MODULAR ONLINE MONITORING SYSTEM TO ALLOW CONDITION BASED MAINTENANCE FOR MEDIUM VOLTAGE SWITCHGEAR

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ABSTRACT

Nowadays the concern to have a better maintenance strategy of an electrification system is being one of the key results of on-line monitoring and diagnostic approach. This paper illustrates a new modular solution for on-line condition monitoring in order to implement condition-based maintenance for medium voltage (MV) switchgears and breakers. The solution can predict potential failures allowing maintenance scheduling in advance.

In order to cover most of the MV switchgear and breaker failure modes dedicated sensing technologies can be applied.

Circuit breaker failure modes regards for instance: open and close commands malfunction, charging mechanism malfunction, current interruption issues (contact wear) and overheating. Switchgear failure modes regards mainly insulation deterioration and loose connections.

The on-line monitoring and diagnostic solution can detect in advance the mentioned failure modes by means of specific sensors pluggable whenever required on new or existing switchgears.

Innovative algorithms process all the information provided by sensors, to provide health indication for each component and failure mode. Moreover, an overall health index of the monitored equipment is calculated and represented by a traffic light. The red, yellow and green colors indication with corresponding alert messages gives indication on predictive maintenance planning.

The solution allows savings on maintenance costs (OPEX), asset lifetime extension (CAPEX), as well as prediction on failure (outages liabilities).

INTRODUCTION

Most used maintenance practices are typically based on original equipment manufacturers or industry standard guidelines. The majority of these guidelines refer to a time-based maintenance program adapted in some cases with the equipment usage (e.g. number of operations of a circuit breaker). As described in [1] the need of minimizing maintenance costs while maximizing the return on equipment, and a changed scenario with increased aged assets and reduced workforce, result in an increased request to manage the risk of failure of the installed base. This trend is clearly visible in several industries, where the operator not only focuses on availability and reliability of the assets, but also on predictability, which refers to the need of detecting a potential failure in advance, and schedule accordingly maintenance. This is why such maintenance strategy is called condition based or predictive based maintenance approach, meaning it is relying on the real health condition of equipment. In order to run effectively these new strategies, and take advantage of the failure prediction, the best approach is to select the proper condition monitoring solution, as described for a circuit breaker by IEEE in [4].

The primary reason for monitoring is to provide diagnostic information that can be used to take decisions based on equipment conditions, as shown in [3]. Measurement parameters must be carefully selected to provide the expected diagnostic benefits.

Although offline testing and condition assessment remain valid methods for circuit breaker health analysis, they have an intrinsic time and cost limitations to let predict components failures and therefore avoiding downtime.

Many components and subsystems contribute to the proper operation of the circuit breaker. Monitoring should identify the condition of a substantial portion of subsystems or at least the key subsystems necessary for successful operation to be effective. Before selecting the monitoring solution, it is important to classify the failure modes, define, and categorize components and subsystems of the equipment. Considering the medium voltage circuit breaker the analysis shown in [2] drives the choice of which are the most important failure modes to be monitored and which technology can be used. This step is important in order to find the right balance between costs and benefits of an on-line monitoring system. This balance might vary depending on the consequence of failure of the Medium Voltage (MV) switchgear within the plant, as well as on the equipment type. For instance on certain equipment is easier to install sensors or it might already embed sufficient electronic data sources. Therefore the on-line condition monitoring solution needs to be modular and scalable to adapt and being cost effective for most of the installation.

Considering the most important equipment failure effects on loss production the following paragraphs, describe two important monitored assets: circuit breaker intended as mechanism, main contacts and auxiliaries, and switchgear panel focusing on the primary parts (bus bars, cable joints, and insulators). Moreover, in order to serve properly the predictive based approach, the condition monitoring solution has to report relevant Key Performance Indicators (KPI), like asset health condition, alerts and messages to drive the service personnel in running further inspections or maintenance. The described monitoring and diagnostic solution provides a comprehensive support by means of calculated outputs simple to understand.

