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A3 TRANSMISSION AND DISTRIBUTION EQUIPMENT
PS3 – Digitalisation of T&D Equipment

Benefits of high-resolution/high bandwidth acquisition of conventional voltage and current transformers for controlled switching: illustration with latest generation of controller

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SUMMARY

Controlled switching devices are now essential to assist circuit breaker operations in a broad range of applications. These devices, to operate properly, require accurate measurements of various types, first of them being the voltage and currents in immediate circuit breaker vicinity.
From the first returns of experience of the new CSD synchronous switching controller, this paper presents the advantages of large bandwidth and large sample rate acquisition of conventional voltage and current transformers for controlled switching applications. Evolving electronic techniques allow for high bandwidth, high resolution and high sample rate analogue to digital conversion without compromise on insulation level and EMC immunity. Size and weight of such equipment's can be noticeably reduced, allowing for installation in various situations, such as local cubicles and marshalling boxes.
With such acquisition circuits, the observed phenomena in the field are now comparable to those traditionally observed in power laboratories during circuit breaker type tests.
First advantage is of course an improved manual analysis of transient records for everyday operation of circuit breakers in the field or during commissioning phase. During commissioning, fine tuning of settings is greatly facilitated: making times can be easily measured, either from current or voltages.
Second advantage is for automatic processing in the controlled switching device. Improved amount of available data can help to develop new algorithms to improve synchronization (for example adaptive feedback control loops based of newly measured phenomena's), but also can be useful for monitoring of the circuit breaker (for example, based on signature or fingerprints identifications).
Of course, higher sampling rate means heavier record files. This difficulty is now easily overcome with large available data storage memories associated with high end embedded operating systems for file management. Consequently, even with increased record size, the whole service life of the circuit breaker can be stored directly in the controller. From this perspective, data science to extract trends from a very large number of records (the famous "big data") may serve to detect drifts or abnormal behavior in circuit breaker operations and improve knowledge of circuit breakers during their entire service life. Research and development teams in charge of high (or medium) voltage circuit breakers would be very interested in such data from the field (where constraints may be different from those described in circuit breakers type test standards).
A brief perspective with digital substation will also be introduced. This comparison will highlight the limitations of sample values digital networks in term of sample rate, bandwidth, and transient measurement, with illustration from LPIT standards (IEC61869 series).

KEYWORDS

Controlled switching, bandwidth, accuracy, conventional, voltage, current, records, transients, reignition, making times, chopping, TRV, RRDS, RDDS

I. Introduction - Context

Controlled switching devices deal with both mechanical and electrical aspects of a circuit breaker. However, the final performance of the opening or closing operations are only related to network electrical aspects (making times for closing, current breaking time for opening).

Of course, low mechanical scatter circuit-breakers improve performance of controlled switching applications, as already described in [1].
However, focus on high voltage quantities remains the preferred approach to assess the overall performance of a CSD, and to implement extra algorithms based on their observation, in addition to most common compensation or correction routines based on circuit breaker ambient and mechanical parameters.

Modern CSD with advanced signal processing techniques combined with high resolution, high bandwidth acquisitions can integrate new features to improve performance. This paper focuses on the measurements that can help to improve switching performances, manually (performance statistics, compilation of return of experience, post event analysis) or automatically (feedback loops) and the technology breakthrough which makes it possible.

II. Field measurements: accurate observation of HV phenomena

A. Power transformer switching

Aim of controlled energization of unloaded power transformer is to limit inrush current due to core saturation. Making times of each phase shall match magnetic flux condition of each winding or leg of the transformer, either static (core residual flux) or dynamic (AC flux imposed by previously energized phases). At least for first phase(s) to close, targets are moving from one operation to another, according to residual flux conditions.
It is thus essential to obtain a correct measurement of making times, in any case, whatever the strategy (computed targets from residual flux or fixed targets “historical” strategy).
The required accuracy of such reading is far below milliseconds range. Immediately, it is seen the interest of high analogue bandwidth and high data acquisition rate.

