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Connecting Controlled Switching Devices in Power Plants to Analytics Tools in Sorgenia's Operations Centre to Increase the Service Life of Apparatuses

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SUMMARY

Controlled Switching Devices (CSDs) or "Point on Wave" relays have been in use since the early nineties primarily to mitigate harmful transients when switching shunt reactors, capacitor banks, transmission lines and power transformers spread across large transmission grids. In addition to mitigating switching transients, today's CSDs monitor both the electrical and mechanical wear as well as the precise speed of operation of the circuit breakers they interface with and control. Thus, these can be viewed as "guardian angels" for the circuit breakers. CSDs turned over the years into a digital dimension. Today's CSDs are producing sizeable amounts of highly valuable information about the switching apparatuses they control.

This paper discusses the benefits of leveraging the untapped potential of under-utilized data generated by a growing pool of CSDs. It is also introducing a new method for enabling on this basis the pro-active maintenance of a fleet of high-voltage circuit breakers. The purpose of this method is to increase the dependability of the circuit breakers, to anticipate their malfunctions and to lower their risks of failures, with overarching goal to improve daily switching and power system operations.

The Asset Health Management System (AHMS) developed for Sorgenia, one of Italy's largest independent power producers, implements a balanced combination of computational tasks at two levels: by CSDs in the relay room of their power plants for real-time processing, and then by analytics and data science tools deployed in a utility-level network control centre. CSD-computed data, such as the electrical and mechanical wear collected in electrical substations one circuit breaker operation after the other, helps determine, once consolidated at utility level and observed over a certain period of time, truly effective key performance indicators or KPIs that enable a customizable, fleet-wide, approach to diagnostics and prognostics: intelligent ranking of circuit breakers, identification of critical assets, prioritization of inspections and maintenance. Consolidated field data, together with CSD journals of alarms and events, are grouped and aggregated. They are then enriched by system operators with relevant artefacts and criticality analyses, including FMECA and HAZOP studies and other kinds of fault-tree analyses. The ensemble constitutes a sound shared Knowledge Base, covering the monitored assets and providing new grounds for assessing data-driven degradation models, as well as for educated prognostics and modern reporting within an actionable AHMS.

KEYWORDS

Digital Transformation, Controlled Switching Devices, Inrush Current Mitigation, Circuit Breaker Wear, Predictive and Proactive Maintenance, Asset Health Management, Fleet Management, Big Data.

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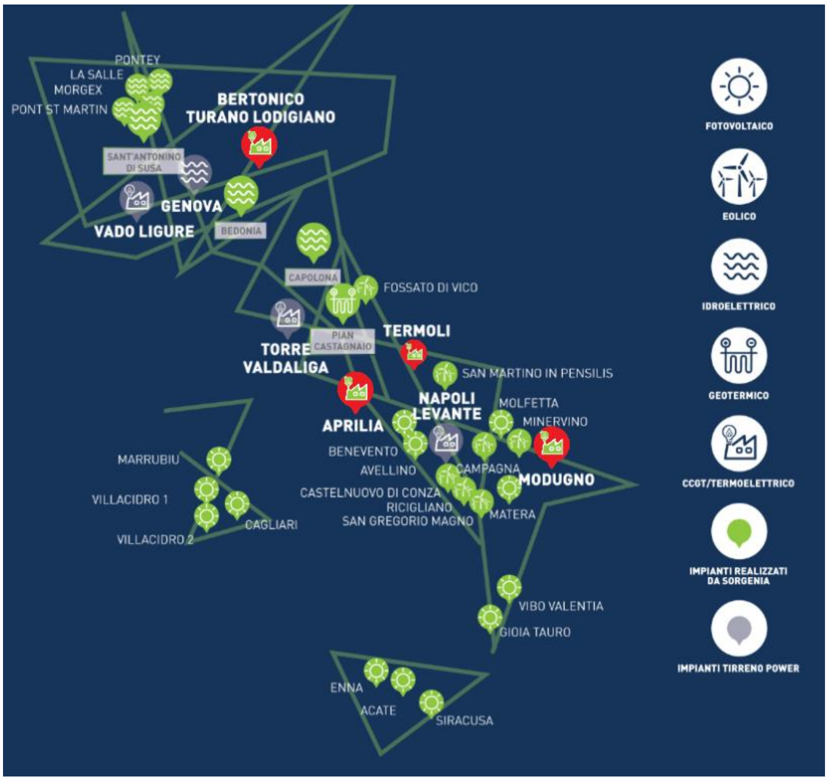
INTRODUCTION

