ID: 10866 **Session 2022**
A3 – TRANSMISSION AND DISTRIBUTION EQUIPMENT
PS3 – Digitalisation of T&D equipment

Advanced High Voltage Disconnector Condition Monitoring

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SUMMARY

High voltage disconnectors (HVD) are devices providing, in the open position, an isolating distance according the specified requirements (e.g. IEC 62271-102 [1]), and they are also capable of carrying currents under normal conditions.

Based on this main characteristics, high voltage disconnectors are mainly used to reconfigure the network at the substation level and provide isolating and earthing conditions (in case of earthing switches) to carry out maintenance operations, respecting all the required safety rules. Both use conditions do not impose a high level of operation for these devices. In fact, experience shows that a thousand close-open operation are usually high enough to cover the typical expected lifetime on this switchgear and controlgear.

Disconnectors usually provide isolation and safety conditions to carry out maintenance operations, on other high voltage switchgear and controlgear (as circuit-breakers), requiring a more frequent operation rate.

Modern high voltage circuit-breakers (SF6 or Vacuum) requires less maintenance than the one required for old technologies (e.g. air-blast, oil). Therefore, HV disconnectors are even less challenged than before, in term of number of operations. Despite of the recent existence of hybrid HV designs (GIS – AIS), these concepts are nowadays residuals in the installed base and conventional HV disconnectors (open-air devices), based on a mature technology (simple and visible) remain being the preferred option of most of the TSO all over the world.

However, to improve reliability and reduce the frequency of the maintenance periods of conventional HV disconnectors, different condition monitoring systems begins to appear in the marketplace based on connected systems, monitoring the motor consumption during HV disconnector operation. Experience shows that this parameter helps to control the degree of mechanical aging of the transmission and main contact (dust, grease hardness, …).

This paper presents the outcomes of a partnership pilot project launched with the Substations Maintenance Department of the Spanish TSO (Red Eléctrica de España - REE) to install an **Advanced High Voltage Disconnector Condition Monitoring System (ADCM)**. This advanced smart architecture is not only monitoring the current consumption of the motor but also measuring the temperature of the main conductor and verifying that the closed position has been properly achieved during the closing operation. These two additional and advanced monitoring devices are implemented in the HV disconnector through wireless sensors, placed at the main current path of the HV disconnector. All the monitoring parameters (motor consumption, operation time, temperature and achieved closed position) are managed and remotely communicated through an IED. Additionally, all this monitoring architecture has been designed and qualified in the laboratory before being installed in outdoor conditions under specific environmental conditions.

Once the qualification has been passed satisfactorily, a field test has been also initiated on two different type of disconnectors:

- Double break disconnector for rated voltage of 245kV
- Double break disconnector for rated voltage of 420kV

At the time this paper is written a cumulated experience of more than 20 months is available with disconnectors installed in real operation conditions, being operated several times during this field test. A third sample of pantograph 420kV disconnector is already prepared and ready to be installed on site, once the high voltage substation will be selected by REE.

In this field test period, several data have been collected (temperature, achieved close position, motor consumption, operation time, ambient temperature, and humidity), opening the way for a data analytic period.

KEYWORDS

High Voltage Disconnector, wireless sensors, thermal monitoring, position monitoring, consumption monitoring, cybersecurity, edge control, predictive maintenance.

1. BACKGROUND OF THE PROJECT

Spanish TSO (REE) is currently in charge of the maintenance of around 10.000 disconnectors (245kV and 420kV). Thermography (once a year), Local Operations (twice every 5 years) and General Maintenance Service (once every 6 years) have been, up to now, the main maintenance actions implemented to keep the performances of the disconnectors along the lifecycle. Local operations have been historically made by skilled and trained people (at least 2 persons) to assure that the disconnector always achieve full closed position (taking over the toggle point). To reduce the overall cost of the HVD maintenance strategy, a collaboration has been initiated between REE and a switchgear and controlgear supplier to find advance monitoring techniques that contribute to minimize the need of skilled operators on site for maintenance. ADCM has been co-design for that purpose.

2. COMPONENTS DESCRIPTION

To fully achieve the functionality of an ADCM, an extensive variety of stand-alone sensors and IED's (Intelligent Electronic Devices) have been tested. The sensors and IED's described in this chapter have been identified as the ones giving the highest cost-effective ratio in relation with:

- the High Voltage substation mission profile,
- the easiness and safety of the integration in the High Voltage Disconnector
- the way that the data obtained need to be consolidated and communicated by the IED's.

2.1 Stand-alone sensors

2.1.1 Environmental sensors (temperature and humidity)

Environmental sensors have been used to continuously monitor both the temperature in the disconnector main current path (self-powered, see Figure 1) and the ambient temperature/humidity (10 year duration - battery). Both are equipped with Zigbee IEEE802.15.4 [2], 2.4GHz wireless communication. Depending on the layers/enclosures of separation between the sensor and the receiver, the sensor is able to communicate with the receiver at distances going from 10 to 100 meters.