Figure 1 shows typical power transformer energization traces recorded by the CSD. Making times as well as all stray effects are clearly visible. Regarding global performance, it is easy to distinguish between inrush current due to first phase to close and inrush current due to subsequent phases. As target is different between first and subsequent phases to close (residual flux VS dynamic flux), different adjustments are to be applied (individualized for each phase), in case of excessive inrush.

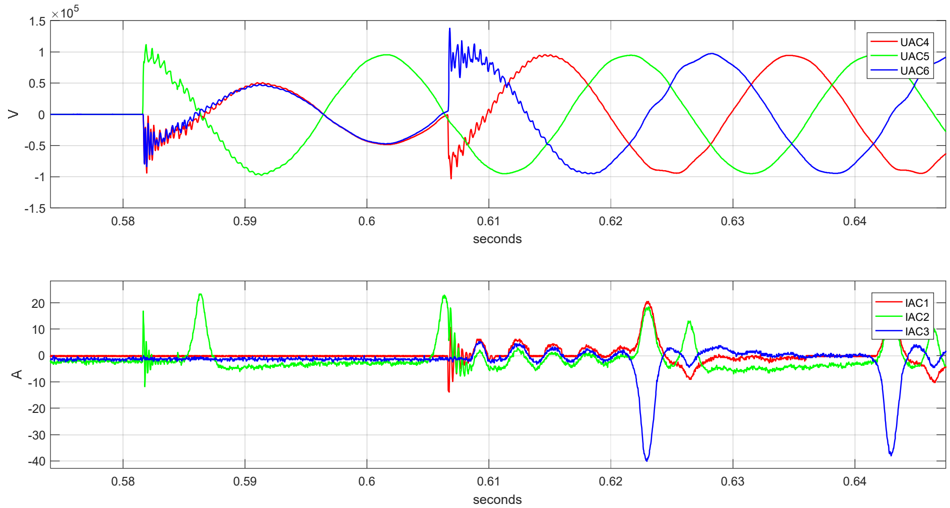

Figure 1: Typical example of power transformer energization load voltages and currents (CSD archive)

Making times can be measured from voltages measured at transformer terminals, when available, but it can be difficult to automate this measurement in a dedicated embedded algorithm for last phases to close (due to voltage sharing between phases). Moreover, as the goal of power transformer energization is to reduce as much as possible the inrush current, it may be difficult, at a first glance, to obtain making times from current. The particular shape of no-load magnetizing current makes these currents not a good candidate to accurately measure making times.
However, thanks to extended measurement bandwidth, it is now possible to capture the tiny part of inrush current of power transformers due to stray windings stray capacitances or short piece of network (short circuit length) between circuit breaker and power transformer. Same observation can be made with shunt reactors, as illustrated in the following of this paper. This brings an extremely accurate and non-ambiguous reading of making times, as shown in Figure 2. We now consider these currents as a better candidate than voltages to automate making time measurements, as it is phase to phase independent information.

