AN INNOVATIVE PERFORMANCE MODEL FOR MONITORING AND DIAGNOSTICS OF MEDIUM VOLTAGE SWITCHGEARS

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Abstract - This paper illustrates an innovative performance model for monitoring and diagnostics of Medium Voltage (MV) breakers and switchgears. Scope of the performance model is to assess the current health condition and to predict the future health condition of MV equipment and, thus, to provide relevant information for any successful condition-based and predictive maintenance strategy.

The performance model presented in this paper is based on the central role of failure modes, causes and mechanisms. It is modular and scalable in order to take into account different scenarios of data availability (from static product nameplate data to dynamic condition monitoring and test data) and MV equipment of different manufacturers. In addition, the accuracy of the performance model in assessing the current health condition is calculated as depending on the actual data availability and equipment knowledge.

The application of the proposed performance model in the petrochemical industry is presented in the second part of the paper by two practical cases. In the first case, the performance model is implemented based on historical data, asset inspections, operator interviews and performance tests. In the second case, sensors data from advanced condition monitoring solutions is included in order to increase the accuracy of monitoring, diagnostics and prognostics of MV equipment.

Index Terms — Performance model, monitoring, diagnostics, prognostics, medium voltage, breakers, switchgears.

I. INTRODUCTION

The concept of asset management is evolving rapidly in all industries due to the availability of new technologies like low cost sensors, Internet of Things (IoT) and advanced data analytics. In the past, asset management within utilities and industries consisted of not much more than a spreadsheet populated with asset register, installation date, expected lifetime and maintenance schedule. Nowadays the meaning of asset management has broadened dramatically and, depending on the maturity of the market and of the asset owner, it might include management of intangible assets, fleet management, financial analysis, and so on.

The specific asset management strategy has a strong influence on the maintenance activities. Asset owners have a wide spectrum of options ranging from basic strategies like run-to-failure and preventive maintenance, up to more advanced strategies like condition-based, predictive and reliability centered maintenance.

Focusing on electricity distribution companies and petrochemical industries, a clear trend towards extending maintenance periods for medium voltage (MV) switchgear can be identified. According to [1], this trend brings with it a need for asset condition assessment and for diagnostic techniques to give confidence in the continuing safety and reliability of the equipment. In addition, several markets and customers face the following similar business needs about operation and maintenance of the installed base:

- Cost and criticality of a failure
- Reliability requirements
- Balance between costs and risks
- Health safety and environmental

Condition assessment is the pillar of any advanced maintenance strategy. An overview on the current status and open research topics related to the condition assessment of MV breakers and switchgears is given in [7]. According to [2] the asset manager needs condition assessment to calculate the risk associated with failure, and therefore better plan maintenance, retrofit and replacement budgets. Also the ISO 55000 [3] clearly defines the benefits of asset management highlighting the crucial role of risk. Briefly, risk is defined as a combination of the probability of failure and the consequences of the occurrence of the failure. The consequences of failure occurrence can be also defined as criticality or importance level of the asset.

In real life, the probability of failure is calculated mainly by:

- Recurrent condition assessment based on observations, inspections and tests
- Continuous asset condition monitoring with dedicated sensors and analytics

Both solutions require a mathematical model which get tests and/or sensor raw data as inputs in order to estimate the asset health condition and calculate the probability of failure as outputs. This mathematical model is also known as performance model.

This paper illustrates an innovative performance model for monitoring, diagnostics and prognostics of MV switchgears. In the first part of the paper, the performance model is defined and the input data required by the model as well as its outcomes are presented. A short description of the general concept of the performance is reported. In the second part of the paper, the implementation of the performance model for two industrial case, representative of two customers in the petrochemical industry, is discussed. In the first case, the performance model is applied by considering observations, inspections and tests as input data. In the second case, condition monitoring data are also available for the assessment of the current health condition and the prediction of the future health condition of MV breakers and switchgears.

II. PERFORMANCE MODEL

A. Definition

A *performance model* is defined here as a *mathematical model assessing the current health condition and predicting the future heath condition of a device or a system over time*. In addition, the performance model provides information on the nature and causes of a potential impending failure. According to [4], the health of a device or system is the "extent of degradation or deviation from an expected normal condition". Referring to the definition of diagnostics as the identification of the nature and cause of device or system failure and prognostics as the "prediction of the future state of health based on current and historical health conditions" [4], the performance model is, in other words, a mathematical model for condition monitoring, diagnostics and prognostics.

