LARGE SCALE PQ, TEMPERATURE AND ENERGY MONITORING IN SECONDARY SUBSTATIONS

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ABSTRACT

This paper deals with an ongoing project for monitoring distribution transformers and their associated low voltage network. The main goal is not only to deliver a set of statistics and figures for assessing power quality, but using it for improving network operation and maintenance.

Instead of relying on complex data-management systems for gathering and analysing the information throughput, a simpler and low-cost edge-computing approach has been designed and built into the PQ device firmware.

One of the most challenging issues has been the estimation and coding of the hot-spot temperatures based on existing IEC standards.

Moreover, the system is open for future enhancements without incurring in massive and costly changes in central data-management systems.

INTRODUCTION

It is a widely extended throughout the world to deploy power quality monitoring systems in primary substations, mostly on medium voltage bus-bars. The main reason for this well-known practice is not only the high cost of devices, but also the exponential expenses on associated communication and data management centres.

Even though there has been a massive deployment of smart energy meters, due to the intrinsic limited features of these devices, they do just provide some sort of rudimentary monitoring which can only be useful for a first-time filtering. Thus low voltage monitoring is usually out of scope and limited to portable and expensive instruments.

As result secondary transformers are most of the times poorly monitored. Sometimes average power is measured every 15 minutes, leading to some sort of overloading monitoring. However this is not a widely extended practice throughout our distribution network, being applied on a miniscule set of transformers. This type of measurement is not even a good signal for the real overloading and aging of a transformer.

A new challenging project has started in order to improve the monitoring of these transformers and their associated low voltage network. Instead of using very expensive and complex power quality monitors, we decided to use low-cost devices with plenty of features on energy and power quality monitoring. These devices are not intended to be fully compliant to IEC 61000-4-30 [1], but instead to deliver really useful data for the operation and maintenance of the distribution network.

Next follows the main features of these devices and their installation:

- Similar price to low cost instantaneous voltage and power monitors.
- Inbuilt large memory for storing power quality, event and waveform data.
- In order to improve the expected lifetime no battery is used.
- Current is measured by using split core transformers.
- Indoor temperature monitoring.
- Estimation of the hot-spot temperature of transformer based on IEC 60076-7 [2] and former IEC 60354 [3]. These algorithms do take into account internal time constants so they allow to keep track of the real transformer loading and aging. Moreover due to the intrinsic power quality capabilities of the device, harmonics are taken into account for the overloading and aging algorithms. This is even more necessary now, when a massive deployment of electric cars and distributed generation is ongoing.
- Flexible communication ports and protocols for easy integration into existing and future networks.
- The most valuable data is available by simply querying instantaneous magnitudes. Thus, there is no need to carefully download internal files for later uploading and processing on a central location.
- 3-phase power supply, thus avoiding lack of power when one phase is lost. Moreover, it allows detecting this type of failure and reporting in advance.
- Even without battery, it can record up to a few hundred milliseconds interruptions or very deep sags. This data is available by querying the device on a single query. When a medium voltage feeder trips, every device along the line will be queried asking for the last recorded voltage dip and its depth. By matching this data to the feeder topology, a location of the fault can be estimated.
- Direct connection of internal end-customers to an inbuilt web interface with plenty of energy, aging and power quality data. The main goal is to avoid costly and unnecessary centralized data centres.

The main benefits of this approach are as follows:

- A closer look on the transformers, leading to better maintenance and planning works based on real loading and aging.
- Automatic and instantaneous location of faults along medium feeders.

- Internal end-customers will have access to plenty of event and power quality information without data processing delays.
- A better look of the real power quality closer to the end customers will be available.
- By matching energy measurements together with the smart meter data, many frauds might be detected and thus non-technical losses fairly reduced.

ON-SITE INSTALLATION

Each installation consists of a PQ device in a plastic housing together with voltage and current connectors (see fig. 1) . There is also an external temperature probe (PT100 resistor) for measuring the indoor temperature. Current is measured by split-core transformers of 1500/1 ratio.

Each device has an internal display for on-site verification of the most valuable data, .e.g. voltages, currents, powers, power factors and temperatures. They do also have RS232, RS485 and Ethernet ports for connection to existing and future communication appliances. Communication is possible via MODBUS through the serial interfaces RS232 and RS485, or by HTTP or FTP through the Ethernet port.

fig. 1 PQ device inside plastic housing.