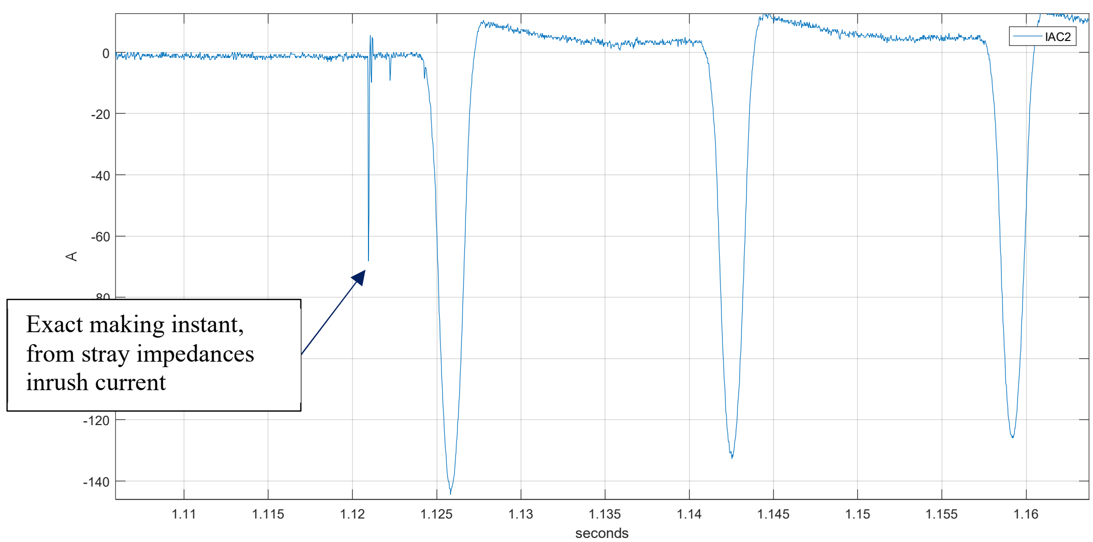

Figure 2: Example of power transformer energization current, superposition of magnetic and capacitive inrush currents (CSD archive)

B. Reactor switching: focus on small inductive current interruption

Upon reactor switching, it is crucial to control circuit breaker arcing time during opening operations. Arcing time must land inside the reignition free arcing time window ([5]), with sufficient margin regarding minimum arcing time. Recommended arcing time may vary from one circuit breaker to another, and from one installation to another.
Therefore, there is a strong interest to detect reignitions and also to check for the interruption margin, operation after operation. Reactor switching success is mainly driven by dielectric withstand ("cold gas" withstand).

First, it is depicted in Figure 3 a typical reignition. A blanking time of about 300µs is observed after first current zero (targeted breaking), before current starts to circulate again between circuit breaker contacts. This delay corresponds to the time of rise of the Transient Recovery Voltage, before it exceeds the circuit breaker withstand.

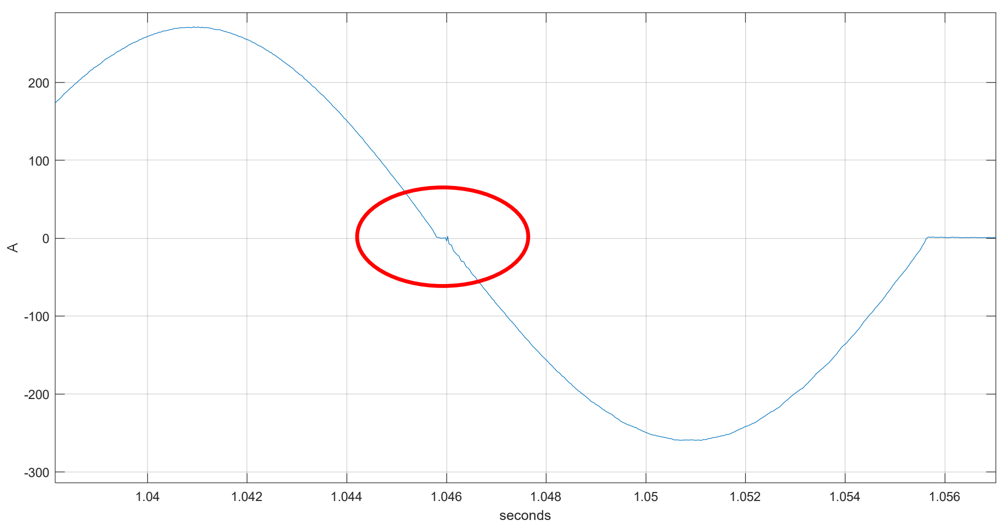

Figure 3: Example of shunt reactor de-energization: load current and reignition 250µs after current zero (CSD archive)

Then, still upon shunt reactor de-energization, CSD record illustrated by Figure 4 shows a phenomenon called NSDD (Non-Sustained Disruptive Discharge). Occurrence of this phenomena indicates that the dielectric limit is not far. Therefore, this phenomenon is worth to be monitored in the field, operation after operation, to detect in advance a dielectric withstand weakening.