CIRCUIT BREAKER CONDITION MONITORING

It is difficult to obtain a definitive information on the causes of faults of MV circuit breakers, however, considering statistics and manufacturer service experience it is quite common to group failures in the following categories: mechanical, auxiliaries, insulation or dielectric, and electric, meaning the capability to break current. Actually, there are also external causes related for instance to maintenance activity. Statistically the most important faults in order of severity are mechanical, insulation or dielectric, and electrical primary parts faults.
In order to predict these potential failure modes, it is important to select and monitor information of the corresponding circuit breaker (CB) components like open and close command, spring charging mechanism, auxiliaries, and variables indirectly linked to failure causes, like trip current, temperature, etc. Mainly, as a technical reference for breaker monitoring, [5] [6] [7] describe high voltage cases. It is important to remind that high voltage scenario differs from MV for asset complexity and value.

Focusing first on the mechanical degradation, the most important variables for such analysis are the followings:

- Open time
- Close time
- Spring charging time and gear motor current analysis
- Number of operations
- Operation frequency (inactivity days)
- Auxiliary voltage

The travel curve and timing can be estimated from the open /close command to the open/close status read from the auxiliary contact.

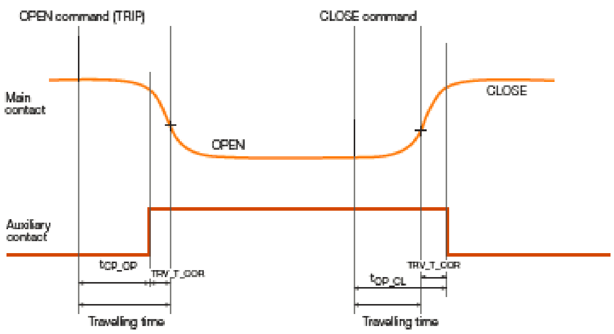

Figure 1: Travel curve estimation by auxiliary contact

The online monitoring system can easily trace above-mentioned variables with following binary inputs:

- Open command
- Close command
- Auxiliary contact

These inputs are existing in any circuit breakers and available easily on terminal blocks in the low voltage compartment.
In order to analyze the mechanical condition of the spring charging mechanism, it is important to measure the spring recharge time, from the close command to complete spring recharge, by means of the available limit switch signal.

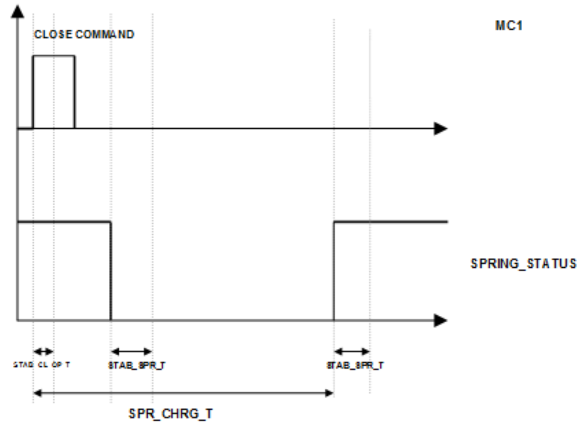

Figure 2: Spring charge time estimation by limit switch signal

The calculated timing variables are then used to manage the Health Index of the opening/closing/charging mechanism.

Moreover, another crucial monitored value is the current flow powering the spring charging gear motor during the charging operation. To measure such current flow, a small clamp-on sensor based on Hall Effect is connect to the monitoring system. This sensor is clamped onto the wire used to power the gear motor (installed in the low voltage compartment).
During the operation, the sensor calculates a Total Harmonic Distortion (THD), which is a measurement of the harmonic distortion: it is the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

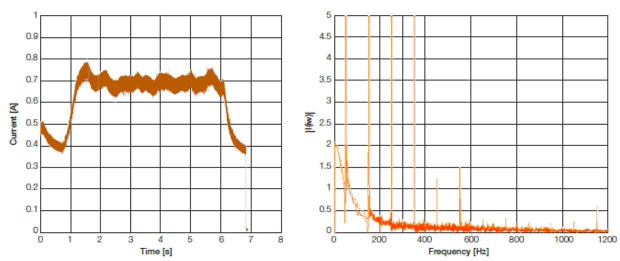

Figure 3: Spring charging gear motor current flow analysis

For a diagnosis, the sensor can analyze the total spectrum

and divide in two frequency bands: high frequency and low frequency.
Therefore, it is possible to detect if there is a mechanical or electric problem into the gear motor, in fact: high frequency signals are related to electrical problems (e.g. brushes anomalies), while low frequency are related to mechanical problems (e.g. gear tooth anomalies).
Another important diagnosis is about the wear out of arcing contacts or primary contacts of the circuit breaker, because this information is directly linked to the remaining life of the breaker itself. The estimation of such contacts erosion (ablation of main nozzle) is derived from phase currents, arcing time, etc. at every operation.

