TOWARDS SMART DIGITAL CIRCUIT BREAKERS ENABLING ADVANCED CONTROL AND DIAGNOSTIC FEATURES

Marco TESTA  
ABB spa, Italy  
marco.testa@it.abb.com

Diego Pagnoncelli  
ABB spa, Italy  
diego.pagnoncelli@it.abb.com

Pierino Bertolotto  
ABB spa, Italy  
pierino.bertolotto@it.abb.com

Marco RIVA  
ABB spa, Italy  
marco.riva@it.abb.com

ABSTRACT

In the modern smart grid concept the role of the MV Circuit Breaker is progressively changing from “simple” protection device to active apparatus able to interact directly with the main installation-specific electrical quantities and coordinate the operations. Advancements in sensor technologies and growing in the usage of sensor systems have paved the road for making the power grid more reliable, robust, and intelligent. Low-cost sensor developments and innovative sensor solutions are expected to transform the traditional way of operating power systems to the extent that the potential impact is often compared to that of the Internet in the early ‘90’s. The paper introduces the new generation of MV apparatus and discuss example of applications where the integration of the new generation of IoT sensor and control electronics, allowed to exploit the extension in quality performance of the apparatus and of their operations in service, as well as opening the way for new business models.

INTRODUCTION

In mission critical applications in addition to the extension of the electrical and mechanical performances, reliability and continuity of the service are the most demanding critical factors that characterize the new generation of apparatus Smart and Ultra Performance Circuit Breakers – SUP CB.

The state of the electric power supply (voltage, frequency, harmonic components, etc..) and load conditions (current values, displacement, etc..) are considered in the control and in the execution of the commands allowing the circuit breakers to implement specific strategies able to optimize current interruption, mechanical and electrical life by appropriately adapting their behaviour to the power system conditions.

This innovative achievement is made possible by advanced embedded electronic system able to drive an extremely strict control over the contact movement in the interruption chamber for each individual pole, as reported in Figure 1.

The operation could be single phase or simultaneous on the three phases and the opening and closing instants can be then synchronized with the current and voltage trend while the speed of the contacts could be modulated depending on the current measured (thus on the state of the grid and load), thereby influencing breaking behaviour. [1, 2]

In addition to the limited impact in the power grid, thanks to the possibility of adaptive operation, the SUP CB enables the integration of advanced monitoring and diagnostic methods, providing relevant information for a successful condition-based and predictive maintenance.

Figure 1: a) Servo-drive Vacuum Circuit Breaker concept and b) VD4 AF apparatus

MONITORING, DIAGNOSTIC AND PROGNOSTIC

T&D asset monitoring and management applications extensively utilize sensors and sensor systems for various functionalities ranging from alarming to online and non-destructive condition assessment.

The measurement functions in the area of asset management have been traditionally focused on the condition-based maintenance, monitoring, and health assessment of power equipment. Figure 2 shows the M&D principles as reported in IEC EN 13306:2017 The power system components that are mostly equipped with some kind of monitoring system include transformers, circuit breakers, load tap changers, surge arresters, regulators, reclosers, HV and MV vacuum/GIS switchgear, insulators, and shunt elements.

Figure 2: Maintenance according EN 13306:2017
The total cost of the equipment and its potential failure consequences usually determine the need, complexity, and features of the installed monitoring systems. Not all the components of the power system have a structured monitoring system installed, but every piece of equipment is typically equipped with sensors for measuring, monitoring, or control applications.

The availability of smart and effective embedded electronic device already integrated in modern MV equipment allows to extend the functionalities and the capability analysis of the M&D [2]. Signal processing, sometimes even complex, can provide the user with an overview of the general state of a circuit apparatus for the purpose of planning maintenance or informing the assistance service when faults have occurred.

