onto physical processor modules according to their processing requirements. Each task executes in a private protected environment and implements a single abstraction for the rest of the system. Messages are used by modules to request services from other modules. The message system provides an efficient mechanism for passing information between processors and synchronising local processes, and encourages strong logical separation between tasks, given the different requirements in both time response and bandwidth [1].

Hence, the architecture of this solution comprises the following major building blocks, as depicted in Figure 1:

- At each and every substation, autonomous, smart sensors strategically located in critical components are integrated over a hybrid communications network: (i) cabled, for easy distribution of power supply, in the control house, being based on CANbus [2] for robustness and flexiility, and (ii) wireless, whenever it is not practical and/or feasible in order to comply with electrical security regulations, by resorting to a proprietary technology based on a ISM (Industrial, Scientific, and Medical) sub-GHz radiofrequency (RF) band (433 MHz), given its superior EMC and radio-range in environments hostile to RF signal-propagation;
- Data gathered at each substation are concentrated and pre-processed on site, with an embedded industrial-grade PC located there. The integration of data collected from a number of substations is carried out by a central station – the co-ordinator centre –, which supports a common remote database based on Microsoft SQL Server, as well as web-services concerning the appropriate data handling and presentation for status assessment and diagnosis – according to the SCADA paradigm –, from virtually anywhere in the world; remote communication is carried out over a WAN-IP network (e.g., cabled fibre optic, or a 'mobile' public network over GPRS), and human interaction needs no more than light terminals, as thin clients.

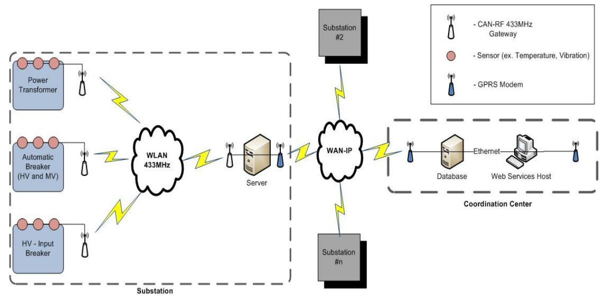

Figure 1 – Overall system architecture

Powering the smart sensors that are located out of the control house was a bit of a challenge, so as to avoid the typical pitfalls whenever using batteries in the open field, especially those deriving from high temperatures, and the consequent maintenance costs. Thus, smart sensors installed in both HV circuit breakers – taking their release vibration signature –, and HV disconnect switches – for motion detection, and measurement of both alignment and temperature of busbars – were provided with appropriate energy harvesting and storage devices, by resorting to supercapacitors being charged by small (8 x 8 cm) solar cells. Figure 2 shows a wireless vibration smart sensor standing next to such a power supply.

Figure 2 – Wireless smart sensor powered by energy harvesting

DATA HANDLING

Special emphasis was put on the human interfacing to technology, by lifting up the traditional focus from the level of applications to that of services — applications are devised and built for machines, and services are built for people — therefore aiming at serving user's needs, but relieving them from low-level platform concerns. In this manner, disparate services in the broad scope of Asset Management could be programmed and currently invoked from on single communication and computing platform, despite the fact that they are essentially very different when it comes to dealing with information, from initial gathering, through intermediate handling, to final presentation.

At the present time, the applications software at the co-ordinator centre has been built-up so as to effectively support the two required approaches to assets' information:

(i) a SCADA system, promptly presenting all the relevant information in graphic formats, and providing a set of tools for a long-term, strategic asset management, and (ii) an alarm issuing station serving the short-term maintenance needs, thus remotely transmitting warning and alarm messages adequate to the urgency in the required response procedures, as defined by the health assessment criteria that has been adopted for the different equipments in a substation. As ultimate goal, only achievable after some more database 'learning', this system should include an automatic worksheet generator, thus issuing electronic worksheets directly to maintenance teams on the field.

For the decisive human role there involved, the SCADA system was the first to be developed, which implied a special emphasis on the human interfacing to the system, so as to obtain features of paramount importance:

- Simple and objective data rendering, thus alleviating people from the so frequent 'mazes' of over-information;
- High level of diagnostic ability and alarm triggering resulting from 'hidden' background data handling;
- The paraphernalia of function buttons and dialogue boxes available to programme and select the type of data handling that most suits each purpose of analysis – especially valuable during the extensive work in order to understand behavioural trends that are to be adopted as criteria of predictive maintenance.

Examples of relevant computer 'screens' are shown in Figures 3 and 4, where results being presented correspond to actual data, i.e., data that had been taken in real operational circumstances. Figure 3 depicts the time description of the transient currents in a HV circuit breaker during shutdown, as well as the current pulse through the command coil: besides the complete current waveforms, also the release time can be properly evaluated.