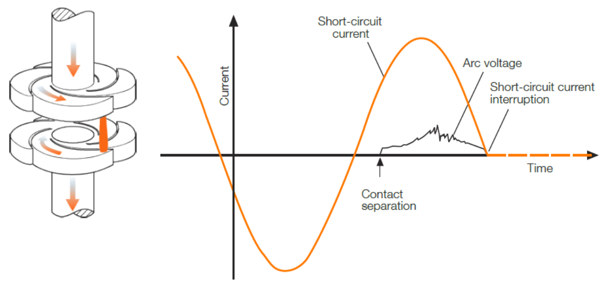

Figure 4: Contact wear estimation by phase current analysis

The online monitoring system provides a clamp on current sensors based on Hall Effect, which can be used to monitor the three phase currents. Such sensors with the previous estimated operation timing is used to calculate the poles accumulated energy and therefore estimating their remaining life.

A third failure contributing cause is about environmental conditions of the breaker compartment, as well as external causes. Some of these are good candidates for the monitoring solution, like for instance temperature of the breaker compartment. Others, like exposure to chemical or solvents, dust, water can be considered more effectively by time-based inspections.

Last but not least, a good monitoring solution shall identify always the monitored equipment. For a generic switchgear, this is not an issue because the monitoring device and sensors are installed or connected to the equipment; however, in the medium voltage scenario it is a bit different. In fact, a withdrawable circuit breaker (normal in MV switchgears) can be disconnected and moved to another panel, while the wiring in the low voltage compartment remain fixed to the existing terminal blocks. Therefore, the monitoring device must track this change in order to correctly map the operational history and estimations of the proper breaker, not mixing up data. The described monitoring solution can track the exact serial number and therefore identify the breaker by means of Radio Frequency Identification (RFID) technology, which automatically and in contactless mode let the monitoring device identify the installed breaker.

SWITCHGEAR CONDITION MONITORING

As stated in [1] most important failure causes in MV switchgears refers to dielectric and insulation problems, which can generate discharges, arcs, and other major faults, especially close to bus bars, cable joints, main contact joints and close to instrument transformers.
The temperature of these primary circuits has a dominant influence on the switchgear insulation life. If a loose joint within the switchgear creates a hot spot on the primary circuit, the insulation close to the hot spot can suffer serious deterioration due to excessive heating. The lifetime of the insulation decreases rapidly resulting in weak areas sensitive to dielectric stressing during subsequent operation. As a rule of thumb, the insulation lifetime reduces by half for each rise of 10°C in insulation average temperatures. An aged insulator increases dramatically the switchgear probability of failure in form of an internal arc fault, which can result in long-term power supply outage and huge consequences of failure (costs).
Since periodical visual inspections might not accurately estimate the remaining life of insulators, the detection of primary circuit hot spots becomes one of the crucial health condition monitoring tasks, and a key input to implement condition-based maintenance.

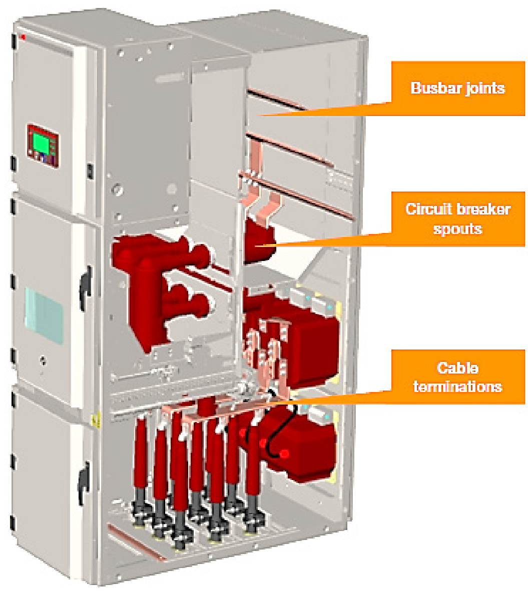

Figure 5: Medium voltage switchgear primary parts hot spot

A hot spot in the switchgear can develop as result of different operational situations, such as:

- Loose joints due to vibrations, unusual operating shocks
- Power cable loose connections as result of severe short circuits and aged clamping arrangement
- Mechanical damage of sliding power contacts during

equipment handling outside the panels
- Ablation of contact surface of sliding power contacts due to excess of racking operations above the prescribed limits
- Contacts resistance increase caused by oxidation or corrosion due to unfavorable environmental conditions (humidity, marine ambient, air chemical pollution, etc.).
- Long maintenance intervals due to equipment utilization in continuous process plants.