Many optional signals can be integrated in the smart Apparatus Control Unit to improve the diagnostics functions and, looking ahead, to create and validate a prognostic algorithm in addition to the parameters enabled to be monitored by the control units:

- state of the actuators (magnetic actuators/servomotors); the state of the wiring and windings of the servomotors is constantly monitored by the control unit so as to ensure that the main operating components are in a good condition;
- full motion control; the control unit monitors the position, speed and torque of the servomotors during every opening and closing operation so as to keep the user informed about the operation that has just been performed;
- micro motion control; the control unit commands the servomotors to make micro movements when the apparatus is in the closed condition for monitoring position, speed and actuation torque. This control has the important task of checking the state of the actuation chain before commanding an opening operation, thereby guaranteeing the very highest reliability and responsiveness, especially in apparatus where the number of operations is low;
- synch signal; the quality of the signal is constantly monitored in terms of presence of primary voltage, frequency and harmonic distortion. Actuation is automatically adjusted by the control unit according to the variations in these latter two parameters so as to always ensure a high level of synchronism;
- insulating fluid pressure (dry air or greenhouse free gas); thanks to the integrated pressure switch, the control unit can recognize three pressure levels of the fluid inside the poles (OK, Warning, Low), thereby ensuring dielectric insulation during operations or in the open condition;
- energy storing unit; the voltage of the switched capacitor is periodically monitored to ensure that there is always sufficient energy for the sequence of operations before switching is commanded;
- state of the control unit; to ensure that everything always functions properly, the control unit constantly performs self-diagnosis as to its temperature and the voltage and current circulating around it.

Thanks to the enormous quantity of information available, being able to develop prognostic algorithms for the purpose of predicting imminent faults is the new frontier of diagnostics. This issue is being addressed by important research and development efforts requiring large quantities of statistical data to create and fine-tune life models of the apparatus [3, 4, 5]. These developments are leading to a cultural and organizational revolution as to Asset Management, i.e. all those activities aimed at reducing running costs by extending the life cycle of tangible assets and reducing the likelihood of faults or accidents.

As an example the Figure 3 shows the results from a analysis report provided by an Asset Management System (the example make reference to “My Remote Care” [6]).

![Figure 3](image)

Figure 3: The categorization of plant substations chart, in the Importance/Condition matrix, gives an overview of the current condition of each substation on the plant, linked to its importance.

The predictive maintenance implemented in Life Expectancy Analysis Program (LEAP) by means of advanced algorithms, allows to estimate where to invest the operational budget in order to reduce the risk of failure in order to address both system-oriented and component-oriented maintenance [7, 8, 9, 10]. Accessing to the “My Remote Care” portal [6] the field service can check the details of the alert and asset as reported in Figure 4. The Event Manager lists the latest events from the connected substations.

![Figure 4](image)

Figure 4: In case of an alert, a message is sent to the users: no need to be in front of a screen 24/7, just wait a trigger.
TECHNOLOGY TRENDS ENABLING IOT SERVICE AND PEOPLE ECOSYSTEMS

The advent of smart grids and the ever-increasing and pressing demands from both Public Utility companies and private industry for greater continuity of service and a better quality supply, have given rise to further requirements including management of the energy flows generated by renewable sources of variable input. Transmission and Distribution System Operators (TSOs & DSOs) are experiencing in these years a technology transformation, which includes the deployment of distributed Intelligent Electronics Devices (IEDs), two-way communications systems and information technologies to enable greater monitoring and control of their distribution systems.

The outstanding progress of electronics, information and communication technology has led to new digital solutions able to meet the functional requirements of the market in a flexible and integrated way. These technologies will increase the volume of data flowing into a utility's Information Systems, which in turn will need to be stored and managed.

One strategy, which seems to be the most popular option, is to collect all of the data possible and figure out what to do with the data at a later date. As the amount of data increases that needs to be stored/managed, there is a corresponding increase in Information Technology infrastructure, skill sets, and cost. [11]

Also Industrial Processes are now experiencing a revolution owing to the steady increase in the use of Internet Technology in industrial production. Industrial devices are being increasingly connected to each other and to a public or private network. In this context, industry's production systems will become increasingly capable of exchanging information on their own, of self-supervising themselves and performing actions automatically. All this takes the name of the Internet of Things Service and People (IoTSP). Switching apparatus are active part of this revolution since power grids are key elements for continuity of service and production efficiency.