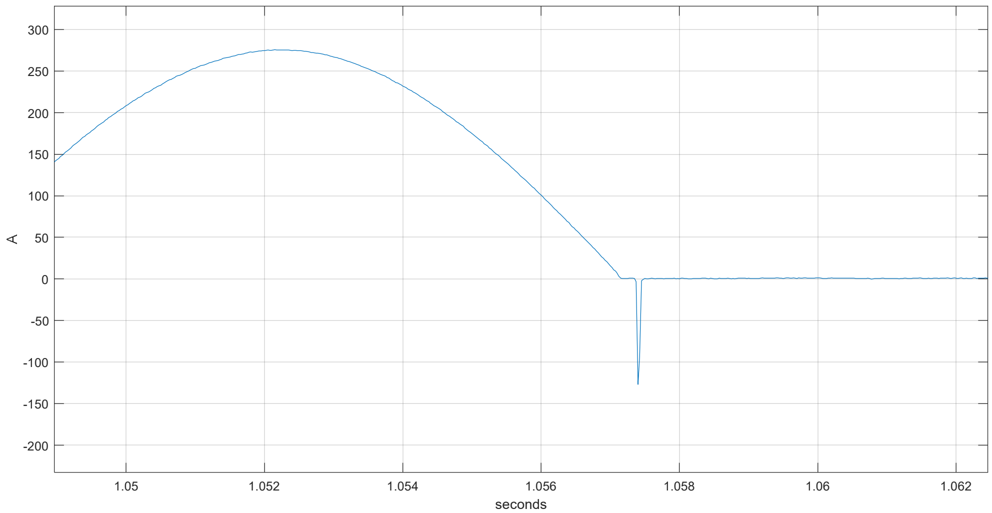

Figure 4: Example of shunt reactor de-energization: load current and NSDD 500µs after current zero (CSD archive)

Controlled energization is optional, aim is to avoid excessive current DC component immediately after energization. For that it is usual to target source voltage peaks. However, it is worth to note that repeated long prestrike times may have long term consequences for dielectric parts of interrupting chambers.
It is illustrated in Figure 5 the above-mentioned inrush current due to stray capacitances at load side, which helps a lot for a very accurate making time measurement during energization.

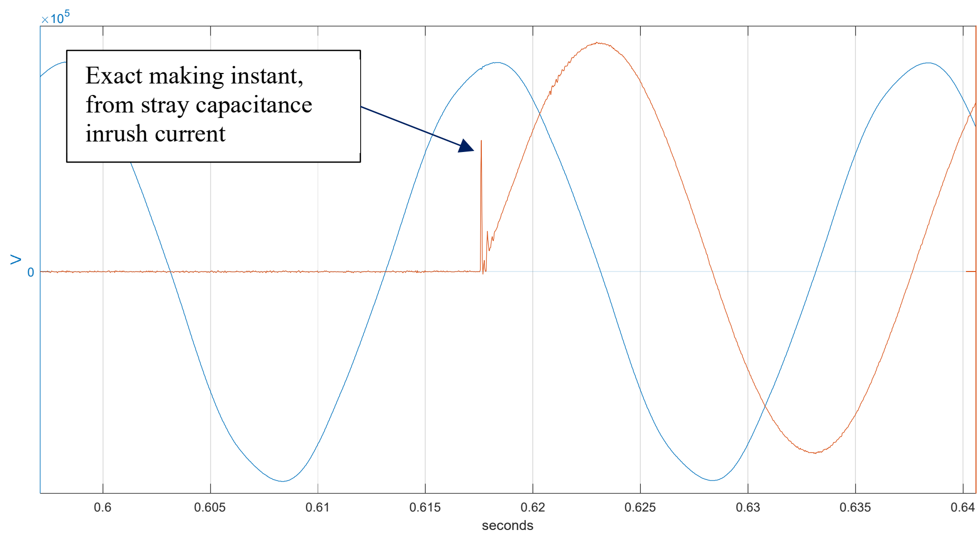

Figure 5: Example of shunt reactor energization: source (sync) voltage and load current (CSD archive)

After that, Figure 6 illustrates a shunt reactor switching situation in which voltage transformers at load side were present (practically, very rare situation). Therefore, an image of the so important transient recovery voltage can be captured, during de-energization. Transient Recovery Voltage (TRV) can be compared with dielectric withstand of the circuit breaker (Rate of Recovery of Dielectric Withstand, RRDS, which starts from contact separation instant). This comparison yields successful interruption or not (reignition).