Air travellers are aware take-offs and landings are the most stressful stages of a flight for not only the aircraft but also for the passengers. By analogy, one can say the making and breaking of an HVAC power system's load are the roughest moments in the life of not only the circuit breaker (C/B), but also for the load and the overall power system. Such switching events, if repeatedly occurring at an adverse point on the voltage sinewave, will cause the premature wear of numerous system assets, including the breaker itself, its load, neighbouring loads, measuring instruments and surge arresters. The transients generated by uncontrolled switchings are a frequent cause of catastrophic equipment failures and inadvertent protection trips. They led to extended and costly system outages and downtimes in a number of occasions [1]. Therefore, significant efforts are put at not only reinforcing the power system, its assets and operation procedures to mitigate such transients but also on maintenance programs to ensure the proper operation of the circuit breakers.

Controlled Switching Devices (CSDs) are now widely used as a pro-active means to mitigate the risk and magnitude of switching transients, i.e., the root cause for equipment wear and failure. Controlled Switching Devices achieve this objective by selecting the ideal instant where the circuit breaker main contact shall open or close to minimize the disturbances, which requires being closely linked to C/B conditions and behaviour through non-intrusive sensors and the capture of network signals. Given that the CSD knows the exact operating time target for each C/B operation, it is an unmatched tool for monitoring many aspects of C/B and related equipment health, including, among others, C/B operating time drift and mis-operations as well as cumulative mechanical and electrical wear. Escalating this data at a global corporate level allows for building smart Asset Health Management Systems (AHMS) that can be used to not only optimize maintenance capitalizations and operations but also to further the prevention of incidents and protection of system assets.

This paper discusses how such solutions are being deployed by Sorgenia to reduce losses and to meet both grid connection requirements and asset monitoring and maintenance cost minimization objectives.

CASE STUDY: SORGENIA'S HOLISTIC APPROACH TO SWITCHING ASSET PERFORMANCE AND MAINTENANCE



Sorgenia is the leading private operator in Italy in the domestic power and natural gas market. Energy efficiency, sustainable development and digitalization are the principles underpinning its growth, both as producer and as supplier of electricity and gas to end user clients. It ranks fifth as a domestic producer of electricity, with a balanced portfolio of renewable energy resources and Combined Cycle Gas Turbine (CCGT) plants spread across the peninsula (as shown Figure 1).

Figure 1: Sorgenia's Power Generation Facilities in Italy (2019).

Cycling of CCGT plants is an important source of operational flexibility in the electricity generation system. It entails frequent start-ups and shutdowns of conventional units, twice a week on average. To not undergo frequent transformer re-energization transients, the step-up transformers of such units are left energized without load when the units are stopped (approximately 4,000 hours a year each). Sorgenia estimated the no-load transformer losses to be 600 MWh/year/unit (approx. €36k/year/unit).

In 2014, Sorgenia started deploying CSDs in its CCGT plants (in red Figure 1) to save such costs by permitting the impact-free shutdown of the step-up transformers every time the gas turbines are stopped. Sorgenia also looked for the possibility of leveraging their existing field CSDs as a cost-effective alternative to sourcing dedicated devices for the remote monitoring of their fleet of circuit breakers. At last, Sorgenia decided to invest in an advanced Asset Health Management System to support both the predictive/proactive maintenance of its switching assets and an efficient fleet management solution.

MITIGATING POWER TRANSFORMER SWITCHING TRANSIENTS

The term "switching transient" refers to harmful voltage and current transient or disturbance phenomena occurring when a circuit breaker energizes or de-energizes a load. This can occur at make time, when switching on, fast switching or re-energizing AC power system assets such as power lines, power transformers, harmonic filters, shunt reactors and capacitor banks. Switching Transients also encompass re-ignition events occurring when breaking such loads. The make-time transients are generally caused by either a current or voltage step the energized load opposes to.

