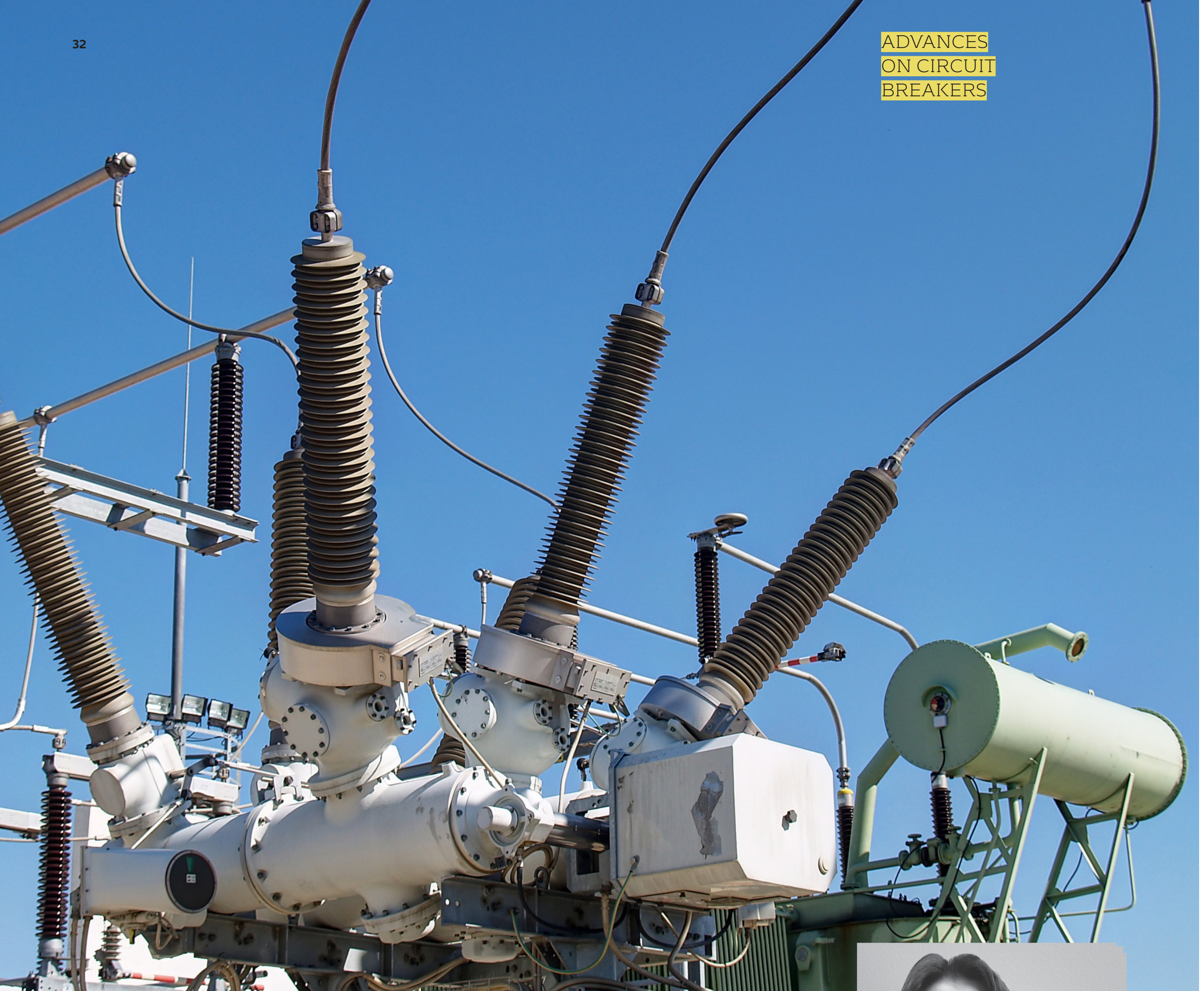
ADVANCES ON CIRCUIT BREAKERS



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Automated real time ML-based Circuit Breaker Trip Coil Analysis

by **Marco Tozzi**
and **Michael Skelton**

A key requirement from electricity networks is to provide safe, efficient, and reliable power to customers. When faults occur due to weather, equipment failure, or accidental damage, then the Circuit Breaker must quickly disconnect the fault to protect the network upstream and maintain supply to the majority of customers. Therefore, the Circuit Breaker can be considered the guardian of the power network.