Figure 1 Self-powered wireless thermal sensor

2.1.2 Position sensors

Historically, the position of the main current path of the HVD have been communicated to the substation control room through a set of contacts, from the contact block, placed at the control cabinet of the HVD. In order to improve the reliability of this signal, REE challenged a switchgear and controlgear supplier for getting the indication of the effective closed position, from the HVD main current path, without affecting the reliability of the HVD main contact itself.

Different types of self-powered wireless switches have been used depending on the integration needs and the different types of HVD main contact to be monitored. Figure 2 shows one of the sensors used. All types of the sensors used are equipped with a Zigbee IEEE802.15.4, 2.4GHz wireless communication module. In this type of switches, the energy for the status communication comes from the movement of the lever itself. This energy supply system makes this kind of switches specifically adapted when a non-intrusive approach is needed. Wireless position sensors have been used to accurately communicate to the IED's that the High Voltage Disconnector full closed position has been effectively achieved.

Figure 2 Wireless switch – lever type

2.1.3 Motor consumption

Together with the temperature of the main contact and the mechanical indication of having achieved the full closed position, the current monitoring during the closing operation was identified as one of the key parameters to obtain, in order to decide about a proper and normal behaviour of a HVD during a closing operation.

In order to keep and achieve a high level of non-intrusive monitoring on the full system, different types and technologies of LVDC current measuring sensors have been analysed (see Figure 3). A Hall effect sensor, ready to be integrated in an electronic card has been finally chosen to monitor the motor consumption during HVD operations.

Figure 3 LVDC current monitoring sensor

2.2 Sensors integration

Once sensors have been identified, tested and validated as stand-alone devices, an integration step is needed. The main objectives for this integration are to keep the main objective of collecting the required data but:

- Not affecting the performance and ratings of the different types of HVD
- Not affecting the capabilities of the sensors, in term of data acquisition and communication
- Being adapted to the HV substation mission profile along the lifecycle (outdoor ambient, electrical constraints, maintenance, …)

The integration of the position sensors depends on the architecture of the HVD main contact. A double indication has been designed to have a n-1 criterion for the closing signal. Full accurate close position is delivered when the two signals sent by the position sensor are consistent with the effectively closed position.

The integration of the LVDC current sensor in a PCB has been made in order to treat and interconnect adequately the sensor inside the LV cabinet of the HVD. The PCB has been also integrated in the LV cabinet in order to get an easy access to the motor supply connection. The main supply motor connection is wired to the motor, but just passing through the toroidal sensor, being then non-intrusive from the motor circuit perspective.

2.3 Intelligent Electronic Devices (IED's)

2.3.1 Zigbee receivers

Different Zigbee receivers have been used depending on the signal type to communicate. An external antenna has been also tested and implemented on site to improve the capability of the receivers to get signals from different sensors installed along the High Voltage Substation

2.3.2 Programmable relay and analog acquisition module

A basic programmable relay equipped with an analogical/digital module has been also integrated in the global architecture to easily convert and process the analog signals coming from the current sensor. Additionally, the PLC is equipped with digital inputs/outputs giving an appropriate flexibility for the customer to treat different digital inputs coming from different sensors and communicate in a simple and wired mode the information to the control room in a very basic approach.

2.3.3 Main central unit and communication modules

The main intelligent device is a modular central unit capable of controlling and monitoring, all the signals and inputs needed. Hereafter, it will be referred as RTU (Remote Terminal Unit). Among other characteristics, the RTU integrates a significant number of protocols as IEC 101/104, DNP3, IEC 61850, Modbus. The RTU is also ready for cybersecurity management according to IEC 62443-4-2 [3] and manages a comprehensive set of algorithms to provide the relevant alarms to inform the maintenance and operation teams.
These have been key characteristics to select it as the main intelligent device, not only for the current pilots but also for the future next steps of this project (see clause 4)

3. ADVANCE DISCONNECTOR CONDITION MONITIORING SYSTEM

3.1 System architecture and functional description

The enhanced capabilities of the ADCM require the proper collection, and processing, of many types of data. Figure 4 shows a simplified view of the system architecture.
There are different types of data to be collected:

- Environmental conditions: temperature and humidity via Zigbee sensors
- Temperature in main contacts via Zigbee sensors
- Proper closed position achieved via wireless Zigbee switches
- Motor consumption during (open/close) operation through a dedicated hall effect sensor mounted on a PCB and its analogical/digital module of the PLC
- Duration of (open/close) operation monitored by the PLC based on the different available inputs (current signal and effectively closed position)