Since the performance model described in this paper provides an assessment of the probability of failure, remaining useful life, risk, root causes of an impending failure, etc., for a device or system, it represents the foundation of any preventive, predictive and proactive maintenance solution. In the following subsections, the input data, the outcomes and the general concept of the performance model are described more in detail.

B. Input data

A large variety of input data from different sources and of different types and structures might be available to the performance model for condition monitoring, diagnostic and prognostic purposes. The input data landscape and its availability mainly depends on the nature of the asset, on the maintenance policies and strategies of the asset management organization and on the specific industrial sector. On the one hand, part of the input data is necessary to build and validate the performance model. On the other hand, part of the input data is needed to run the performance model for a specific device or system. The input data necessary to build, validate and run the performance model can be split into four main categories:

1. (Device or system) Operator data
2. (Device or system) Manufacturer data
3. (Performance model) User entries
4. External data

A list of possible input data for MV breakers with some corresponding examples is illustrated in TABLE I.

TABLE I
POSSIBLE INPUT DATA FOR THE PERFORMANCE MODEL

Input data	***Category***	***Examples***
Nameplate data	Customer Data Manufacturer Data	Manufacturer, breaker type, rating, production date, etc.
Application data	Customer Data Manufacturer Data User Entries	Industry, application, owner, operator, location, breaker criticality, etc.
Life and maintenance data	Customer Data	Installation date, delivery date, maintenance date, maintenance actions, etc.
Condition monitoring data	Customer Data	Online/offline monitoring data, test data, etc.
Operational data	Customer Data	Load, trip current, switching frequency, etc.
Environmental data	Customer Data External Data	Temperature, humidity, pollution, etc.
Reliability statistics	Manufacturer Data External Data	Failure rate, distribution function, distribution parameters, etc.
Recommended actions	Manufacturer Data	Preventive maintenance actions related to particular values of the product or system health condition, etc.
Reference values	Manufacturer Data	Reference thresholds for warning/alarm related to condition monitoring data, etc.
Model parameters	User entries	Reliability horizon, etc.

C. Outcome

As mentioned previously, the outcome of the performance model is related to assessing the current health condition, to predicting the future health condition and to identifying the nature or cause of a potential impending failure of MV breakers or switchgears. With this respect, the variables listed in TABLE II have been identified as the main outputs that the performance model must be able to determine and assess.

TABLE II
OUTCOMES OF THE PERFORMANCE MODEL

Output	***Description***
PoF	Probability of Failure
HI	Health Index
RUL	Remaining Useful Life
R	Risk of failure
RC	Root Cause of a potential impending failure
RA	Recommended Action (e..g. mitigation action, maintenance activity)

The Probability of Failure (PoF) is defined as the probability of a device or system failure within a specific time window. The Health Index (HI) is a measure of the current health condition of a device or system. HI can be easily derived by the POF. The Remaining Useful Life (RUL) is an estimation of the time to the next maintenance activity or failure. The Risk of failure (R) is the combined impact of the probability of failure and the consequences or criticality of that failure. The Root Cause (RC) is an indication about the nature or cause (usually expressed in terms of component or failure mode) of a potential impending failure. The Recommended Action (RA) is an indication of the action (e.g. mitigation action, maintenance activity) to be performed in order to avoid a potential failure and/or to reduce its consequences and criticality.

The performance model is meant to take into account different scenarios of input data availability as well as of knowledge about the device or system reliability. This variability in input data availability and device or system knowledge may strongly affect the accuracy of the outcomes of the performance model (as listed in TABLE II). With this respect, an algorithm to assess the accuracy of the performance model given a specific configuration of input data and knowledge about the equipment reliability has been developed by the authors. The algorithm to assess the accuracy of the performance model is not described here since it is not in the focus of this paper.