The case of power transformer switching is different. The inrush current observed when energizing an unloaded power transformer (Figure 2) is not caused by a reaction of a power device to a voltage or current step. It is rather due to the magnetic saturation of the transformer's iron core when voltage is re-applied to its windings.

Figure 2 shows the recording of the uncontrolled energization of a 330 MVA Power Transformer at Sorgenia's CCGT Plant in Turano. The inrush current (in brown) reappearing every cycle in a long long hum reaches, in this event, 5 p.u. (five times the nominal current).

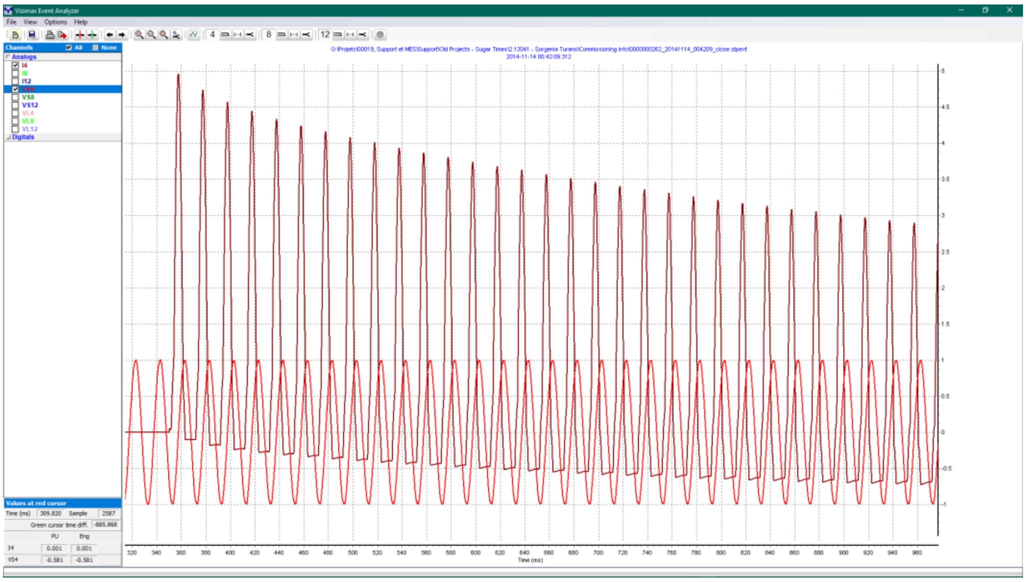


Figure 2: Uncontrolled Energization of a 330 MVA Power Transformer in Turano CCGT Plant

A controlled closing will prevent or mitigate the saturation, therefore the energization inrush current, by closing the breaker at a precise moment where the AC voltage trend fits the core's magnetization state or "flux" as if there were no de-energization. This is done by making the breaker close, electrically, at a point on the grid voltage sinewave where the prospective flux (i.e., the instantaneous value of the flux if the breaker were closed and the power transformer were energized) matches the value of the residual flux "trapped" in the iron core of the power transformer at the time it was last de-energized [2]. The CSD calculates this residual flux as the mathematical integral of the voltage applied to the coil of transformer throughout the voltage collapse and decay stage of the de-energization. This requires measuring the voltage on both sides of the breaker: a "Vs" voltage on grid side for synchronization purposes (to determine when to command the closing of the breaker in order to hit the matching point), and a "VL" on power transformer side (no matter whether primary, secondary or tertiary winding) to determine the residual flux in each phase, as illustrated Figure 3.