Marco Tozzi received the M. S. degree in Electrical Engineering from the University of Trieste in 2005 and the Ph. D. degree in electrical engineering in 2010 from the University of Bologna. From 2007 to 2011 was Project Manager and Technical Advisor in Techimp, Italy, being involved in research activity on diagnostic of insulating systems by Partial Discharges analysis. From 2012 to 2022 was Product Designer and then Senior Product Manager for Camlin Energy, involved in designing solutions for holistic transformer monitoring. Since 2022 he is Sr. Technical Advisor for Camlin Energy, involved in asset diagnostics, consultancy services and optimisation of monitoring and maintenance programs. He is author or co-author of more than 40 technical and scientific papers.

Circuit Breakers can be slow to operate, or fail to trip due to defects in the trip coil and operating mechanisms caused by friction, often due to lack or wrong type of lubrication. International statistics indicate that 80% of the observed failures are linked to operating mechanism and auxiliary control circuits [1]–[4], possibly causing catastrophic failures [5-6].

The traditional offline test and inspection can be difficult to plan due to the operational constraints and require a significant amount of time and resources, while leaving the problems that arise in-between regular inspections unnoticed. Moreover, the standard test could not detect the causes of a slow trip. Before an off-line test is performed, the breaker is first tripped, and then isolated from the system. Then the offline test kit is connected, and the breaker is tripped again. However, the first trip, which was not recorded, could show a longer opening time due to a mechanical defect. The issue could be cleared after the first operation and show no criticality during off-line testing. For example, faulty lubricants and/or questionable lubrication practices [7] often create a sticky compound causing slower movement of the mechanism during the first trip and, very likely, normal timing during the second trip.

To prevent the breaker from failing to trip, it is recommended to periodically test the operating mechanism through a planned trip operation with the breaker online and without affecting customer supplies. This can be done with a hand-held device by recording the first trip current profile, the DC battery voltage, and the three AC interrupted currents. This procedure has been carried out successfully for years, as documented in [8]: "circuit breaker signature analysis can be used as an excellent tool to assess the condition of our breaker operators, prioritize maintenance and minimize equipment outages".

The interpretation of the data requires an expert operator to compare the recorded curves with "reference" ones to identify the malfunction of the breaker: this can be challenging considering the test devices could be used by any operator in the substation, even without the necessary experience.

The following article proposes a new Machine-Learning-based method able to provide a diagnosis and suggested action automatically by comparing the last recorded trip operation with a reference profile generated with advanced AI techniques using a statistical population of curves relevant to breakers having the same trip coil mechanism.

The diagnosis is done in less than 5 seconds, and the field operator, even if inexpert, can understand if a major or minor maintenance is needed. They can then provide feedback to the asset manager from the field, and open a workorder immediately. This removes delays caused by waiting for data analysis and reduces the time-to-action to seconds.

Circuit breaker signature analysis can be used as an excellent tool to assess the condition of breaker operators, prioritize maintenance and minimize equipment outages.

Michael Skelton has been working for Northern Ireland Electricity (NIE) for over 33 years and has extensive experience in the planning, design and operation of distribution and transmission networks. He joined the Camlin Group in 2009 as Product Manager for the High Voltage Monitoring and Testing products, such us DGA monitoring, Bushing monitoring and Circuit Breaker testing equipment. He is now consultant for Camlin Energy, working in the Technical Advisory Group and his current activity involves diagnostics on Circuit Breakers (CB) and the application of ML/AI analytics on the CB First Trip data.

The basics and the importance of the First Trip Analysis

The method enabling the assessment of the operating mechanism health by monitoring the current flowing through the trip coil was developed back in the 90s [9], extensively described in literature, and widely adopted in the utility industry [9-14].

The trip coil circuit is an electromagnetic circuit with reluctance in the magnetic part, and inductance and resistance in the electric part. The mechanism consists of a solenoid around a movable plunger, a latch, a spring and a mechanical connection to the main contacts; once the control circuit receives a command signal, the coil is energised (typically from station DC batteries) causing the plunger to move and hit the latch mechanism as shown in Figure 1. This activates the movement of the operating mechanism and discharges the compressed spring mechanically connected to the main contacts, which open. After a short delay the auxiliary contacts open and disconnect the coil from the substation voltage, causing the coil current to go to decay to zero. As the plunger moves, the reluctance of the magnetic part reduces, increasing the inductance of the electric circuit. As the rate of inductance increases, the rate of change of current decreases.