The increase availability on the market of new low cost solutions supporting IoTSP applications represented a strong driver in the migration of the IED’s design from the traditional architectures based on microcontroller to new Cortex-A ARM® architectures. This new family’s devices, coming from consumer electronics application (mobile and data com. hub), integrate a wide range of high performance peripherals and benefit of low costs, low power systems, small packages and a high level multi-tasking operating system (i.e. Linux) typical of the personal computers.

The aim is often twofold: thanks to the use of programmable microprocessors (key components for Industry 4.0 and connectivity), it is not only possible to have an easier, more effective and low cost integration of the basic functions but, thanks to the flexibility of the new platform, new functions can be added in the future with limited impact on the application.

As we will see an increase of electronics to drive and control safety-critical equipment throughout the grid, possible failure of electronic devices is a concern for future.

Systems where the user’s safety is at stake (such as those that protect installations that could even be life threatening if faults were to occur) are particularly challenging from the design standpoint. Besides user safety issues, requirements such as reliability, ease of maintenance, availability and security of the information content must also be considered in such cases.

Dedicate design process and architectures has to be selected for the circuit solution and investigation of precursors to failure in electronics and prediction of remaining life of electronic components are key importance factor.

Current research efforts in prognostics for these power systems focuses on the identification of failure mechanisms and the development of accelerated aging methodologies and systems to accelerate the aging process of test devices, while continuously measuring key electrical and thermal parameters. Preliminary model-based prognostics algorithms have been developed making use of empirical degradation models and physics-inspired degradation model with focus on key components like electrolytic capacitors and power MOSFET's (metal-oxide-semiconductor-field-effect-transistor). [12]

The availability of reliable circuit solution in the design and prognostic strategy allow to use embedded electronics device in the most mission critical application: avionic, automotive, marine and railways.

THE CLOUD: THE NEW PARADIGMA FOR A SMARTER T&D GRID

The collection and organization of the data/information from circuit breakers in substations across the system allow making deductions about the system switching state and performance that affect reliability [13].

Some of this information is also obtained by Supervisory Control and Data Acquisition (SCADA). The redundant and more detailed information from circuit breaker monitors can be used to verify the consistency and increase redundancy of the measurements thereby increasing robustness of data and reducing operation errors.

The use of the embedded intelligent control system coordinated with the innovative sensors (IoT) allow the possibility to assess the environmental and operational parameters (“real” operative conditions of the apparatus) in real time, opening the way for a new era of monitoring functionalities, and enabling new business models based on them.

Combining local computation capability with the advantages of the cloud-based technologies, the data collected from the sensors of a single devices, can be centrally collected and correlated together to achieve fleet level data analysis.
A so composed system can be divided in three different layers as per the Figure 5.

![Layer Diagram](image)

**Figure 5: The three main system’s level embedding from local to clouds services**

The lower layers are needed from the upper to provide the required data to make the functionalities of an upper layer working. This means that is possible to have only the device layer, but there is no reason to have only the cloud layer if there are no devices in the providing data to the upper stages. Taking advantage from the different layers point of view, each one has the possibility to access different data perspective and quantity of data, as well as having different computational power to elaborate those data to do their functionalities:

- **Device**: In the local layer we have the devices with embedded sensors and intelligence. Each one has a local computation capability in order to collect and analyse collected data. The analytics available here are only related to the specific device and amount of storage available in it.

- **Edge**: The edge is the local interface for the cloud system. It is responsible for collecting the data from the single devices and transferring them to the cloud, as well acting as a local interface for the whole system, routing the data between all the components. Depending on the complexity of the device, some cloud functionalities can be delocalized here, to work on a subset of local data, enabling group level analytics.

- **Cloud**: Instead of the local and edge layers, where there are many devices, the cloud is just one. It’s the place where all the data form the devices are coming thanks to the functionalities provided by the edge layer. Taking advantage from the big amount of storage and computational power available, fleet level analytics and machine learning techniques can be deployed here.