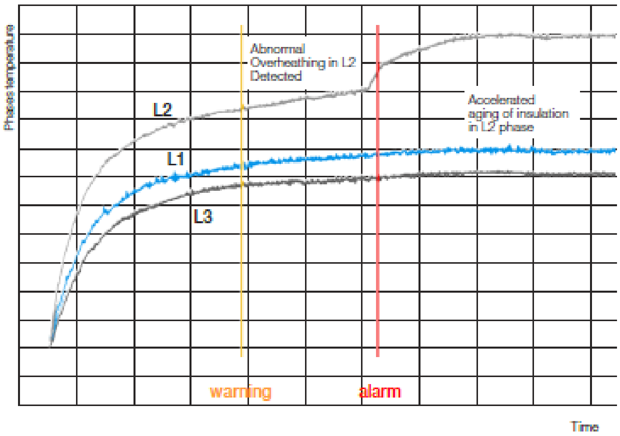

Figure 6: early detection of hot spot over heating on switchgear primary parts, due to a loose joint on phase L2

The described monitoring solution provides infrared sensors to measure hot-spot temperature of main joints in the MV switchgear. In particular, the most effective installation considers eight measured contactless points distributed in the bus bars compartment, breaker main contacts and cable compartment.

MODULAR MONITORING SOLUTION

The MV switchgear monitoring solution has very strict constraints in term of electronic costs as well as easy and fast installation without major changes on the assets. Therefore, to be very effective the presented solution offers a modular and scalable approach in order to tailor the monitoring and diagnostic application to most of the cases.

Figure 7 describes briefly the most important parts of the monitoring solution. The configuration scales from a limited set of sensors up to a full setup. For instance, it is possible to monitor just the mechanical operations of the circuit breaker with binary inputs, or scale up adding clamp-on current sensors for phases analysis as well as spring charging gear motors. Alternatively, even run just thermal monitoring of MV switchgear primary parts, up to a full monitoring of breaker and switchgear together.

The hardware solution has been designed in order to guarantee the functionality and reliability of the circuit breaker, even when one of the electronics of the monitoring solution fails. Moreover, future sensors can be plugged to the monitoring device adding also the corresponding diagnostic software function. These sensors shall be as much as possible easy to install and to operate, meaning not requiring changes on the asset, nor further calibration after commissioning.

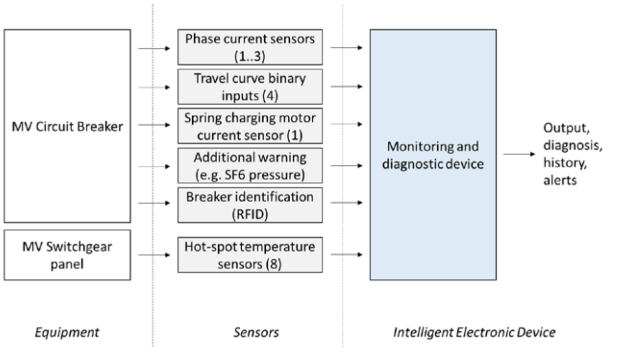

Figure 7: Hardware diagram of the monitoring solution

MONITORING AND DIAGNOSTIC KPI

A purely monitoring device, offering sensors data outputs, is not enough for condition and predictive based maintenance. For instance, inform at every circuit breaker operation about the last open time or about the actual temperature of the breaker compartment does not imply any specific action or planning. The ultimate goal, instead, is to alert service personnel and let them effectively schedule mitigation actions based on clear information. The described solution offers a set of diagnostic algorithms converting raw sensors data into valuable information in a flow described in Figure 8.