Therefore, if a DC Hall Effect probe is clamped around the coil current

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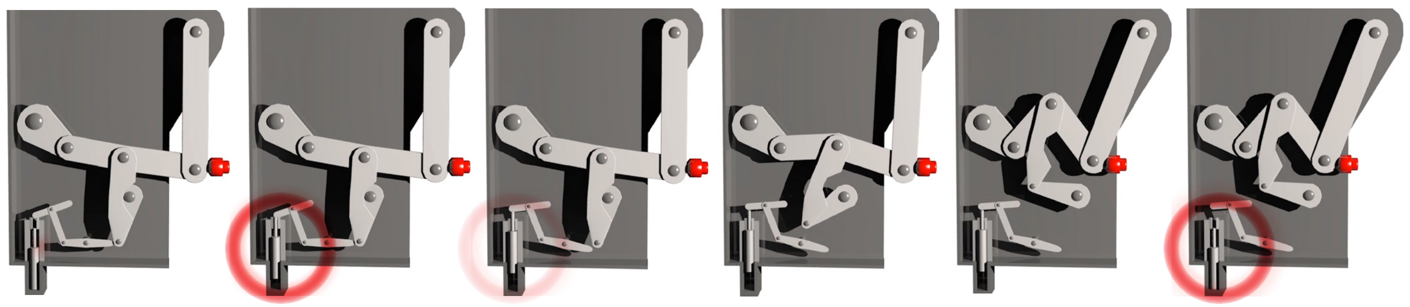


Coil energized, Plunger begins to move (A)

Plunger strikes the latch (C,D)

Latch unlocked, plunger strikes buffer (E)

Main contacts starts to open (E-F)

Main contacts open (F) Auxiliary contacts open (G)

Trip coil de-energised (H)

Figure 1. Step by Step process of a trip mechanism

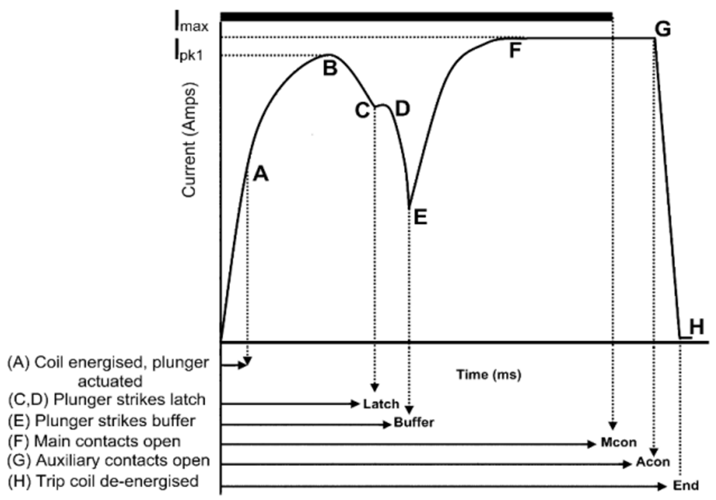


Figure 2. Trip current profile

circuit, a current profile can be recorded during the trip and close process which increases and decreases over the time depending on the changes in the reluctance and inductance: the recorded profile of the current will have a shape similar to that shown in Figure 2, with an increasing current reaching a peak, a plateau, and then a rapid decrease.

By comparing the actual trip/close profile with a reference one (depicting normal operation), we can understand if there are delays causing a slow trip and, most importantly, the cause of the slow trip.