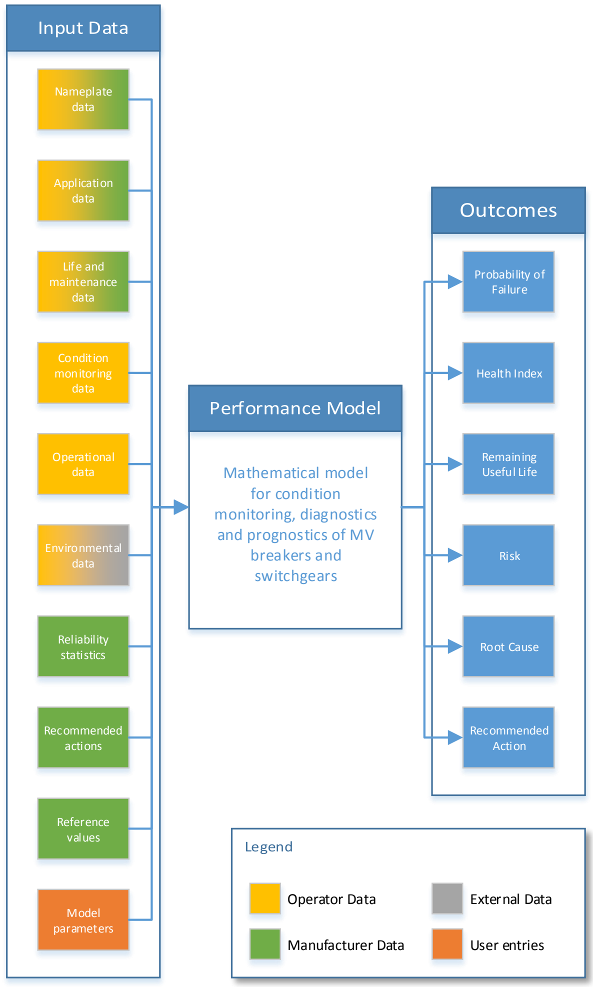

Fig. 1 Input data and outcome of the performance model.

D. General concept

The performance model proposed in this paper is based on the concept of *competing failure modes*. Usually there are many failure modes that can result in the failure of an individual device or system. In this paper we take the view that each failure is related only to one failure mode. With this approach, the failure modes "compete" as to which one causes the failure for each particular unit [5]. This approach can be represented in a reliability block diagram as a series of failure modes in which each block represents a failure mode. An exemplary implementation of the reliability block diagram for a MV breaker according to the competing failure modes approach is shown in Fig. 2. The failures modes considered here are taken from [6] and represent a comprehensive view of all possible failure modes that can lead to a failure of a MV breaker. Additional failure modes has to be introduced when a MV switchgear is considered. These additional failure modes are not reported in this paper.

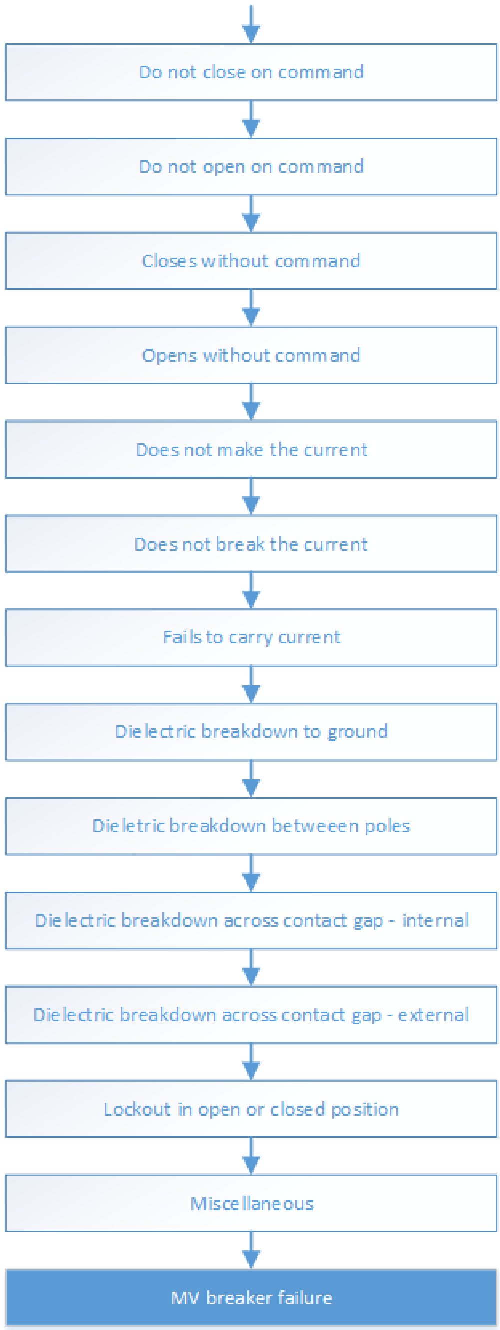

Fig. 2 MV breaker as series of failure modes.