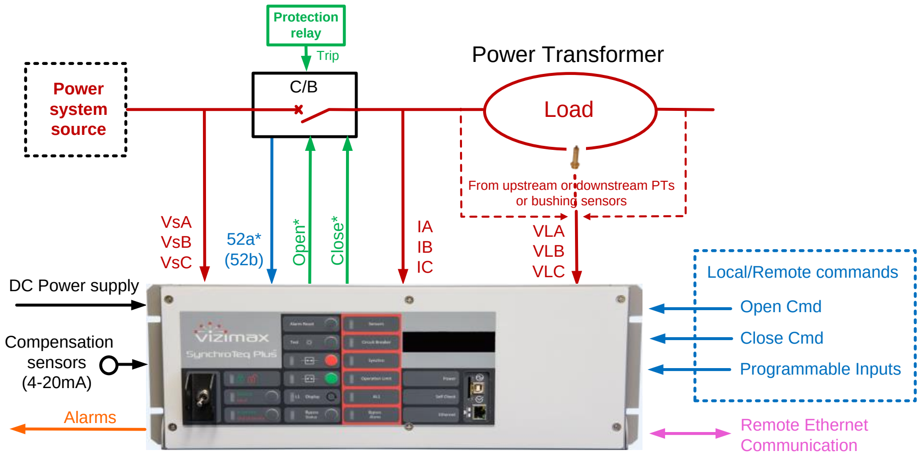


Figure 3 Controlled Switching Device Acquisitions and Controls

Where the circuit breaker's three poles can be operated independently, as is generally the case of applications in excess of 245kV, the match can be such that the transients are virtually eliminated [2]. Where the circuit breaker's three poles are simultaneously operated (aka 3-pole operated or gang-operated) by a common shaft, as is generally the case of lower voltage circuit breakers and switchgears, a proven best match strategy is used [3].

Figure 4 shows the recording of a controlled energization of the same power transformer in Sorgenia's Turano plant as in Figure 2. The three current curves, all flat, evidence that magnetization inrush currents are literally eliminated by the controlled closing. The small and negligible artefacts one can see after zooming dramatically where phase 12 and then 4 and 8 close are no magnetization currents. These as caused by the stray capacitance of the transformer windings.

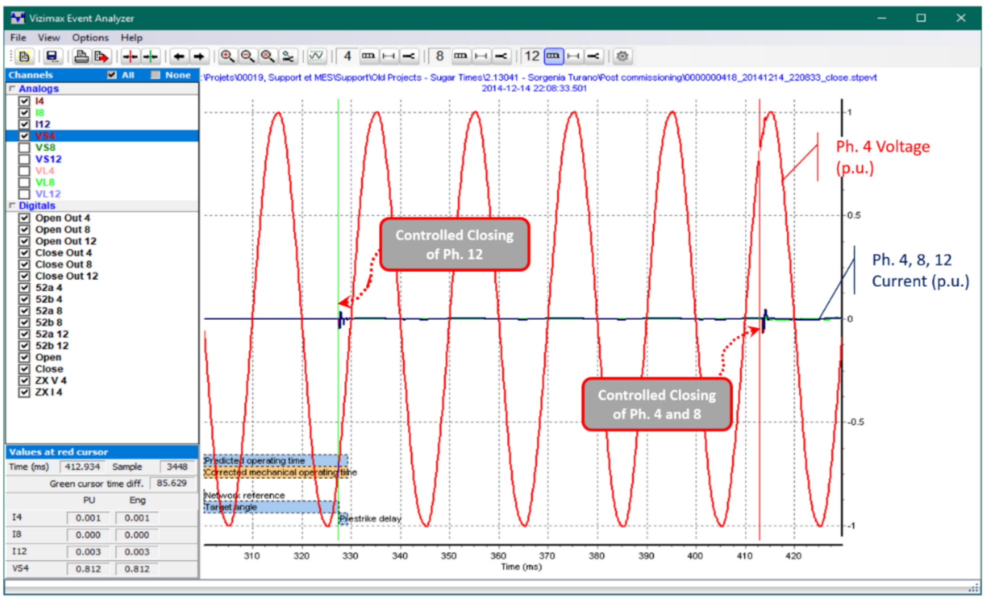


Figure 4: Controlled Energization of a 330 MVA Power Transformer in Turano CCGT Plant

ASSET HEALTH MANAGEMENT & MAINTENANCE PLANNING

Maintenance approaches are commonly categorized under four modes:

- Reactive or "corrective" maintenance really means detecting and correcting defects and system deficiencies as they occur.
- Preventive or "preventative" maintenance aims at mitigating the risk of failure through precautionary maintenance operations whose planning can be arbitrarily pre-determined, for instance every other year, or condition-based, for example every time the number of C/B operations (a statistical indicator of the C/B wear) or the accumulated i^2t (an actual measurement of thermal wear of the C/B) reaches a certain threshold. Such calculated values are called Key Performance Indicators (KPIs).
- Predictive maintenance extrapolates future wear and risk of failures based on KPI history.
- Proactive maintenance whose principle is to eliminate the underlying conditions of the asset degradation before they develop.