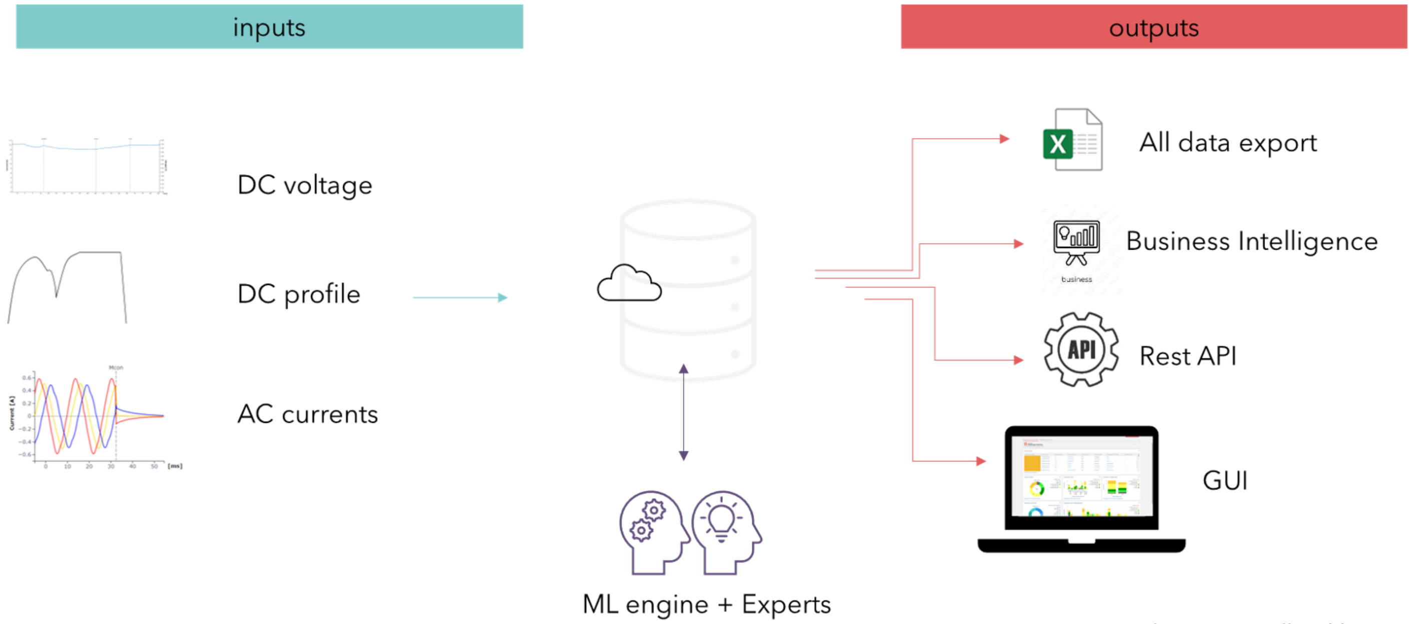


Figure 3: overall architecture

Some of the failures that are usually detected result from:

+ Supply Voltage (too high, too low, inconsistent, battery issues, poor connections)
+ Trip/Close Coils (increase or decrease of resistance, degraded contacts, CB fitted with incorrect trip coil, misalignment of coil, insufficient lubricant)
+ Auxiliary Contact Performance (auxiliary bounces, faulty operation)
+ Latch mechanism (friction or insufficient lubricant)

Application of Machine Learning to Current Profile Data

The challenges: do the right thing at the right time

The assessment of the breaker capability of tripping within the right time is done by comparing the latest recorded curves with a reference one, which represents "normal" behavior.

The reference template can come from:

+ Factory test, OEM provides the trip curves
+ Commissioning test
+ Historical data
+ First vs second trip

There are however challenges in the data interpretation:

1. The reference curve can change over the time due to degradation of components
2. The analysis is very subjective and requires skills and knowledge of data interpretation and circuit breaker operation
3. If the analysis is deferred to the Subject Matter Expert (SME), delays can occur between the test and the suggested action, after the (often over-burdened) SME has received and analyzed all the data
4. Inexperienced operators could fail to connect the sensors properly, and realize this days later upon data analysis

The solution: an augmented intelligence tool

These challenges can be overcome by using an intelligent digital solution that ingests the recorded data while the operator is still in the field, processes it in real time, and provide immediate feedback on:

+ quality of data
+ possible defect
+ suggested maintenance action

The solution is created by analyzing a significant amount of historical data coming from families of breakers having the same trip coil mechanism, using Machine Learning and advanced analytics combined with the experience of the SME labelling the data and providing feedback after the maintenance.