According to the concept of competing failure modes, by knowing the probability of failure of each failure mode *i* it is possible to determine the probability of failure of the product or system. The probability of failure of a failure mode *i*, PoF_i, is defined here as the probability that the failure mode *i* will cause a potential product or system failure within a specific time window. After determining PoF_i for each failure mode *i*, it is then possible to assess all the outcomes of the performance model as reported in TABLE II. Based on the available input data the probability of failure, *PoFi*, the remaining useful life, *RULi*, the health index, *HIi*, the risk and the recommended action for the failure mode *i* can be calculated according to the algorithm illustrated in Fig. 3. If continuous condition monitoring data is available for the failure mode *i* the first step of the algorithm is the assessment of the health condition of the product or system with respect to

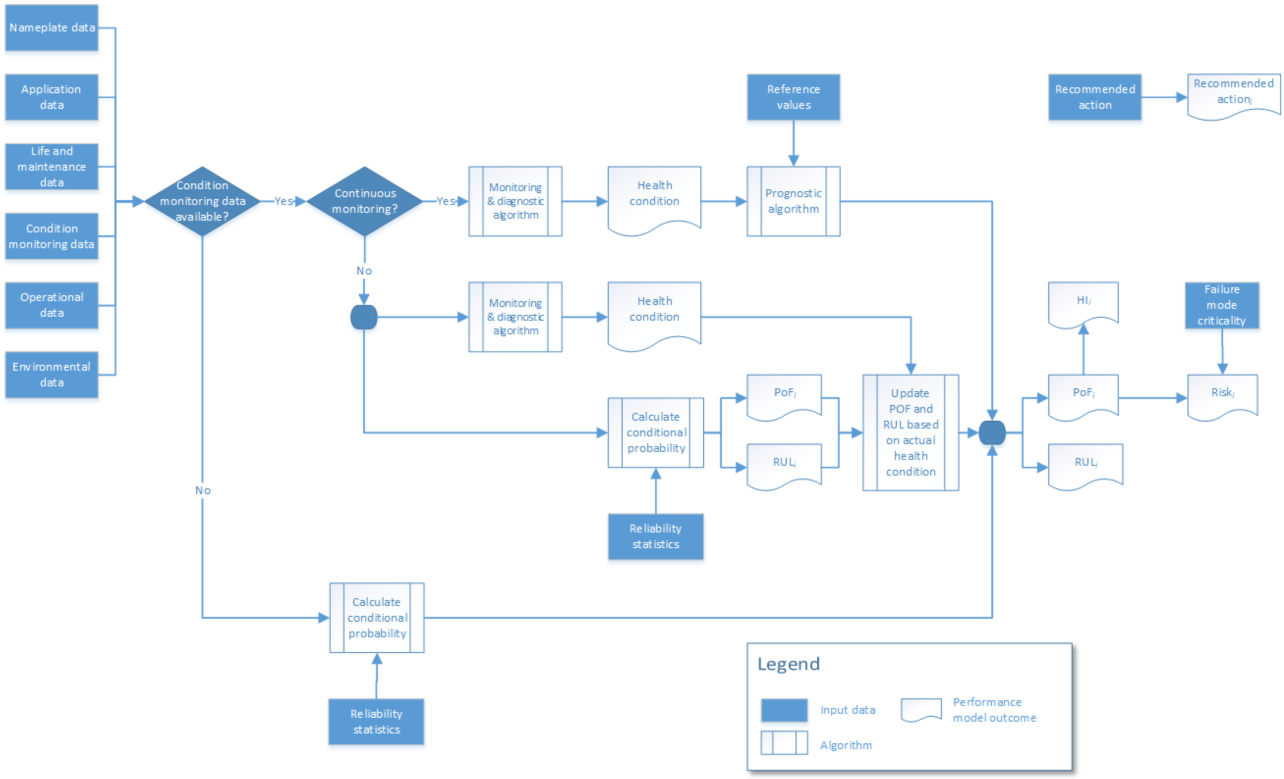

Fig.3 Algorithm for the determination of the outcomes of the performance model for the failure mode *i*.