Dedicated Application Programming Interface (APIs) can be then used by customer to retrieve data to be analysed on 3rd party systems. Those data can include RAW data, as well as results of analytics, reports, etc…

On each site, the smart-devices are communicating the information locally to a local edge gateway responsible for the cloud communication.

On the cloud layer, thanks to the combination of big data and machine learning techniques, a further level of prediction and failure detection analytics can be achieved. With an accurate calculation of the apparatus health status, concrete recommendations on potential upcoming maintenance activities and risks can be provided to customers to better manage their assets and avoid unexpected loss of service.

On other end, exchanging those information with the protection devices, we can improve the safety, reliability, as well as selectivity coordination using the health index, and dynamic interruption capability, to adapt the protection scheme according to the real time condition of the assets, and the type of fault that has to be cleared.

The recently introduced centralized protection systems, can be further improved by this concept, using the communication capability of the smart-breakers to directly exchange data with the central devices that directly manage the protection scheme as well as the interfaces and measurement point with the breakers.

Thanks to the creation of this kind of ecosystem, a new era of business model, based on services will come also in the Medium Voltage business. In specific environments and applications, thanks to the always-connected devices, an asset can be proposed as-a-service under a pay-per-use contract. And many other things like: ordering spare parts, buying warranty extensions, require a technician on-site, or simply request a consultancy on a detected problem, will be further improved by those kinds of devices.

### CENTRAL MONITOR UNITS

Several Circuit Breaker Monitor (CBM) have been proposed in literature: unit located at the circuit breaker cabinets in the switchyard, concentrator PC and GPS clock receiver located in a control house, and wireless point to multipoint network connecting IEDs located in the switchyard with the PC located in control house [13], use of expert system [14] or model base agent [15].

The last generation of electronics platform enabling IoT, as previous anticipated, is changing the paradigm and by the internet-based support offered opening the way for new services as mentioned in the previous chapter.

A new dedicated IED family has been therefore introduced for embedding in the apparatus at “device” level.

The CMU (Central Monitor Unit) in addition to support the collection of environmental, operational and status data and the transfer to the cloud allows also the local computation enabling the advantages not only of the cloud-based technologies for remote monitoring but also the local. CMU can be considered as a “merging unit” embedded in the apparatus (IEC 61850-7-2).

In order to support flexibility in HW and SW the CMU architecture is based upon a common CPU devoted to local computational and storage devices (one or more uP and memories are assembled on the unit) and a customized
Carrier Board where the communication transceivers, the analog and digital interfaces and the power supply are installed.

Having a common CPU and a high-level operating system allows an easier development and maintenance of common SW. The flexibility to adapt the CMU to different applications/products is delegated to the customization of different Carrier Board benefit of optimization in the cost and the space (unit volumes, development time, market requirements, target cost, ...).

With the progressively integration and connection of more smart devices, cyber-security solutions with latest cryptographic techniques are mandatory to prevent cyber-attacks and to protect the sensitive information [16].

The new generation of devices have native integrated embedded security solutions to build trusted IoT products, reliable and secure. Financial institutions, retailers, governments already benefited from the ecosystem of hardware and software tool to realize built-in solutions provided by the chip-manufacturers.

CONCLUSIONS

An increasing availability of information in conjunction with a remarkably accurate control of contact movements allows new digital switching devices to cover a broad range of pioneering applications.

With all the required electrical and mechanical quantities available and by means of a powerful electronic control system, a circuit breaker could adapt its behavior to suit the grid situation to the type of load and provide additional diagnostic and prognostic functions in order to minimize its impact (due to switching effect, maintenance or failures risk) on the grid itself and at the same time to increase its electrical and mechanical life. The Central Monitor Unit as well as the architecture scenario of the cloud-based services and business have been discussed.

This new generation of digital apparatus and the combination power system and IT systems, theoretically already available or feasible, will certainly have to be assessed in an open dialog between users and manufacturers.

REFERENCES