The overall architecture (Figure 3) consists of a centralised cyber-secure data center where the data are collected and processed combining an ML engine with human expertise. The role of the human SME should not be underestimated, being crucial in the training and assistance to the AI-based automated system. The cloud-based database ingests data from various sources, including online monitors, and provides actionable outputs, including prescriptive actions, that can be sent to Work Field Management systems via a standard API mechanism.

In terms of implementing the solution (Figure 4), it is necessary to select a family of breakers with the same operating mechanism and gather the historical current profile, even from different users, to generate a template. Then features are automatically extracted whenever a new record is processed, the data are compared to the template and processed to identify defects and classify severity according to a Health Score.

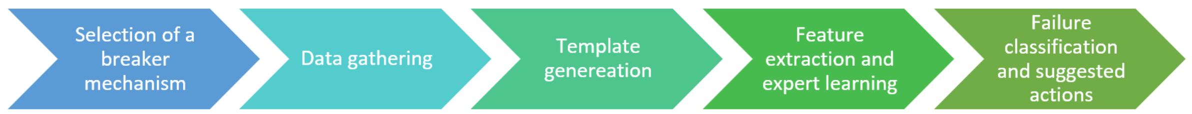


Figure 4: Step by step deployment of an automated digital solution

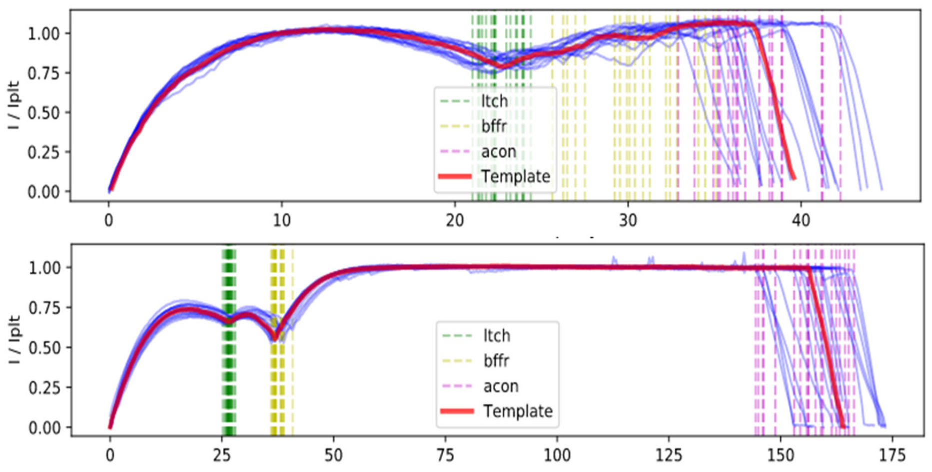


Figure 5: Template extraction from a number of profiles coming from the same type of breaker

Figure 5 shows the overlap of tens of current trip profiles of two specific types of breakers labelled by the SME as "normal" in terms of health. The red trace is the template generated by the algorithm used from now on to compare with any new data. The template could still change and improve over time, learning from the new data and feedback. This is a key advantage of the proposed solution: the ability to generate and dynamically improve a template that is the best fit within a number of different "normal" profiles of the same breaker type, based on a statistical population of curves; this is more effective than using just one curve, since it takes into account a certain variability of the key-points due to standard operation and ageing.

In the final stage maintenance instructions for Asset Management are created automatically.

Defect List
No defect
Defect in trip coil operation
Defect in auxiliary contacts operation
Defect in the battery
Defect in the battery circuit
Defect in main contacts opening

Table 1: Example of possible defects

Action List
No action
Repeat Test
Lubricate the trip coil
Lubricate the operating mechanism
Identify the cause of battery voltage drop and rectify
Check battery charger operation and replace it if necessary
Check alignment of the auxiliary contacts and clean them
Replace the Trip Coil
Clean and lubricate the operating mechanism

Table 2: Example of possible actions

Condition Group	Urgency
1. Good	No action
2. Suspect	Test again within 6 months
3. Defective	Inspect in the next planned maintenance
4. Critical	Plan an emergency maintenance

Table 3: Example of urgency

CASE #1: Healthy HV breaker

The grey trace represents the template generated by the automated algorithm, while the colored trace is the most recent trip current profile.

The color of the last trip depends on the status of the breaker and is determined by the algorithm; here it is green, showing there are no issues.