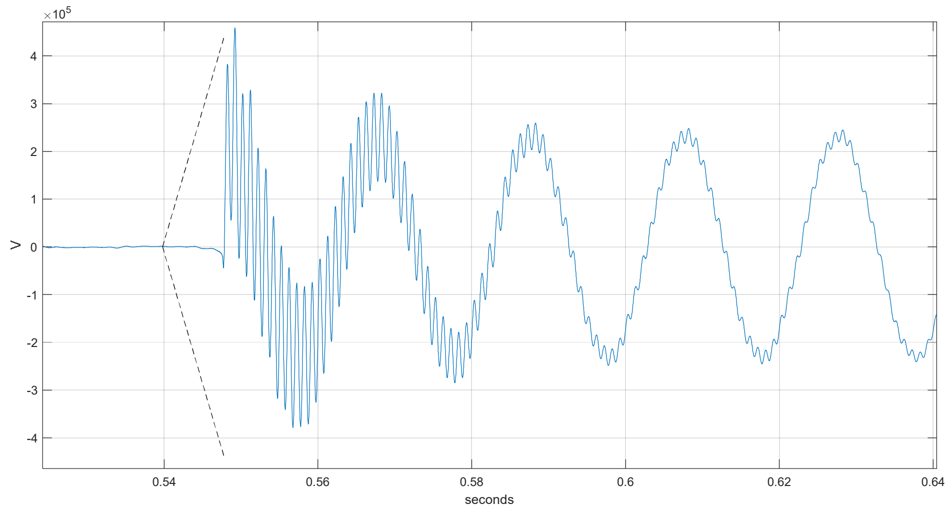

Figure 6: Example of shunt reactor de-energization: voltage across circuit breaker, transient recovery voltage and superimposed RRDS slope (CSD archive)

Another interest of such a measurement, is to validate a network model which serves as prospective assessment of circuit breaker applicability. Indeed, the capacitive and inductive elements values can be derived from the frequency of the transient ($\omega=1/\sqrt{LC}$).

C. Capacitor bank switching (circuit breaker retrofit)

Figure 7 illustrates an example of a highly challenging commissioning: a capacitor bank controlled by an "old" circuit breaker (1988) with poor characteristics of RDDS and mechanical scatter (about 140 ms mechanical closing time).

During several live tests needed to correctly adjust circuit breaker parameters (unknown at the beginning), the inrush currents were reduced from several kA (>10pu) to about 1.7pu (1pu = 200 A). Despite additional difficulty of non-optimum high voltage current transformer ratio in the bay (resulting in low secondary current and poor signal to noise ratio), the making times were correctly assessed and needed adjustments were introduced (set prestrikes).

For that, prearcing times have been set to unusually high values, to target zero crossing of source voltage.

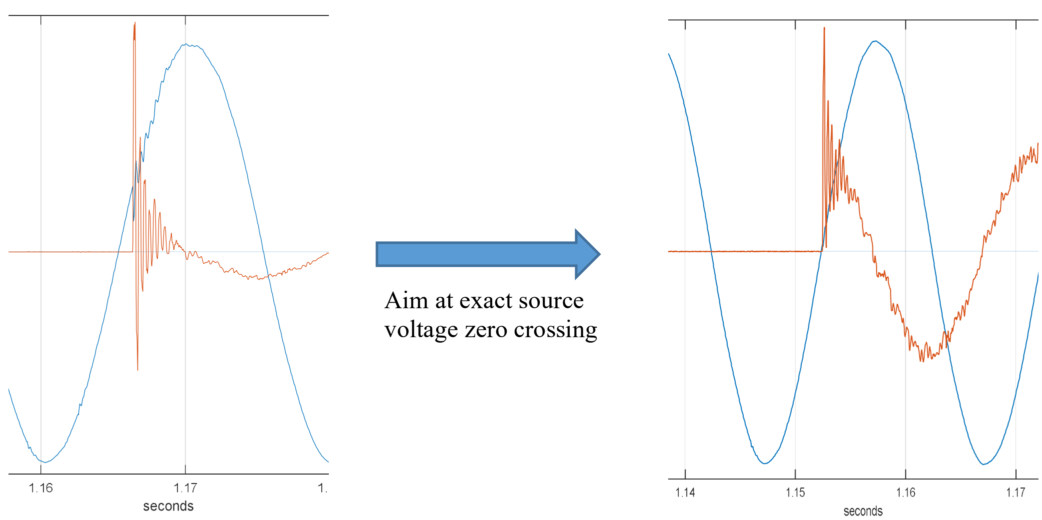

Figure 7: Example of capacitor bank energization improvement: source voltage and load current (CSD archive)