It is quite common for these meters to have separate terminals for its power supply, so they can be connected to an UPS in a substation or an industry site. Although it was decided to not use any battery due to the increasing costs and early aging, it was mandatory to be able to keep it on during one phase lost. A very simple solution based on a half-wave rectifier was designed, thus creating a simple DC supply and improving the ride-through capability during voltage dips and interruptions

TRANSFORMER MAGNITUDES

Monitoring transformer temperature is most of the times expensive and complex. Although there are very accurate methods based on fibre optics probes (see IEC 60076-7), they could only be applied on distribution transformers during the manufacturing process. Monitoring top-oil temperature might seem easier and cheaper, but hot-spot temperature might be quite higher.

IEC 60076-7 and IEC 60354 formulas

IEC 60076-7 is entitled "*Power transformers – Part 7: Loading guide for oil-immersed power transformers*". Its predecessor IEC 60354 ("*Loading guide for oil-immersed power transformers*") is somehow simpler and easier to be implemented in a computer language, although does not change the underlying formulae.

As stated in IEC 60076-7 table E.1, the hot-spot to top-oil (in tank) gradient at rated current for distribution transformers can be approximated by 23ºC. According to table 5 of this standard, a winding exponent can also be fixed at 1.6. Thus by using its equation no. 5 the overall top-oil to hot-spot temperature rise can be approximated by

$$23K^{1.6} \tag{1}$$

being K the load factor for each phase (RMS phase current as a fraction of nominal current). At rated power this formula leads to 26ºC, 52ºC for twice, etc. Assuming a rated hot-spot temperature of 98ºC for non-thermally upgraded insulation paper (IEC 60076-7 table 1), it is obvious that the hot-spot temperature rise cannot be neglected nor assumed constant.

For distribution transformers the top-oil temperature rise can be taken as uniform within the tank. According to equation no. 5 and table E.1 of this standard, this temperature rise can be approximated by

$$55\left(\frac{1+5K^2}{1+5}\right)^{0.8} \tag{2}$$

being as high as 55ºC at full load and 132ºC at twice the rated power. Since the top-oil temperature is assume to be uniform (see IEC 60354 page 31), the 3-phase average of the oil formula will be taken as overall estimation of the top-oil temperature rise.

These two aforementioned formulas correspond to the steady-state temperature rises. Indeed both top-oil and hot-spot do have different time constants. IEC 60076-7 emulates such behaviour by two first-order decoupled systems, but the solution is stated as a set of differential equations which are then transformed into difference equations.

Table 5 within the standard states that time constant for oil can be set at 180 minutes (3 hours) and 4 minutes for the winding. Its annex C describes practical calculations of the time-dependant temperature rises with a 3-minute resolution, which is not bad but of the same order of the winding constant. On the other hand the PQ device does have quite powerful processing capabilities, so that time step can be fairly reduced. Several tests were made down to 1-second intervals, although a 5-second window was selected because otherwise PQ processing was affected. However a 5-second time constant is two orders of magnitude shorter than the winding time constant, so it is by far low enough.

First order system approximations

As stated above, IEC 60076-7 estimates that both top-oil and winding are decoupled first-order systems. Then it tries to be as accurate as possible in the definition of the differential equations and their associated difference equations. However in order to deploy a more stable algorithm with a similar degree of accuracy, a simpler and probably better method is built. Instead of relying on incremental steps of temperature (which could lead to divergence within the algorithm), it emulates the first-order system by smoothly approaching its steady-state value.

Being n the time step (in seconds) within the algorithm, any temperature rise is updated according to a τ-second moving window:

$$T_{rise}|_{next} := \frac{n \cdot T_{rise}|_{\infty} + (\tau - n) \cdot T_{rise}|_{now}}{\tau} \qquad (3)$$

The overall top-oil and hot-spot temperatures are calculated as follows:

$$T_{top-oil} = T_{ambient} + T_{rise\ oil} \qquad (4)$$

$$T_{hot-spot} = T_{top-oil} + T_{rise\ hot-spot} \qquad (5)$$

The method stated in (3) gives a very good approximation to the time-decay formula of a first-order system, being its error always below 0.16%. In fact it is not possible to see any difference when plotted together with the exponential formula:

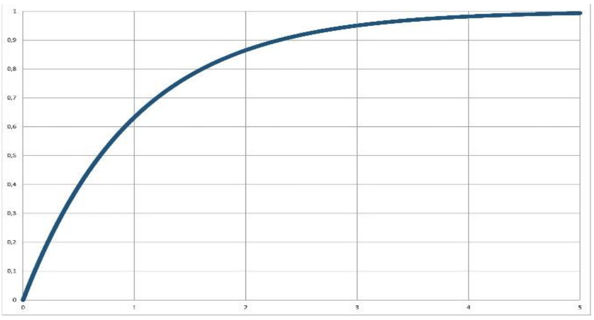

fig. 2 Time-decay function of a first order system (τ scale)