Buffer, Acon (auxiliary contact) and End (trip coil de-energized) timings are automatically extracted, and the keypoints are visualised overlapped to the trace

The profile shape analysis indicates that the breaker is opening with a small delay within 4 ms, which is acceptable, and results from the natural inertia when a circuit break has been inoperative for a long time.

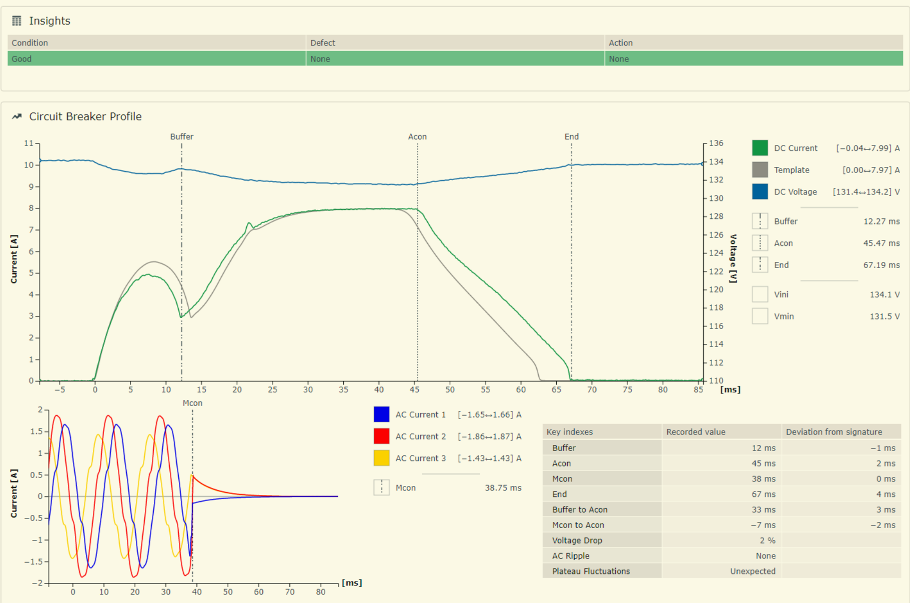


Figure 7: Normal healthy trip

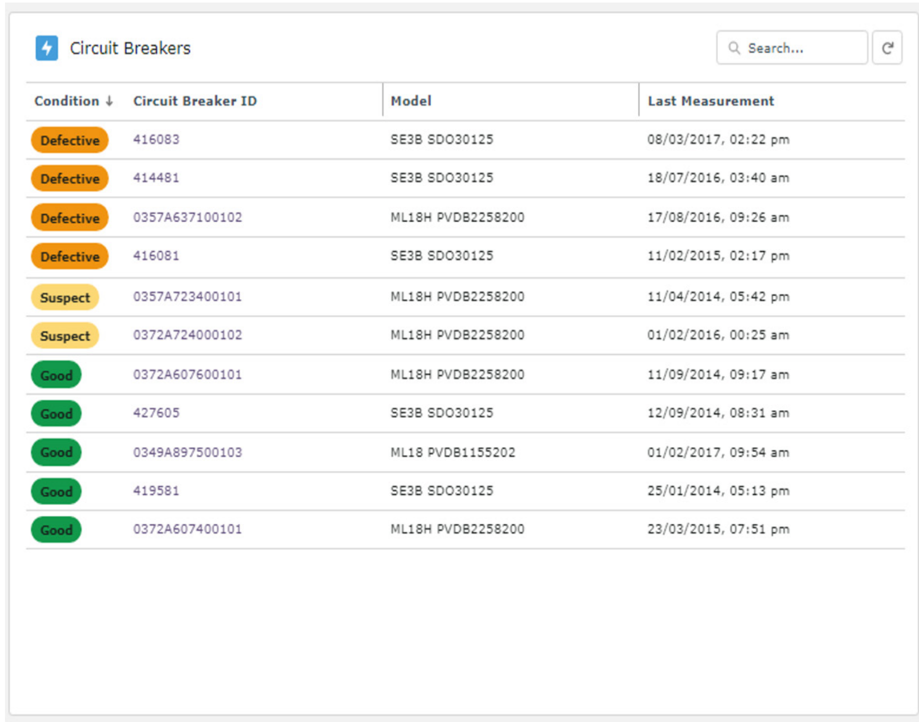
Automated prescriptive actions

The algorithm is able to evaluate the possible defect, suggest an action, and assign a health score to the breaker to provide a priority list to the end user. Tables 1 and 2 showcase some of the defects and actions automatically generated by the algorithm. Table 3 shows the health categories with the relevant urgency.