D. Harmonic filter switching (old circuit breaker retrofit)

Very similar to previous example (same substation, same circuit breaker model), it is illustrated in Figure 8 the need to measure harmonics (quality metering) to assess the performance of a harmonic filter. It is worth to not that inrush current high frequency transient (rapidly damped) can be distinguished from steady state harmonics.

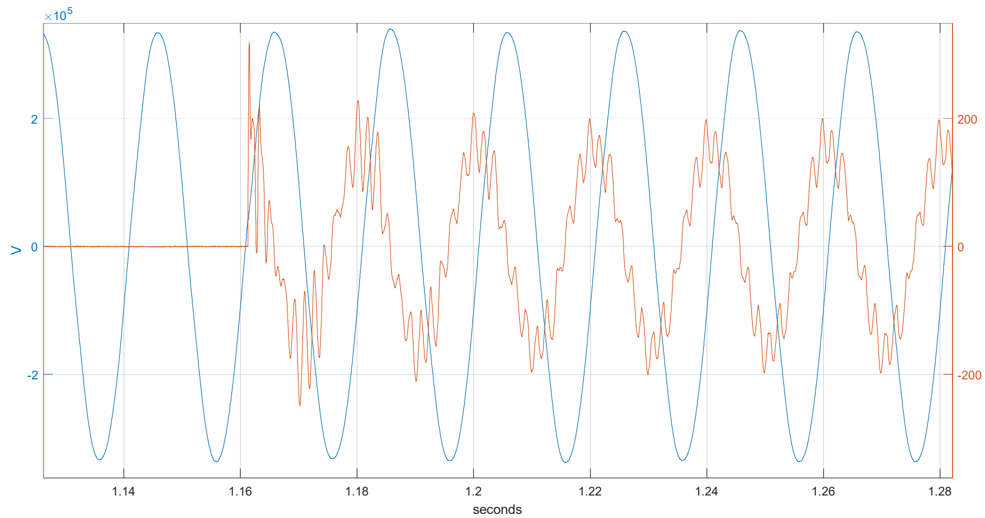

Figure 8: Example of harmonic filter energization: source voltage and load current (CSD archive)

E. Measurement of chopped current

During inductive current interruption, chopped current before network natural current zero is a key information since TRV is directly correlated to this value (and by consequence, success of interruption) and VTs rarely available at load side. It is thus of great interest to follow-up this value during service life. In Figure 9, it is measured a chopped current value of about 7A.

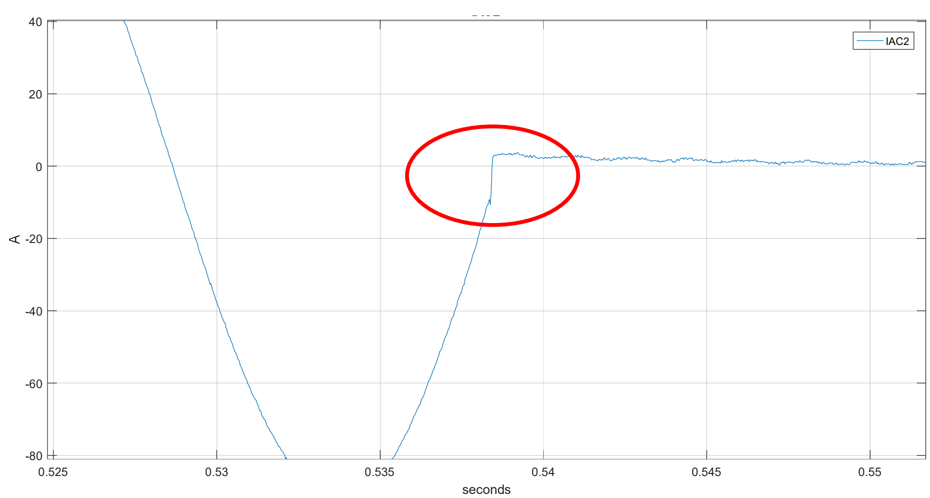

Figure 9: Focus on current zero, reactor switching: chopped current (CSD archive)

III. What to do with such measurements

With this new technology, several functions are now accessible.