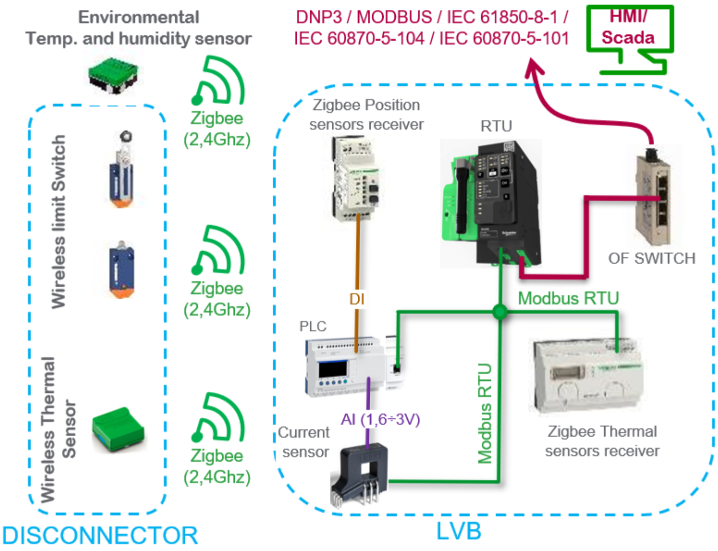


Figure 4 System Architecture

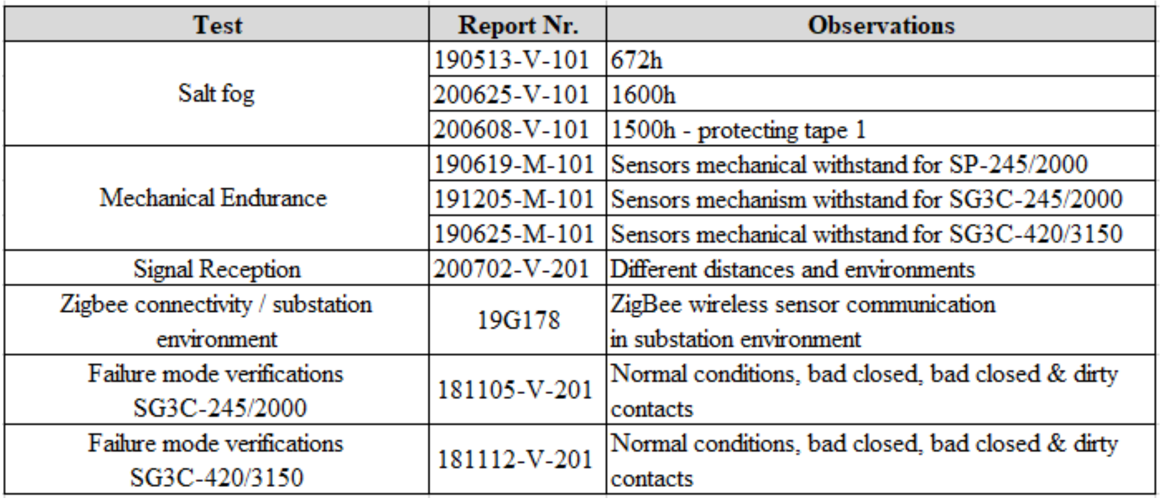
The RTU works as the Central Processor Unit of the system. It is in charge of receiving all the signals from the sensors and satellite devices, to process them, thus generating the required alarms, by the implementation of proper algorithms, and recording the event logs. The RTU also assumes the task of communicating upstream the ADCM via an optical fiber switch. Due to its versatility, many different protocols are available, such as DNP3, MODBUS, IEC 61850-8-1, IEC 60870-5-104, and IEC 60870-5-101.
Within the ADCM, the RTU acts as master in a MODBUS RTU network comprising a Zigbee concentrator and a PLC as slaves. Modbus RTU is a widely accepted serial level protocol due to its ease of use and reliability. Modbus RTU is widely used within Building Management Systems (BMS) and Industrial Automation Systems (IAS).
In a downstream step, wireless thermal and position sensors communicate via Zigbee protocol. The Zigbee concentrator collects the analogical incoming data from temperature and humidity sensors and sends it upstream to the RTU via MODBUS RTU. In the same way, the Zigbee digital concentrators gather the binary signals from the position switches and send them to the PLC, and from it, upstream to the RTU via MODBUS RTU.

It can be said that the PLC works as a gateway transducing analogical measures (operation duration, and maximum motor consumption from the hall effect sensor) and binary data (disconnector opened/properly closed status) to MODBUS RTU protocol upstream to the RTU.
Zigbee is an IEEE 802.15.4-based specification for a suite of high-level communication protocols used to create personal area networks with small, low-power digital radios, such as for home automation, medical device data collection, and other low-power low-bandwidth needs, designed for small scale projects which need wireless connection.