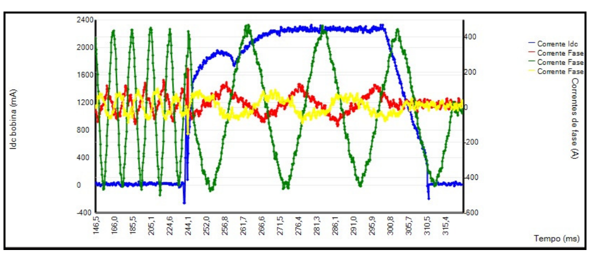

Figure 3 – Transient release currents in a HV circuit breaker

Complementary to the previous time representation, Figure 4 illustrates the frequency description (power spectrum) of vibration following a release of a HV circuit breaker, where spurious signals have been eliminated through a low-pass filter set to 312 Hz.

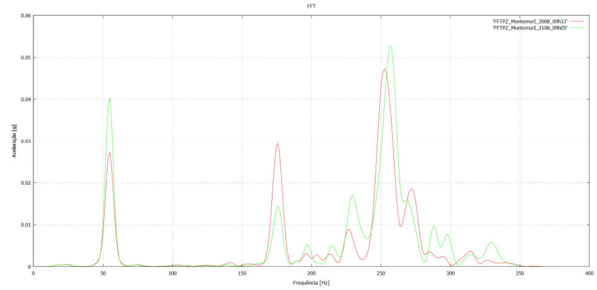

Figure 4 – Power spectrum of vibration following a release in a HV circuit breaker

Having calibrated data referring to all pieces of equipment being monitored, the next step consisted in trying to work-out some common pattern describing a standard behaviour under normal working condition, which could be used as criterion applicable to all equipments sharing the same brand/type/ production series/age/time of service. That proved to be unfruitful, as amplitude data vary significantly from one piece of equipment to another of the same sort, despite the fact that trending (variation rates) are pretty much equivalent.

Therefore, in order to obtain solid references of 'normality' against which current new data could be compared for the purpose of diagnostic analysis, the idea of 'class of equipment' was abandoned, and such references were adopted on an individual basis, i.e., each apparatus was given its own standard reference. The criterion that was recently adopted for the health assessment of the electromechanical equipments in a substation corresponds to a window centred in the up-to-date determined average value of the relevant variables, allowing for a margin of $\pm \sigma$ (standard deviation), which represents a margin narrow enough for a serious evaluation.

Figures 5 and 6 depict different time series, where the upper limit only (red line) is meaningful to determine the working condition of a MV circuit breaker, and of a TTR switching motor and power transmission gear in a power transformer, respectively.

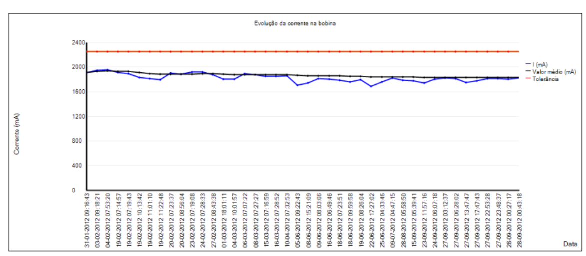

Figure 5 – Command coil current in a MV circuit breaker

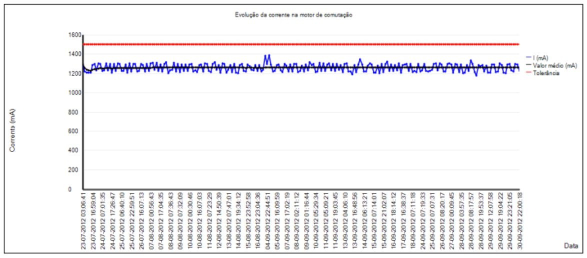

Figure 6 – Power supply to the TTR switching motor in a power transformer

Given the poor number of events having occurred at some organs under observation, namely circuit breakers, the respective reference figures still lack statistic significance and, therefore, no message warnings and alarms are being set for those appliances.

CONCLUSION

The solution presented here is a good example of an innovative approach to industrial instrumentation systems that integrate small, smart, and deeply embedded 'field' devices in large numbers, whose interoperability must be ensured with nested communication mechanisms, over disparate networks. Also, by pursuing a trend of resorting to wireless technologies and the Internet, in line with the vision condensed in the ITU's prospective paper entitled "The Internet of Things" [3], such an approach has been rightfully dubbed as 'Instrumentation Cloud'.

Thus, by easily extracting value from the intelligence in each device and piece of equipment – smart sensors, intermediate gateways, and the co-ordinator centre – very significant gains were obtained in:

- effectiveness, as personnel could concentrate on economic objectives and safety constraints of the equipments;
- flexibility, for they allowed both incremental growth, and functional versatility, easily coping with changes in requirements;
- cost, considering both capital and maintenance costs, which are significantly lower when compared against traditional instrumentation solutions.

From such capabilities of gathering, analysing, and supporting human decisions – while it does not start sending out worksheets on its own – this represents a valuable tool for the purpose of high-level asset management and, by increasing the amount of intelligence dispersed throughout electrical grids, these better deserve being designated as smart.

Finally, closing the gap between the birth of this idea and the manufacturing of the end product was successfully accomplished, having been the result of a fruitful co-operation between Industry (both manufacturer and final consumer), and Academia.

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