US Department of Energy's Office for Energy Efficiency and Renewable Energy (EERE) [4] claims that effective maintenance programs should implement a medley of modes that are approximately 10% reactive, 25-35% preventive, 45-55% predictive and proactive for the balance. Yet all industry surveys listed in [4] still show that maintenance programs remain predominantly reactive (in excess of 50%) with a total penetration of predictive and proactive modes ceiling at 25%.

SORGENIA'S ASSET HEALTH MANAGEMENT SYSTEM

Sorgenia acknowledges the paramount importance of proactivity in the management of its fleet of switching apparatuses. In addition to deploying, proactively, a number of CSDs to mitigate the root cause of switching-related asset wear and system failures, the utility elected to put in place a consolidated program based on a mix of maintenance strategies going significantly beyond reactive and preventive practices. This is being made possible by the planned deployment of an innovative AHMS that leverages not only the data generated by the utility's growing pool of CSDs but also the power of modern analytics tools.

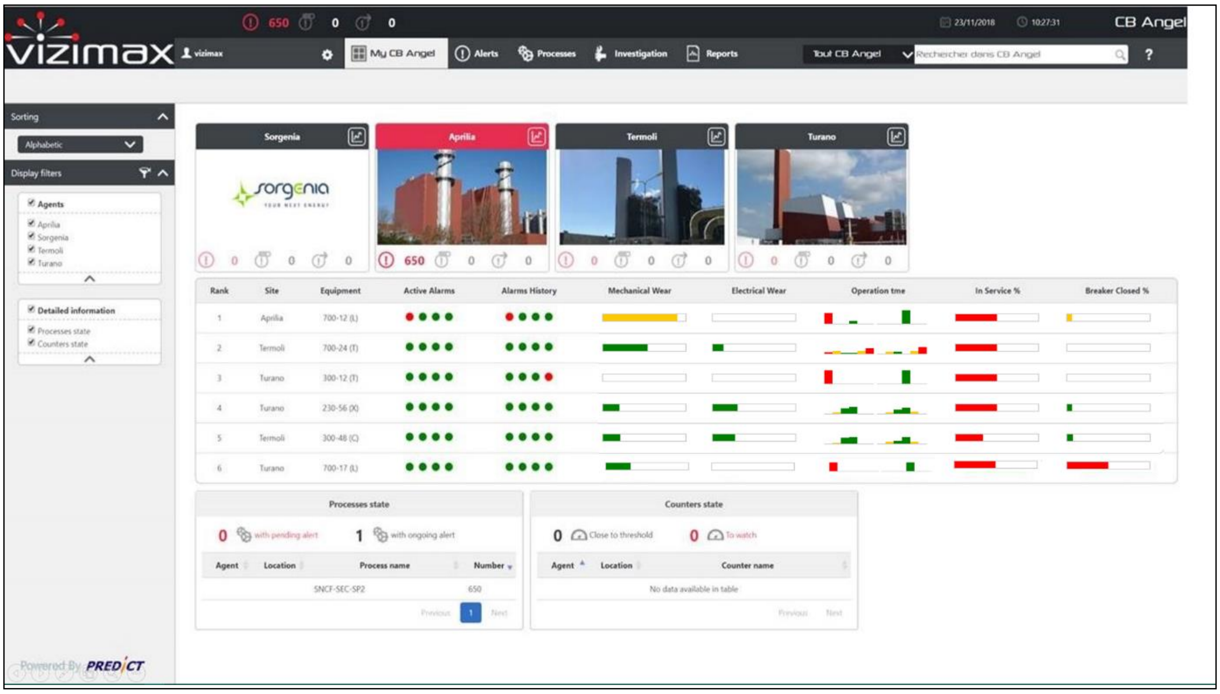


Figure 5: Dashboard of the AHMS

Figure 5 shows the dashboard of the AHMS. All monitored apparatuses are automatically ranked according to priority indices that account for the current state of the assets, their condition according to various KPIs and their criticality from an operational standpoint.