3.2 Development and validation plan

A deep and extensive laboratory validation has been agreed, with REE (see Table 1), and fulfilled, before launching the pilots. The parameters that have been checked are related with actual disconnector verifications on abnormal conditions as:

- Motor consumption, temperature rise, operation times and verified closed position for different failure modes
    - Bad connection on the main contacts (bad contact pressure, dirty surface, ….)
    - Abnormal load currents
    - Blocked connection during closing operation
- Performance during and after mechanical endurance tests (1000 op.)
- Connectivity at different distances and environments
- Mission profile verification – Environmental – EMC

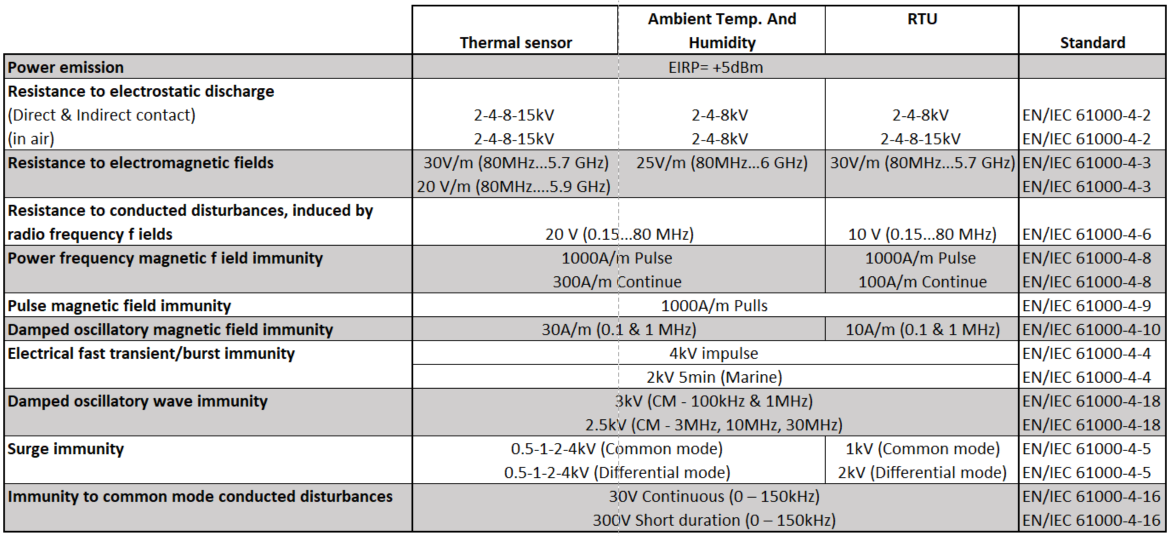


Test	Report Nr.	Observations
Salt fog	190513-V-101	672h
	200625-V-101	1600h
	200608-V-101	1500h - protecting tape 1
Mechanical Endurance	190619-M-101	Sensors mechanical withstand for SP-245/2000
	191205-M-101	Sensors mechanism withstand for SG3C-245/2000
	190625-M-101	Sensors mechanical withstand for SG3C-420/3150
Signal Reception	200702-V-201	Different distances and environments
Zigbee connectivity / substation environment	19G178	ZigBee wireless sensor communication in substation environment
Failure mode verifications SG3C-245/2000	181105-V-201	Normal conditions, bad closed, bad closed & dirty contacts
Failure mode verifications SG3C-420/3150	181112-V-201	Normal conditions, bad closed, bad closed & dirty contacts

Table 1 Validation plan fulfilled before pilot installation

These conditions have been checked for different architectures of disconnectors and parameters as temperature, motor consumption has been also measured. All these data coming from tests, together with the product knowledge along decades of experience, have been the mandatory incoming data to recommend appropriate alarm thresholds levels for every data recorded during condition monitoring.

EMC has been extensively discussed with REE. Sensors and IED's has been submitted to the agreed severity levels, that has been seen adequate to launch the pilots installations (see Table 2). Further on, and because of the difficulty to accurately states EMC values for an actual installation, for instance during service and disconnector operation, this aspect was also identified as one of the key parameters to verify during the field tests (pilot installations). After more than 20 months and several open-close operation in service, no failures have been reported and it has been agreed that the tests and ratings of the sensors and IED's installed, together with their installation conditions, have been enough to perform adequately in some of the REE HV substation.