A. Making times timestamp (close operations)

Adaptive control loop of prearcing times can be introduced: fed by making time measurements (more precisely, making time errors compared with theoretical target) and controlling set prearcing times (the electrical delay between mechanical contact touch and making times, due to Rate of Decrease of Dielectric Strength, RDDS).

B. NSDD, reignition detection, chopped current (open operations)

Adaptive control loop of arcing times can be introduced: fed by occurrences of dielectric events during opening and controlling set arcing times (the delay between contact separation given by mechanical control of the circuit breaker and the targeted current zero, given by network and load conditions).

C. Inrush current frequency and amplitude measurements

Monitoring function: electrical wear can be accurately computed, not only for opening operations (classical application) but also for closing operations. Indeed, it is anticipated a long-term effect on arcing contacts from repetitive prestrike times (circuit breaker operating daily).

D. Comparison between service life and type tests

A recurrent concern with circuit breaker, especially for retrofit applications, is that necessary data to accurately set CSD are not available. These data come from circuit breaker type tests, which can be extremely expensive or impossible to repeat (old CB). With accurate field measurements, statistics can be made and complement of type tests data can be expected, or comparison with type test results. This includes chopping current level, RRDS, RDDS…

IV. Electronics considerations

A. How analogue bandwidth and high sampling rate along with high level of isolation and EMC withstand can be achieved

It is reminded as a preamble that high level of galvanic isolation shall be guaranteed for analogue and digital inputs of a CSD, to satisfy electrical safety requirements (operators and equipment). These requirements come from standards such as [6], [7], [8], [9] (which has superseded [10]).

Typically, an insulation level above 5kV is necessary to satisfy overvoltage category III, up to 300 V nominal input range, pollution degree 2, which are standard requirements for equipment operating in substation environment.
This rather high level of insulation is now achievable with modern electronic components (isolated analogue to digital converters) relieving the designer of the use of bulky magnetic transformers (either voltage or current transformers). The added benefit of such components is the very high bandwidth and sample rate, which is something not achievable with traditional magnetic transformers.
These isolated analogue to digital converters comes with a vertical resolution of 16 bits (practically, about 13bits of effective bits, due to Signal to Noise Ratio of the whole circuitry), which is far enough to detect and measure low amplitudes phenomena among large signals.

The counterpart of using such electronic components instead of magnetic transformers is higher susceptibility to EMC perturbations. This concern led to thoroughly study, test and adjust a sophisticated EMC barrier, to satisfy highest levels of EMC perturbations withstand, without the need of external shielded cables, which could be extremely expensive.

Practically, the minimum requirements to achieve such high-resolution measurements are:

- ≥16 bits analogue inputs (about 13 effective bits)
- ≥40kHz sampling rate (25 µs)
- ≥5kHz analogue bandwidth

Figure 10 shows an electronic board of the new CSD, which aim is to acquire six AC voltages (up to 250 Vrms) from conventional voltage transformers. It is worth to note:

- 100x160 mm board (to fit 3U height mainframe)
- Isolation barrier (reinforced isolation), channel to chassis (left to right)
- Isolated analogue to digital converters across isolation barrier
- EMC barrier
- Isolation barrier between, channel to channel (principal or functional isolation)
- Digital samples evacuation through backplane connector