Effect of harmonics

As stated above, IEC 60076-7 estimates temperature rises as a function of current (i.e. transformer load) and thus losses. However these losses do not take into account the harmonics effect, which can be indeed non-negligible. EN 50464-3 [4] weighs up that loading factor as a function of the eddy and joule losses according to the following equation:

$$K_{factor} = \sqrt{1 + \frac{e}{1+e}\left(\frac{I_1}{I}\right)^2 \sum_{h=2}^{m}\left[h^q\left(\frac{I_h}{I_1}\right)^2\right]} \qquad (6)$$

being e the ratio between eddy current losses at fundamental frequency and DC (typically 0.1), h the harmonic order, q a factor that is dependent on the type of winding and frequency (typically 1.7 for distribution transformers), I_i the i-harmonic current, m the highest measured harmonic (e.g. 40) and I the full RMS current.

Therefore each temperature raise must be weighted up according to the above formula. The selected PQ device is able to calculate every 200-ms up to 40th order harmonic, leading to a very accurate calculation.

For instance, for an ideal 6-pulse rectifier (THD_i=33%) that value reaches 1.27, which means an overheating above 25%. Nowadays there are plenty of loads based on than scheme (e.g. air conditioners), so taking into account harmonics might be considered.

Next follows real data taken from a secondary substation:

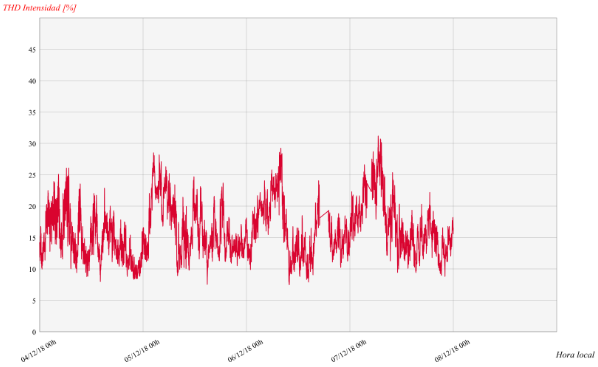

fig. 3 Current THD of an existing secondary substation.

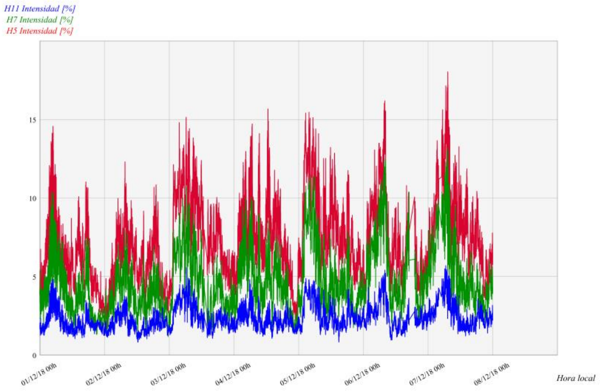

fig. 4 Harmonics 5, 7 and 11 of an existing secondary substation.

It can be noticed that its THD_i is sometimes close to that upper burden (above 30%). Moreover harmonics up to 11th order are well below that value, thus measuring up to e.g. n=15 might not be enough.

Transformer aging

As stated in IEC 60076-7 (section 6.2), aging is basically a factor of hot-spot temperature and type of insulation. For distribution transformers it is rather uncommon to use thermally upgraded paper. Therefore the instantaneous rate of aging can be estimated as

$$V = 2^{\frac{T_{hot-spot}-98}{6}} \qquad (7)$$

leading exactly 1.0 for 98ºC. By using equations (1), (2) and (7), it can be inferred that a typical distribution transformer is designed for reaching exactly 98ºC at full power (*K=1*), ambient temperature of 20ºC and top-oil temperature of *20+55=75ºC.*

That rate of aging can be calculated per phase.

PQ-device implementation

As previously stated, temperature calculations are updated every 5 seconds. This gives a very good trade-off between performance, accuracy and resolution.

As any PQ analyser, this device is able to periodically record measured and calculated variables. Together with the typical 10-minute averaging window for PQ magnitudes (e.g. voltages, currents, voltage and harmonic currents, unbalance, etc.) a larger 15-minute window is selected for energies, temperatures and aging. In short, these are the full set of variables:

- Active, reactive and reactive energies (overall and per phase). Reactive energy is split into four quadrants.
- Ambient and top-oil temperatures (average, lowest and highest).
- Hot-spot temperatures (overall and per phase – average, lowest and highest-).
- Average aging across the period (average and per phase).