	Thermal sensor	Ambient Temp. And Humidity	RTU	Standard
Power emission	EIRP= +5dBm			
Resistance to electrostatic discharge (Direct & Indirect contact) (in air)	2-4-8-15kV 2-4-8-15kV	2-4-8kV 2-4-8kV	2-4-8kV 2-4-8-15kV	EN/IEC 61000-4-2 EN/IEC 61000-4-2
Resistance to electromagnetic fields	30V/m (80MHz…5.7 GHz) 20 V/m (80MHz….5.9 GHz)	25V/m (80MHz…6 GHz)	30V/m (80MHz…5.7 GHz)	EN/IEC 61000-4-3 EN/IEC 61000-4-3
Resistance to conducted disturbances, induced by radio frequency fields	20 V (0.15…80 MHz)		10 V (0.15…80 MHz)	EN/IEC 61000-4-6
Power frequency magnetic field immunity	1000A/m Pulse 300A/m Continue		1000A/m Pulse 100A/m Continue	EN/IEC 61000-4-8 EN/IEC 61000-4-8
Pulse magnetic field immunity	1000A/m Pulls			EN/IEC 61000-4-9
Damped oscillatory magnetic field immunity	30A/m (0.1 & 1 MHz)		10A/m (0.1 & 1 MHz)	EN/IEC 61000-4-10
Electrical fast transient/burst immunity	4kV impulse 2kV 5min (Marine)			EN/IEC 61000-4-4 EN/IEC 61000-4-4
Damped oscillatory wave immunity	3kV (CM - 100kHz & 1MHz) 2.5kV (CM - 3MHz, 10MHz, 30MHz)			EN/IEC 61000-4-18 EN/IEC 61000-4-18
Surge immunity	0.5-1-2-4kV (Common mode) 0.5-1-2-4kV (Differential mode)		1kV (Common mode) 2kV (Differential mode)	EN/IEC 61000-4-5 EN/IEC 61000-4-5
Immunity to common mode conducted disturbances	30V Continuous (0 – 150kHz) 300V Short duration (0 – 150kHz)			EN/IEC 61000-4-16 EN/IEC 61000-4-16

Table 2 EMC values of the components installed in the pilots

3.3 Data management

All the architecture designed for the ADCM is able to get bulk data from the installation. The way the data are manage strongly depends on the customer experience.

The system has been built to be flexible and fully adaptable to the different approach coming from the user. For this project, the way of preparing the data to be communicated has been defined between the Maintenance department of the Spanish TSO (REE) and the HV disconnector and Digital experts.

Extensive number of tests at the laboratory, combined with a huge experience on the HVD behaviour allow us to recommend some thresholds levels for each of the data collected.

Four different alarms have been defined:

P1→DFUR POS: Urgent position alarm
    0 → Disconnector has reached the full closed position
    1 → Even if the disconnector seems closed the main contacts have not reached the full closed position
T1→DFUR T^a: Overheating contact point alarm
    0 → Temperature rise (TR) of the main contact is below the permitted TR according IEC 62271-102
    1 → Temperature rise (TR) of the main contact is above the permitted TR according IEC 62271-102
C1→DFUR CONSUMPTION: Excessive consumption alarm
    0 → Motor consumption does not exceed the maximum value stated for the manufacturer
    1 → Motor consumption exceed the maximum value stated for the manufacturer
T2→DFUR TIME: Excessive operating time
    0 → Closing operation does not exceed the maximum time stated for the manufacturer
    1 → Closing operation exceed the maximum time stated for the manufacturer

Table 3 shows a possible combination of the alarms actual state to give an indication about the level of the risk or criticality of the problems detected.

STAGE	SENSORS		EXPECTED RESULTS	ACTUAL ALARMS STATE						
OPERATION OPEN-CLOSE	P1	POSITION	Change position	P1	0	1	0	0	0	0
	T1	Tª CONTACT	Changes temperature values	T1	0	0	1	0	0	1
	C1	MOTOR CONSUMPTION	Engine consumption within the set values	C1	0	0	0	1	0	1
	T2	OPERATION TIME	Time within set values	T2	0	0	0	0	1	1
					OK	FAILURE	CHECK	CHECK	CHECK	CHECK

Table 3 Example of an actual alarms state combination to define level of criticality or risk of the installation

The algorithms for the alarm managements and for the data analysis are customer based and implemented at the level of the RTU module software. The proposal made on Table 3 for this project is fully and easily adaptable to the customer/user experience requirements.

As an example, Table 3 shows that a "1" state in P1 create a situation of "Failure". It should be noted that a not fully achieved closed position could happen even without a significant temperature rise increase in the main contact, depending for instance on the load. Indeed, this type of "failure" would be hardly possible to detect through thermography or equivalent temperature monitoring systems. However, this type of "failure" has been considered by REE highly risky, as the disconnector could not withstand the electrodynamic forces in case of short-circuit. Therefore, with P1 = 1, the urgent presence on site will be required to check the status of the ADCM. Successive open and close operation will be done by the staff in charge, to check if the "failure" is persistent. If so, disconnector must be put out of service and a complete maintenance service is needed with specific focus on the main contact.

In contrast, the rest of alarms T1, C1, or T2 are considered secondary signals and are communicated to the system operator just as a "warning" (to be checked) and, unless the deviation is significantly high, an urgent action is not needed. The deviation in temperature, current and/or time will be then analysed and corrected after a detailed data analysis.

3.4 Cybersecurity

Any product connected to an IT network is susceptible to become an interface for cybersecurity attacks. The system presented here packs the appropriate requirements designed to meet international cybersecurity standards on an end-to-end approach.