the failure mode *i*. By applying advance prognostic algorithms it is then possible to determine the probability of failure within a specific time window, PoF_i, and the remaining useful life, RUL_i, of the failure mode *i*. In the case than continuous monitoring data is not available, the probability of failure, PoF_i, and the remaining useful life, RUL_i, can be assessed after determining the conditional probability of failure based on manufacturer's internal reliability statistics and the actual age and use of the MV breaker or switchgear. The PoF_i and RUL_i calculated by referring to reliability statistics can be then reviewed and updated in the case that offline condition monitoring data or equipment test results are available. Once the PoF_i is calculated and the given the failure mode criticality (in terms of failure consequences for the operator business and the human and environmental safety), the failure mode risk is simply calculated as the product between the PoF_i and the failure mode criticality. The health index HI_i can be easily derived by the actual health condition of the product or system and can be expressed in different ways (i.e. integer value between 0 and 10, percentual value betwenn 0% and 100%, and so on). Finally, each failure mode *i* is related to one or more recommended actions to be performed in order to avoid a potential product or system failure caused by the failure mode *i.*

By knowing the probability of failure of each failure mode *i*, PoF_i, and the statistical dependency among all failure modes, it is then possible to calculate the *PoF* of the product or system. Analogously, it is possible to calculate the product or system *RUL* as the minimum of the RUL_i of each failure mode. The same procedure can be applied to determined the product or system health condition *HC*. Finally, the recommended action for the product or system is equal to the recommended action of the failure mode characterized by the higher probability of failure or by the lower remaining useful life.

For the performance model described in this paper it is also possible to assess the accuracy of its outcomes. The accuracy of the performance model is defined as the capability of the model to detect a potential failure before it happens. Three main factors contribute to the accuracy of the performance model:

- Coverage (i.e. how many failure modes are covered by the monitoring and diagnostic algorithms).
- Accuracy of the monitoring and diagnostic algorithm in determining the current health condition with respect to each failure mode.
- Accuracy of reliability statistics with respect to each failure mode.

III. APPLICATION CASES

In this section two application cases of the performance model in the petrochemical industry are presented. The two cases differ in the input data available for the performance model. In the first case, in fact, the input data available for the performance model is given by historical data, asset inspections, observations, operator interviews and performance tests. For the second case, on the other hand, in addition to this data, continuous condition monitoring data is also available to assess the current and predict the future health condition of a MV breaker or switchgear. In the following subsections, the input data available for the two cases is reported in detail as well as the corresponding outcomes of the performance model. Based to the requirements of the specific customer, the outcomes of the performance model for the two application cases are a subset of the list of outcomes reported in TABLE II.

A. Performance model based on historical data, asset inspections, operator interviews and performance tests

The performance model presented in Section II can be instantiated and implemented based on historical data, asset inspections, observations, operator interviews and performance tests. This case is representative of many asset owners and operators in the petrochemical industry. In TABLE III the input data available for the performance model is listed. This list is based on a real application case for a specific customer in the petrochemical industry and should not be considered as a list of the input data strictly required by the performance model. In fact, the performance model provides an assessment of the outcomes reported in TABLE II even with a subset of the input data reported in TABLE III. In this case, however, the accuracy of the outcomes of the performance model will be lower since their calculation is based on less information about the history of the MV equipment. The first column in TABLE III gives an indication on the class of failure modes affected by the input data reported in the second column. For MV breakers, switchgears and relays it is possible to cluster the failure modes illustrated in Fig.2 into 7 groups: mechanical, current thermal, dielectric, protective functions, electrical accessories, equipment safety and other.