The state of a C/B is evaluated from several KPIs like:

- The current state of active alarms detected by the CSD;
- Historical alarms over a predefined period;
- The mechanical wear, measuring as the number of times the C/B operated since last maintenance;
- The electrical wear, measuring as the accumulated i^2t or “thermal wear” calculated by the CSD from the actual magnitude and duration of arcs having formed in the breaker’s main chamber;
- Operating time drifts, measuring as the difference between the time it now takes for the breaker to operate and the time it was taking it at CSD commissioning time;
- The amount of time the circuit breaker has been in a closed state (load energized) and the amount of time the CSD has been in service.

From a row item in the displayed list of C/Bs, the operator is given direct access to:

- A knowledge base about that C/B including manufacturer documents, application notes, images, single line diagrams, switching orders as well as Failure Mode, Effects and Criticality Analyses (FMECA) and Hazard and Operability (HAZOP) criticality analyses;
- All relevant CSD configurations, events and waveforms as if s/he were interfacing directly with the CSD;
- Predictive data such as failure forecasts based on the rate of rise of its accumulated i^2t.

Moreover, the AHMS provides miscellaneous analytics and prognostics tools to compare the performance of selected circuit breakers, for instance to graphically compare the rise of their accumulated i^2t (electrical wear monitoring) or to visualize the evolution of C/B operating time deviation histograms over time (motion monitoring). This provides the utility’s operators with a sound base for the preparation of proactive maintenance strategies.

To close the loop, the AHMS also aims to provide actionable elements to fine tune the numerous mechanical and electrical parameters CSDs account for when predicting the time it will take for a circuit breaker to operate. Because every fraction of a milli-second counts in the accuracy of the making or breaking of the power flow, this will in turn improve the performance of the mitigation of inrush currents and increase the service life of all assets impacted by the switching, starting with the circuit breaker itself. For example, the AHMS should permit determining statistical facts and retrieving behavioural data to further increase the accuracy of operating time compensation curves for environmental factors such as the ambient temperature CSDs utilise to adjust a CB’s operating time forecasts, or to fine tune a circuit breaker’s Rate of Decay of Dielectric Strength (RDDS), a piece of data CSDs need to predict switching pre-arc times [2] (i.e., to predict when the current will start flowing).

AHMS ARCHITECTURE AND BENEFITS

The architecture of the AHMS is seemingly traditional, with a fleet of CSDs at the base level generating massive amount of data (e.g., advanced CSDs produce and manage over two hundred data elements each, encompassing status points, alarms, analogue measurements, calculated values, counters and forecasts). As second tier, corporate level servers retrieve this data by secure encrypted telecommunications (TLS over TCP/IP network) and store-and-forward this information (by OPC-UA and in the form of COMTRADE-compliant event files via XML File Exchange) to a big data analysis tool suite. Analytics tools and displays are made available to corporate users over a secure web portal.

This architecture however also implements the paradigms of edge computing whereby all domain-related processing, at first the generation of base health statuses and KPIs, is done at the CSD level. This approach leverages the real-time processing capacity of the CSDs and permits the generation of CPU and data intensive KPIs, for example the accurate computation of a switching's actual i^2t footprint from the switching's actual arc current magnitude and duration, a processing that no centralized solution would have made possible. It also maximizes the de-coupling between circuit breaker domain knowledge (at CSD level) and analytics / visualization tools (on cloud server), with the aim of furthering the continuity of the solution as the technology evolves in either domain. For instance, this approach should allow Sorgenia for the integration, in the future, of new C/B health statuses such as coil supervision and pole motion performance indices. It will also eventually permit the building of a uniform and centralized AHMS built atop KPIs originating from distributed monitoring devices developed for different applications by different vendors.

CONCLUSION

A utility-wide Asset Health Management System leveraging recent developments in big data analytics as well as the C/B-intimate monitoring capabilities of Controlled Switching Devices brings a new depth to the massive amount of circuit breaker health data a fleet of Controlled Switching Devices can generate. It permits creating a thorough set of C/B ageing trends. It also allows for predicting and anticipating failures an effectively proactive way and for planning maintenance operations optimally, in so minimizing the cost, frequency and severity of switching-related incidents. The implementation of the system will eventually allow for the definition and assessment of new performance and wear indicators for the sake of improving the overall efficiency of the utility's health and fleet management strategies.

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