Wireless sensors use ZigBee communications technology, and are factory paired with their corresponding receiver via an encrypted point-to-point connection. Once the pairing is established, they are designed not to be paired with any other device/receiver. This combination makes it virtually impossible, for an external intruder, that is physically within range of the ZigBee wireless network, to obtain sensor data or enter the system from there.

The rest of the elements are securely managed by the main unit, the RTU, which includes, as standard, the cybersecurity features according to IEC62443-4-2. The RTU acts as the single point of communication of the system with any external IT network, guaranteeing the highest cybersecurity standards as listed above when remote communications come into play.

3.5 Pilot installation

At the time this abstract is written, there are two **ADCM** on service sited on the LA CUADRA substation (GÜEÑES/Basque Country/Spain):

- 245kV double-break disconnector
- 420kV double-break disconnector

A detailed description of the arrangement implemented on the 245kV double-break disconnector is shown in the next figures (5,6 and 7). The 245kV ADCM was commissioned and put in service in December 2019.

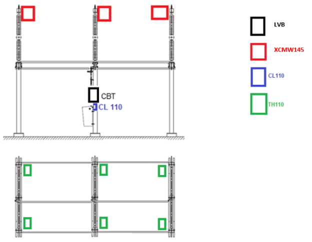


Figure 5 245kV double-break disconnector – Sensors

Figure 5 shows the three-phase arrangement of the disconnector. Position sensors have been placed (red squares) in all three phases but just in one of the set of contacts. It has been assumed that every time one of the main contacts reaches its full closed position the other one reaches also the full closed position, because of the rigidity of the main conductor. There are two thermal sensors that have been installed in each phase (monitoring both contacts of the double-break disconnector) to monitor them separately. Figure 7 shows the integration of the thermal sensor to directly get the temperature from the contact.

As it can be seen in Figure 6, the intelligent control cabinet is placed at the floor level, attached to the frame and close to the traditional controlbox of the disconnector (red LV box). The intelligent control cabinet has been equipped inside a appropriate stainless steel box, equipped with a window in the front door in order to verify the digital status of the signals from outside.

Figure 6 Controlbox integrating all the IED's for the ADCM disconnector

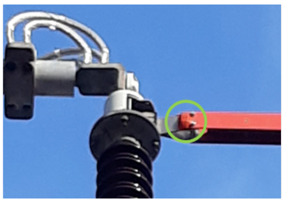


Figure 7 Temperature sensor integration in the main contact

3.6 Actual collected data

The figures below show the data recorded from the system designed and implemented on the two pilots in service

3.6.1 Current consumption and closing time (420kV disconnector)

In order to check the capability of the system to effectively supply the expected data, operation of the disconnector has been planned and carry out for the maintenance department of REE. Figure 8 shows the maximum current value recorded during the closing operation. These values are registered in the IED and fully accessible, directly from the IED or remotely through remote communications.

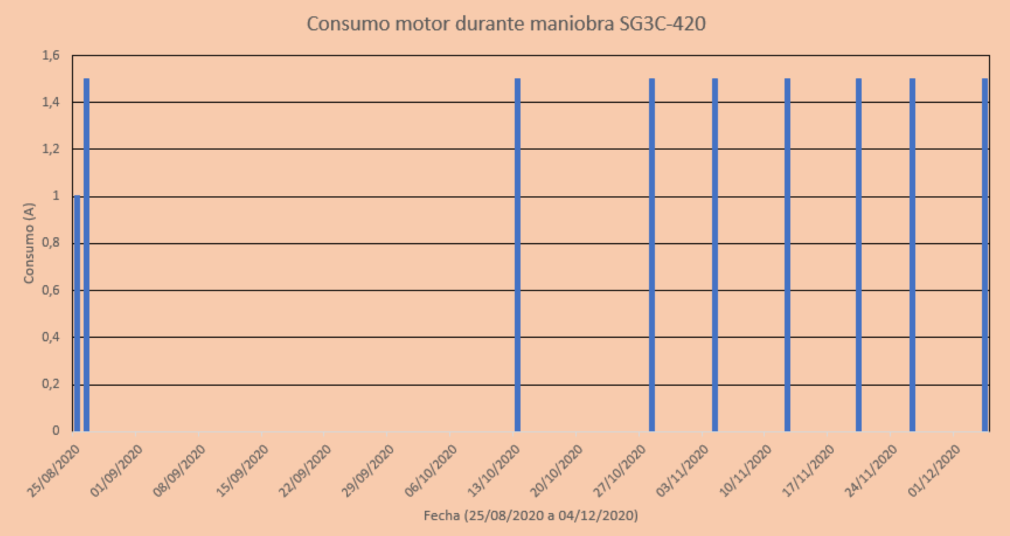


Figure 8 Maximum motor consumption during closing operation *(A)*

3.6.2 Contact temperature (420kV disconnector)

Figure 9 is showing the temperatures recorded for the wireless thermal sensor placed on the main conductor of the disconnector. Temperature measured at the main conductor of the disconnector will depend on the ambient temperature, the current and the state of the contacts. Current through the disconnector is parameter that is well known at the level of the substation.