TABLE III

INPUT DATA FOR THE PERFORMANCE MODEL IMPLEMENTED BASED ON HISTORICAL DATA, ASSET INSPECTIONS, OBSERVATIONS AND PERFORMANCE TESTS

Group	**Input Data**	**Data Sources**
Mechanical	Age	Nameplate data
	Maintenance interval	Life and maintenance data
	% rated operation	Operational data
	Manufacturer	Nameplate data
	Interrupting technology	Nameplate data
	Mechanism type	Nameplate data
	Lubricant type	Life and maintenance data
	Cleanliness (observation)	Environmental data
	Trip function (test)	Condition monitoring data
	Operating time (test)	Condition monitoring data
	Operating volt. rate	Nameplate data
Current Thermal	Loading vs rating	Operational data
	Ambient temperature	Environmental data
	Fans installed	Operational data
	Pole resistance (test)	Condition monitoring data
	Signs of overheating (test)	Condition monitoring data
Dielectric	Age	Nameplate data
	Ambient temperature	Environmental data
	Elevation	Environmental data
	Voltage class & app.	Nameplate data
	Insulation type	Operational data
	Insulation cleanliness	Environmental data
	Insulation resistance (test)	Condition monitoring data
	Hi-Pot (test)	Condition monitoring data
	Vacuum integrity / SF6 pressure	Condition monitoring data
Protective functions	LV equipment?	Nameplate data
	Retrofit trip unit	Nameplate data
	Type of trip unit	Nameplate data
	Last calibration date	Life and maintenance data
	Trip unit age	Nameplate data
	Single phase protection (test)	Condition monitoring data
	# of fault current operations	Operational data
	Time/current OK (test)	Condition monitoring data
	Primary/secondary injection (test)	Condition monitoring data
Electrical accessories	Shunt trip (test)	Condition monitoring data
	Closing coil (test)	Condition monitoring data
	Spring charging motor (test)	Condition monitoring data
	2nd shunt trip (test)	Condition monitoring data
	UV trip (test)	Condition monitoring data
Equipment safety	Interlock condition (inspection)	Condition monitoring data
	Racking condition (inspection)	Condition monitoring data
	Locking devices (inspection)	Condition monitoring data
	Arc flash study (test)	Condition monitoring data
Other	Weather events	Environmental data
	Seismic / vibration	Environmental data
	Operating environment	Environmental data
	Electrical application	Operational data
	Operator experience	Operational data

Based on the requirements of the specific customer considered for this application, the performance model assesses the condition of the MV equipment in terms of reliability ranging from 0% to 100%. The reliability of the equipment can be easily calculated as the complement of the probability of failure, as defined in the previous section. In addition, the performance model can assess the reliability of switchgears, breakers and protection relays separately. In Fig. 4 the outcomes of the performance model are reported for an exemplary substation.

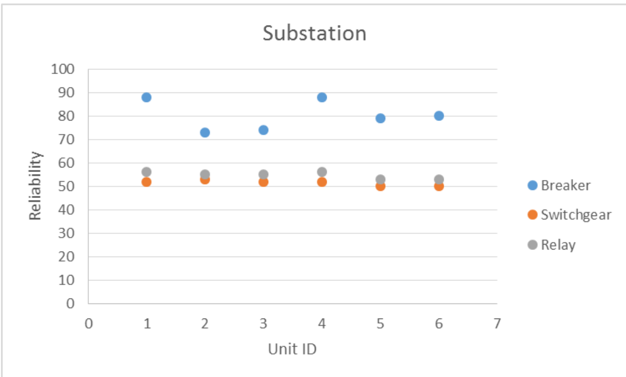

Fig. 4. Outcomes of the performance model.

Recommendations for mitigation actions are provided based on the assessed condition and reliability measures and experience, best practices and industry standards. Mitigation actions can be summarized categorically as follows:

4.1 Remedial Actions: Immediate action required
4.2 Mitigation Actions: Additional testing or investigation to more clearly define the condition and hazard, improve reliability and reduce the risk of failure.
4.3 Best Practices: Recommended best practices
4.4 New Equipment Specifications: Recommended considerations for future equipment specification

For the substation reported in Fig. 4, the reliability assessment performed by the performance model indicates that this substation is below an acceptable threshold and that a plan for replacing the substation as soon as possible should be developed.