This data can be stored for weeks in the device and downloaded either by MODBUS or FTP.

Energy records can be compared with downstream measurements from smart meters and allow a better detection of frauds.

FAULT LOCATION AND ANALYSIS

Another important tool to be exploited is the analysis of both MV and LV faults. In fact these PQ devices are able to record voltage dips, sags and interruptions. It is true that the lack of battery prevents a detailed study of any event, but that drawback is partially amended by the DC supply from the 3-phase half-wave rectifier.

Analysis of LV faults

In case the event source is in the downstream LV network (e.g. fuse is blown), the device does not shut down so a full recording of the event is yet possible. A 10-ms RMS recording for any voltage and current phase is made available few seconds prior and after the event, as well as a 50-µs transient recording.

Analysis of MV faults

The main goal should be to better estimate the fault location along the feeder. Since there is no battery, there is a serious risk of shutting down the device. However there is always some energy available and indeed the DC-supply improves the ride-through performance.

The device is able to work when fed by a single AC-supply and voltage drops below 40%. When fed by the three phases and previously half-rectified, it means a real hard three-phase dip or an interruption. Lab testing has demonstrated that it takes around 300 ms until the device shuts down when subjected to a full interruption, being this time gap below the time that a feeder protection takes for a very hard three-phase short-circuit. Therefore the real shutting down problem will be indeed noticeable for trips of its own MV feeder.

When this happens, the device does not intend to be accurate on recording the voltage dip, but fast and useful. In this sense it starts recording in flash memory the three ongoing RMS voltages. If it suddenly shuts down, when power is recovered it can be queried via MODBUS and get those three measurements and when they happened. The idea is to query any PQ device along the feeder as soon as the feeder is back, without bulky and slow PQ files processing. Thus a residual-voltage image can be obtained along the MV feeder and matched with the existing topology, leading into an instantaneous fault locator.

The most typical distribution transformers in ENDESA by far are *Dy*. Except for very specific regions with MV isolated neutral, the most common neutral grounding in substations is by resistor or impedance. Thus one-phase MV faults are not usually noticeable on LV networks unless there is a subsequent interruption.

However the main goal is mainly to help fault location when directional fault passage and voltage loss indicators are not installed.

MODEL VALIDATION

The most challenging and newest issue is the estimation of temperature and aging of transformer. Although formulas have been taken from the well-stablished standard IEC 60076-7 (dated back to 2005, not even changed for distribution transformers from the legacy standard IEC 60354 from 1991), an on-site verification of temperatures is mandatory.

The existing distribution transformers within the ENDESA network lack of any in-tank temperature probe for remote measurement. However many of them do have simple temperature gauges which can be easily inspected. The PQ device has been programmed for displaying on its LCD ambient, top-oil and overall hot-spot temperatures. Thus it is quite straightforward for trained personnel to take visual measurements periodically and asses the top-oil temperature. Next follows a snapshot of the LCD display:

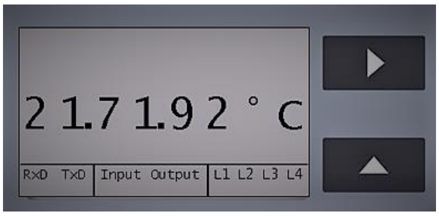

fig. 5 LCD snapshot with ambient, top-oil and average hot-spot temperatures.

By using these on-site visual inspections, the model can be readjusted and both constant values as well as the algorithm itself can be upgraded. In fact the PQ device can be reprogrammed without reloading the full firmware image, just the required algorithms, which makes it a robust and flexible solution.

It will be also explored future collaborations with transformer suppliers in order to make intensive in-factory tests. By far this is the most accurate solution, although consisting of very few samples. Therefore it should be combined with the massive on-site verification. Effect of harmonics should also be an important topic to be analysed together with these manufacturers.

FUTURE ENHANCEMENTS

There are certain fields nowadays out of the scope of this paper, so they could be investigated on future stages:

- Dry-type transformers.
- Outdoor oil-immersed transformers, since the effect of direct solar radiation, wind and rain makes very hard to estimate the exchanged heat across transformer’s surface.

CONCLUSIONS

ENDESA has initiated an ambitious project for monitoring distribution transformer within secondary substations. Well stablished formulas from IEC standards have been used for temperature estimation. Moreover these formulas have been improved for taking into account both harmonics and current unbalance.

A low-cost but flexible and powerful PQ device has been employed, thus allowing recording of PQ magnitudes, energies and temperatures. Other tools have been implemented, such as aided assistance for fault location. Inbuilt standard features such as event and transient recording will allow a better assessment of customers’ power quality.

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