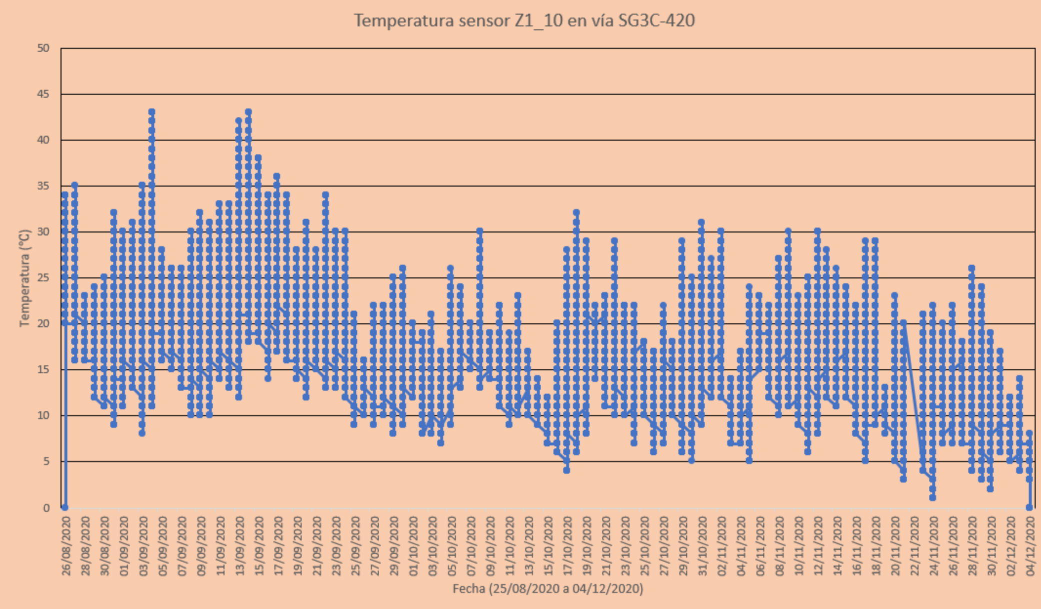


Figure 9 FFE17ADE) sensor placed on disconnector blades (°C)

3.6.3 Environmental parameters of the substation

Located at the level of the disconnector being monitored and close to the intelligent control box, a dedicated ambient temperature and humidity has been also integrated.

Figure 10 show a graph with the humidity measurements obtained during the last quarter of 2020.

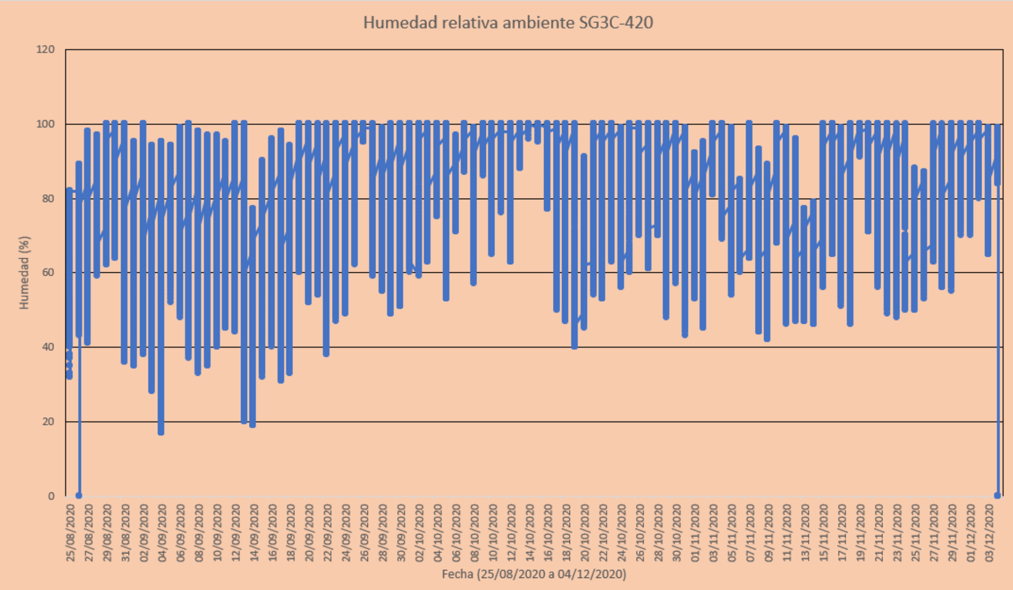


Figure 10 Humidity measured in the area around the intelligent control box (%)

3.7 Total Cost Ownership study

A Total Cost Ownership study (TCO) has been done, both for the new installations and for the installed base, for 245kV and 420 kV HVD's.