B. Performance model based on continuous condition monitoring

For the application case reported in the previous section, the condition monitoring data was limited to the results of some test activities. The performance model was instantiated and implemented mainly based on historical data, asset inspections, observations, operator interviews and performance tests. No continuous monitoring data based on sensors installed in the MV equipment was available. Based on this fact, the performance model referred mainly to manufacturer's internal reliability statistics to determine the outcomes. Visual observations and operator interviews have been then performed with the scope of reducing the gap between the reliability statistics and the actual life of the considered MV switchgears and breakers. In any case, since continuous condition monitoring is not taken into account, the accuracy of the outcomes of the performance model may be limited.

The availability of low cost sensors, IoT technologies and advance data analytics is pushing the adoption of continuous condition monitoring solutions to support the asset management organization. By continuous condition monitoring the risk of an unexpected failure can be further reduced and advanced maintenance strategies like condition-based and predictive maintenance can be adopted. With respect to the performance model, continuous condition monitoring will provide additional real-time sensors data that can be used to improve the accuracy of the outcomes of the model itself and, at the same time, to increase the number of failure modes, causes and mechanisms that are actively monitored.

In TABLE IV a list of continuous condition monitoring data that can be currently used by the performance model to assess its outcomes is reported

TABLE IV
CONTINUOUS CONDITION MONITORING DATA

Group	**Input data**	**Data sources**
Mechanical	Open time	Condition monitoring data
	Close time	Condition monitoring data
Electrical accessories	Spring charge time	Condition monitoring data
	Auxiliary voltage	Condition monitoring data
	Trip current for each phase	Condition monitoring data
Current Thermal	Breaker compartment temperature	Condition monitoring data
Other	Time of inactivity	Condition monitoring data

As for the previous application case, due to its intrinsic modularity, the performance model can also work with a subset of data reported in TABLE IV. In this case, the accuracy of the model may be reduced. On the other hand, the performance model can be extended easily to consider the possible development and installation of additional new sensors. In this case, the accuracy of the model will be increased.

Fig. 5 shows the outcomes of the performance model based on continuous condition monitoring for a specific customer in the petrochemical industry. In this case, the probability of failure is visualized by color codes (i.e traffic light approach) and the remaining useful life is expressed in terms of remaining number of switching operation. As reported in Fig. 5, based on the continuous condition monitoring it is possible to assess the health condition of each components of MV equipment. This leads to a deeper understanding in the health status of the asset and in the potential upcoming maintenance activities required.

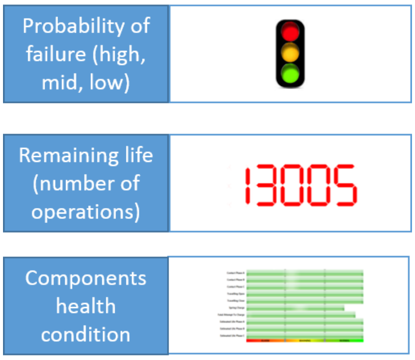

Fig. 5 Outcomes of the performance model

IV. CONCLUSIONS

This paper illustrates an innovative performance model for monitoring, diagnostics and prognostics of MV breakers and switchgears. Since the performance model described in this paper provides an assessment of the probability of failure, remaining useful life, failure risk, and root causes of an impending failure, it represents the foundation of any preventive, condition-based, predictive and proactive maintenance solution. Due to its modularity, the performance model proposed in this paper can work with different scenarios of data availability and can be applied to any class of MV breakers and switchgears. This is reflected by the two application cases reported in the last part of the paper. In the first case, the performance model is based on historical data, asset inspections, observations, operator interviews and performance tests. No continuous condition monitoring data is available. Based on real assessments for substations in the petrochemical industry, it has been shown that the performance model is able to assess the reliability of switchgears, breakers and protection relays. In addition, concrete recommendations can be derived by the reliability assessment. The availability of low cost sensors, IoT technologies and advance data analytics is making the adoption of continuous monitoring system a convenient solution to support asset management for MV equipment. The performance model suggested in this paper can efficiently make use of additional condition monitoring data provided by continuous condition monitoring solutions to improve the accuracy of its outcome and to increase the number of potential failure modes that are actively monitored. In addition, the adoption of continuous monitoring solutions increases the understanding in the health status of the asset to the components level and gives additional information on the potential upcoming maintenance activities required.

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