Real Cases

The following cases were collected by processing hundreds of trip coil profiles captured with a hand-held tester, collecting the AC currents, the DC current of the trip/close coil, and the DC Battery Voltage. The results were generated in real time upon loading the data to the web-portal.

The condition of the breakers is summarised in the following table:



Circuit Breakers

Condition ↓	Circuit Breaker ID	Model	Last Measurement
Defective	416083	SE3B SDO30125	08/03/2017, 02:22 pm
Defective	414481	SE3B SDO30125	18/07/2016, 03:40 am
Defective	0357A637100102	ML18H PVDB2258200	17/08/2016, 09:26 am
Defective	416081	SE3B SDO30125	11/02/2015, 02:17 pm
Suspect	0357A723400101	ML18H PVDB2258200	11/04/2014, 05:42 pm
Suspect	0372A724000102	ML18H PVDB2258200	01/02/2016, 00:25 am
Good	0372A607600101	ML18H PVDB2258200	11/09/2014, 09:17 am
Good	427605	SE3B SDO30125	12/09/2014, 08:31 am
Good	0349A897500103	ML18 PVDB1155202	01/02/2017, 09:54 am
Good	419581	SE3B SDO30125	25/01/2014, 05:13 pm
Good	0372A607400101	ML18H PVDB2258200	23/03/2015, 07:51 pm

Figure 6: Circuit Breaker fleet view sorted by health condition, automatically generated

CASE #2: Defective HV breaker

The last trip recorded is yellow, since there is an anomaly.

The profile shape analysis indicates that the breaker is slightly slower than expected (16ms).

The delay on the auxiliary contact is only 4ms. The voltage seems to be slightly unstable, while the AC currents are not recorded due to poor connection of the sensors, or missing load during the test.

The breaker can still be operated as normal, however there are a few actions to be planned and automatically provided by the system:

- Check the voltage stability of the battery charger. This can be deferred to the next planned maintenance
- Repeat the test in 6 months to verify if the delay has increased. In that case a maintenance of the trip coil is required
- While repeating the test, make sure there is sufficient load to capture the AC current waveforms (check the sensors or try to trip the breaker while on-load)