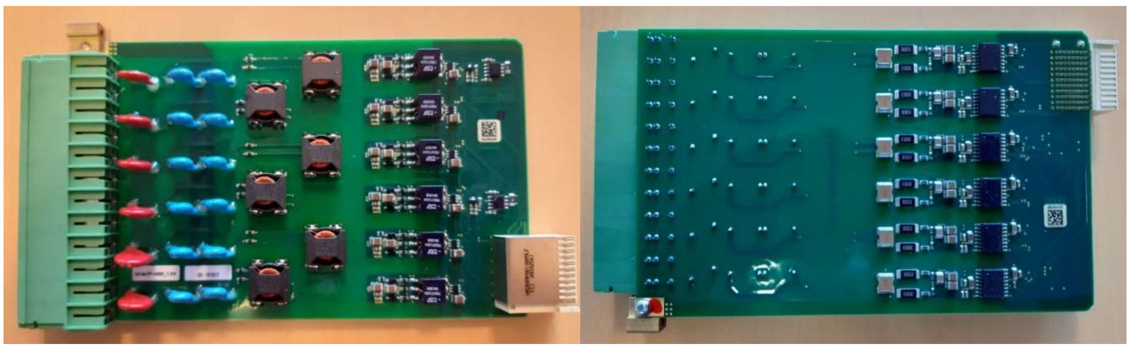

Figure 10: Example of electronic board for 6xAC voltage acquisition from conventional VTs

Such technology is extremely compact and lightweight: it allows construction of compact CSD, without compromise on EMC and isolation, allowing installation in a broad range of locations (local cubicles, control panels) and reduction of carbon footprint.
Housing height of only 3U (133.35mm) is achievable.

B. Records

In binary COMTRADE files, analogue samples are recorded with 16 bits resolution. It is thus the ideal format for native 16 bits systems. Scaling factors are further applied to compute primary or secondary values. Digital channels are also gathered within 16 bits words.
Therefore, a typical application with 21 analogue channels and 36 digital channels involves following record weight (including sample numbers and timestamps, each 32bits wide):
40000*32bits + 40000*32bits + 21*40000*16bits + ceil (36/16)*40000*16bits = 17920000 bits per second of record, thus, 2.24Mo of data per second of record.

With such sampling rate, size of records may be a concern for old designs. Again, thanks to modern non-volatile memories devices (the standard eMMC), with total capacity of 16Go, 32Go, 64Go or more, it is possible to store the whole service life of a circuit breaker (10K operations).

V. LPITs perspective

LPITs (Low Power Instruments Transformers) application and devices are strictly framed by 61869 series standards. This means that bandwidth and sample rate are imposed by the standards.

IEC61869-6, Edition 1.0, 2016 (Annex 6A) enforces minimum requirements for bandwidth and sample rate, as well as optional requirements for special applications (extended accuracy classes):

Table 1: different bandwidth and sample rate requirements in current LPITs standard

	Basic (mandatory)	Quality meter.	High bandwidth DC applications	Special high bandwidth
Bandwidth	13^{th} harmonic (780Hz)	3kHz	20kHz	500kHz
Sampling rate	4800Hz	14400Hz	96000Hz	

Remark: these requirements will be harmonized in the future IEC61869-1(Edition 2.0) with different frequency or bandwidth domains: 13^{th} harmonic, 3kHz, 20kHz, 150kHz, 500kHz.

Practically, to ensure interoperability and to avoid ethernet network traffic bottlenecks, the amount of sample values circulating in such network shall be limited, thus the sample rate, thus the bandwidth.

As controlled switching aim is to reduce transients, controlled switching devices are commonly connected to protection class voltage and current transformers. Therefore, it is anticipated that first controlled switching applications with LPITs will bring less resolution to observe such interesting transient phenomena.

VI. Conclusion

Every record shown in this paper is extracted from real field installation. It is thus depicted the “real conditions” of circuit breakers, and not results from type tests in power laboratories. From years of return of experience and circuit breakers events analysis, it is clear to us that real conditions may be slightly different from type tests. Considering again the example of shunt reactor de-energization, the famous TRV is highly correlated to parasitic capacitances of circuit breaker surrounding network. It is thus extremely difficult to reproduce the variety of practical situations in a standard type test. From that perspective, getting accurate information about circuit breaker operations during service life is of high interest for circuit breaker product managers.

From all this new kind of data, new algorithms are to be developed and tuned. Some of them are already running in the new CSD device. For some others, like introduction of making times in a feedback control loop, we have started an evaluation period of making time automatic assessments, before feeding such a loop.

More than ever, the couple circuit breaker + CSD as a unified product (ideally from a unique manufacturer), is highlighted. It means that for long term performance and consistency of controlled switching applications, technical exchanges between circuit breaker specialists and network / CSD specialists have to take place on a regular basis.

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