3.7.1 New installations

Figure 11 shows the comparison made between a conventional HVD managed as usual through periodic maintenance activities every 6 years, local operations with trained and skilled personal on site to verify the proper closing operation (twice every 5 years), thermography analysis to verify that the temperature of the main connections remains at right level (once per year) and a ADCM equipped with the Advance Monitoring Kit. For the TCO calculations of the ADCM, Local operations and thermography have been eliminated and the maintenance activities has been re-scheduled. This study has been done for an expected service life of 30 years.

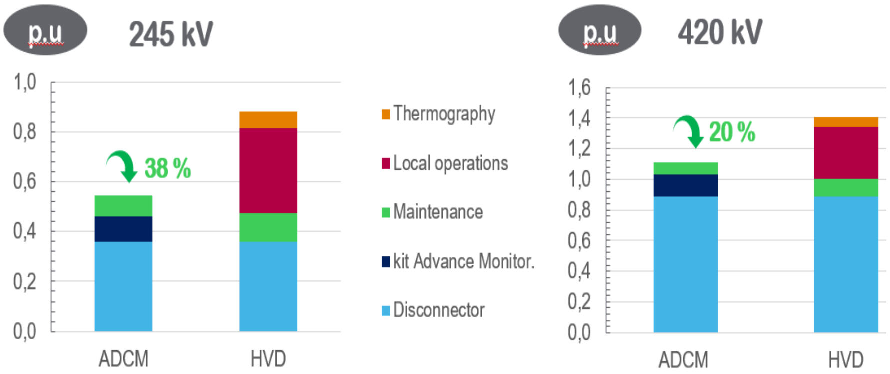


Figure 11 TCO study for new installations in p.u

As it is seen, the main economic driver of the ADCM is the cancellation of the local operation tasks (not needed because of the position sensors), together with the cancellation of thermography (temperature sensors) and the adaptation of the maintenance frequency (consumptions and operation times acquisition).
As it is shown in Figure 11 a TCO reduction of 20-40%, depending on the voltage level can be achieved when installing an ADCM compared with a conventional HVD, reducing significantly the OPEX with a slight increase of CAPEX.

3.7.2 Installed base

Similarly, a TCO has been made for HVD equipment already installed. The study has been done on HVD's installed 15 years ago. It has been assumed, because of the installation of the Advance Control Kit, that the service life can be extended in 10 years. As it is shown in Figure 12, a TCO reduction of 35-55%, depending on the voltage level can be achieved when installing an Advance Monitoring Kit in the installed base compared with a standard maintenance management on conventional HVD's.

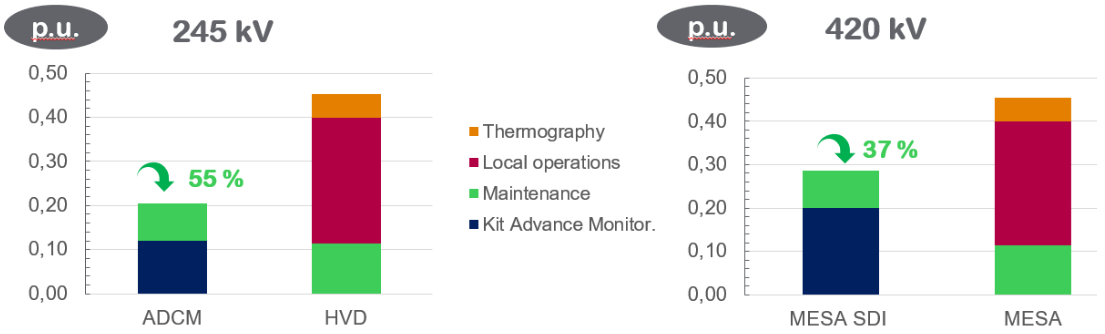


Figure 12 TCO study for installed base in p.u.

4. NEXT STEPS

The goal of the next steps is to allow our customers (network operators) to drive actions based on real-time valuable information and, consequently, improve overall business efficiency.
The main objective will be then, transforming the acquired data into meaningful information & analytics, available anywhere, anytime. To achieve that, the system will go through a further stage of development in which it is foreseen to be provided the following digital capabilities:

- Upstream secure communications
- Additional data treatment and algorithms for advanced alarming
- Web based HMI applications
- Service ready: system capabilities at a cloud level

5. CONCLUSION

An **A**dvanced High Voltage **D**isconnector **C**ondition **M**onitoring has been developed, validated, and implemented through a full partnership between a switchgear and controlgear supplier and REE (Spanish TSO). A set of warnings and alarms has been defined by the REE and a full package of algorithms has been developed by a switchgear and controlgear supplier to allow the maintenance and operation staff of REE, to take the appropriate decisions at the right time. TCO of ADCM is significantly lower than the one for conventional HVD, for an expected service life of 30-35 years.
A project has also been already defined for the next steps, to distribute all the information inside the IT network of REE, fulfilling all the security and communication requirement of the Spanish TSO (REE).

6. BIBLIOGRAPHY

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