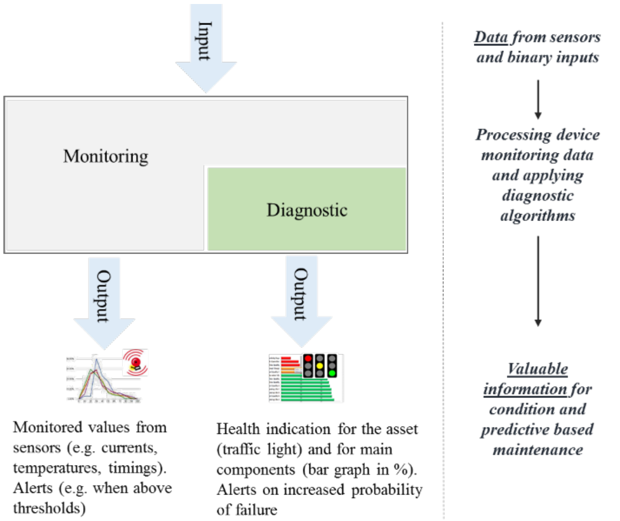

Figure 8: Data flow, from monitoring data to diagnosed information

Specific diagnostic function modules, as shown in Figure 9, evaluate every monitored equipment sub-component producing a sub-health index. For instance, the pole accumulated energy diagnostic function elaborates the measured trip current samples with a custom I^2t function; the open command diagnostic function evaluates in the

simplest version the trend and the absolute open time values; and the loose joint detection function compares the phase bus bar joints hot-spot temperatures each other, and with the environmental temperature.
Based on the availability of input data, the device enables or disables diagnostic functions.

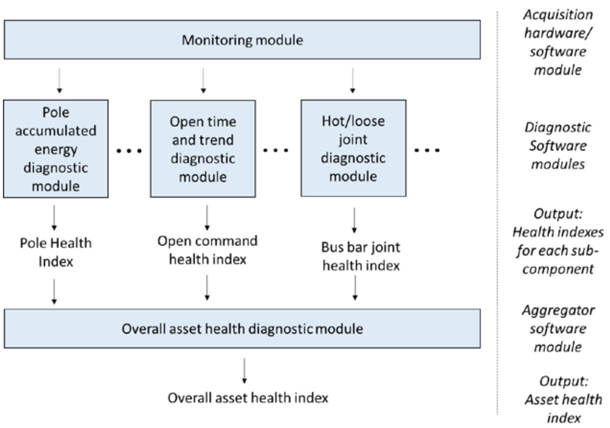

Figure 9: Diagnostic function modules

The sub-components health indexes, also called quality, is represented as percentage value (0-100%), where 100% refers to a new product and 0% its end-of-life. This quality range is divided in three areas as shown in Figure 10: alarm (red), warning (yellow), and good (green).

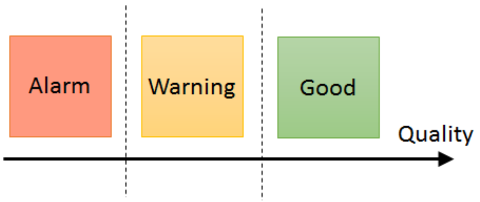

Figure 10: Estimated quality areas

The overall asset health index or quality, which is the minimum of all sub-components qualities, is represented with the same three colors and shown as output of the device as a traffic light.
A component or product with a quality in the green or "good" area is considered in serviceable condition and with no detectable degradation or normal aging degradation. The quality is in yellow or "warning" area when the equipment shows signs of degradation and requires attention with for instance further assessments. A quality in red or "alarm" zone means significant or serious degradation that requires immediate intervention.
This simple approach drives easily the service personnel. In fact, once the operator receive an alert about a yellow or red asset health condition (traffic light), it is possible to dig in the reason (e.g. open command quality) and therefore sub-component (breaker mechanism) to be furtherly inspected or maintained. Therefore, it supports the failure prediction (savings on failure avoidance) and it focuses maintenance on the proper asset and component (savings on preventive maintenance).

CONCLUSION

MV switchgear and circuit breaker condition monitoring is playing an important role in today's effective maintenance strategies. Diagnostic functionality is mandatory in order to predict failures, therefore reducing the risk of failure, and plan mitigation actions of the degrading equipment. The described modular solution implements in one solution both monitoring and diagnostic functionality. Moreover, the outputs represented as qualities (health indexes) make service personnel life easier getting alerts on potential issues and planning effectively mitigation actions.
The flexibility and simple installation of electronic device and sensors allow installation on a wide variety of MV switchgears. Furthermore, the solution is very scalable, letting engineers select the required monitoring functions and sensors, tailoring the predictive approach for both green and brown fields.

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