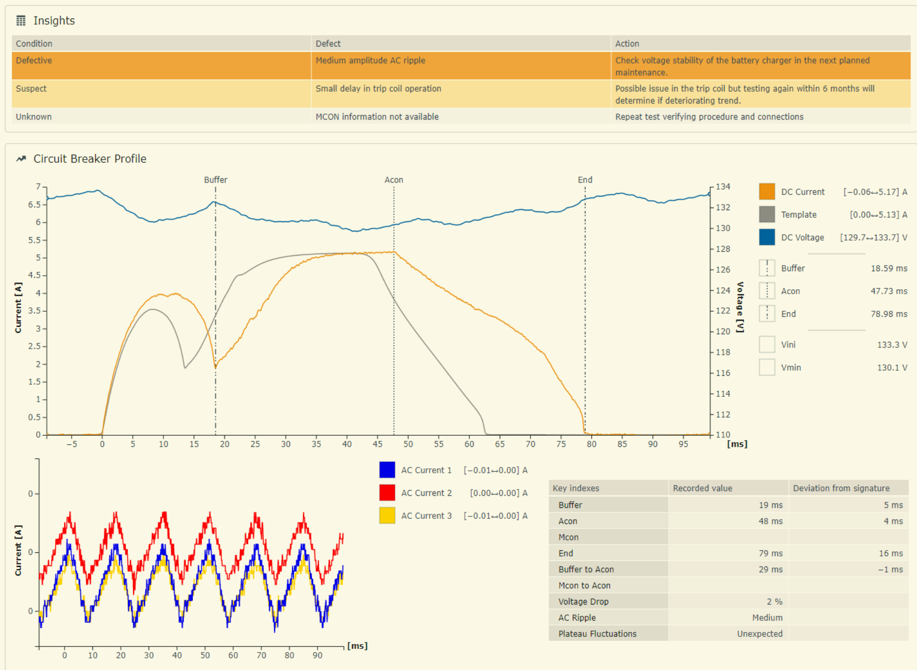


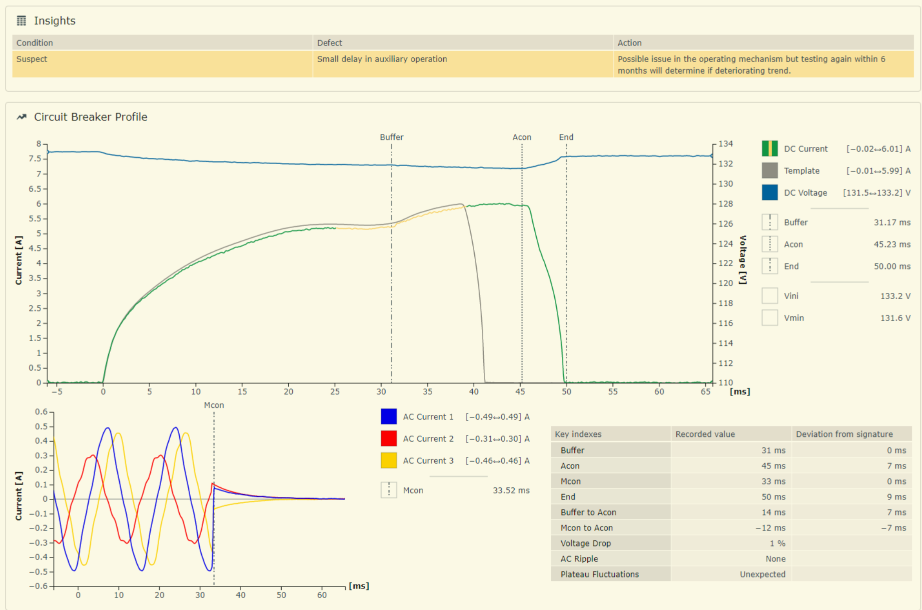
Figure 8: Slower than normal breaker, still good to operate but with possible issue in the battery and trip coil

CASE #3: Suspicious LV breaker (<33 kV)

In this case the last record is in two colors: orange and green, indicating that the trip coil mechanism is operating correctly and the delay is due to the main mechanism.

The profile shape analysis indicates that the breaker is about 10ms slower than expected.

According to the SME and the expert algorithm, the breaker can still be operated as normal, however there are signs of possible issues with the main mechanism.It is suggested to re-test within 6 months, since this could point to degradation over time.



Condition	Defect	Action
Suspect	Small delay in auxiliary operation	Possible issue in the operating mechanism but testing again within 6 months will determine if deteriorating trend.

Key indexes	Recorded value	Deviation from signature
Buffer	31 ms	0 ms
Acon	45 ms	7 ms
Mcon	33 ms	0 ms
End	50 ms	9 ms
Buffer to Acon	14 ms	7 ms
Mcon to Acon	−12 ms	−7 ms
Voltage Drop	1 %	
AC Ripple	None	
Plateau Fluctuations	Unexpected	

Figure 9: Slower than normal breaker, still good to operate, but with possible issues in the main mechanism

CASE#3

CONCLUSIONS

The analysis of the first trip current profile, the battery voltage, and the AC currents is an established technique to assess the braker's capabilities to trip within the expected time, and thus protect the upstream equipment on the power grid.

Challenges in the interpretation and the time needed to prescribe a suggested action can be overcome utilising a digital solution that can ingest data and automatically overlap the measured records with "normal" templates generated using an AI engine and human experience. The solution can indicate the health of the breaker, identify the defects, suggest an action and relevant urgency.

This solution allows inexperienced operators to perform the test in the field and have immediate expert feedback with clear suggested actions. Work orders can be generated on the field and minor maintenance can be carried out immediately.

The overall solution improves the pace of decision-making minimising the time-to-action and optimising the maintenance schedule. In particular, the proposed approach leads to major benefits:

+ Improving circuit breaker performance
+ Minimizing damage to plant and risk of injury to personnel
+ Enabling a condition-based maintenance strategy
+ Reducing operational costs
+ Reducing the time between the test and the action.

The overall solution improves the pace of decision-making minimising the time-to-action and optimising the maintenance schedule.

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