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A Performance Model for Medium Voltage Equipment

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Abstract **– This paper presents a performance model for condition monitoring, diagnostics and prognostics of Medium Voltage (MV) breakers and switchgears. Scope of the performance model is to assess the current health condition, to predict the future health condition and, possibly, to provide indications about the cause of potential failures of MV equipment. The outcomes of the performance model are then meant to provide relevant information for any successful risk-based, condition-based and predictive maintenance strategy.**

The performance model presented in this paper is based on the concept of "competing" failure modes. 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. Finally, the performance model may be easily adapted to any kind of assets.

1. INTRODUCTION

In all industries, asset management is evolving rapidly due to the development of new technologies like low cost sensors, IoT (Internet of Things) and advanced analytics.

Asset management strategies have a strong influence on the asset maintenance policies. The asset management organizations have a wide spectrum of asset maintenance policies, ranging from basic policies like run-to failure or time-based preventive maintenance to more advanced policies like risk-based, condition-based and predictive maintenance. Focusing on electricity distribution companies and process industries, a clear trend towards extending the period between maintenance activities for medium voltage (MV) breakers and switchgears can be identified. According to [1], this leads to the need for asset condition assessment and for diagnostic and prognostic techniques to give confidence in the safety and reliability of the equipment.

This paper illustrates an innovative performance model for monitoring, diagnostics and prognostics of MV equipment. In the first part of the paper, the performance model is defined and the input data required by the model as well as its main outcomes are presented. A description of the general concept of the performance is then presented in the second part of the paper.

2. 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 [2]. In addition, the performance model provides information on the nature and causes of a potential failure so that recommendations and maintenance actions can be derived. According to [3], 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" [3], the performance model is, in other words, a mathematical model for condition monitoring, diagnostics and prognostics. This represents the foundation of any risk-based, condition-based and predictive maintenance policy.

B. Input data

Input data from different sources and of different types might be considered by the performance model for condition monitoring, diagnostic and prognostic purposes. The input data mainly depends on the nature of the asset, on the maintenance policies and strategies adopted by the asset management organization and on the specific industrial sector. Input data is necessary to build and validate the performance model as well as 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 five main categories:

1. Equipment data
2. Life and maintenance data
3. Application and operational data
4. Condition monitoring and test data
5. Environmental and exogenous data

An exemplary list of possible input data for MV breakers with some corresponding examples is illustrated in *Table 1*.

Table 1. Input data categories and examples for MV breakers and switchgears.

Category	Examples
Equipment data	Manufacturer, type, rating, production date, etc.
Life and maintenance data	Delivery date, installation date, maintenance date, maintenance actions, failure causes, failed components, symptoms, etc.
Application and operational data	Industry, application, owner, operator, location, breaker criticality, etc.
	Load, trip current, switching frequency, etc.
Condition monitoring and test data	Contact quality, travel time, vibration, etc.
	Integrity test data, etc.
Environmental and exogenous data	Temperature, humidity, pollution, etc.

C. Outcomes

As mentioned in the previous subsection, 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 2 have been identified as the main outcomes that the performance model must be able to assess.

Table 2. Main outcomes of the performance model.

Outcome	Description
PoF(t)	Probability of Failure within a specified period of time *t*
R(t)	Reliability within a specified period of time *t*
HI	Health Index
RUL	Remaining Useful Life
Risk(t)	Risk of failure within a specified period of time *t*
A	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 Reliability (*R)* "is defined as the probability that a product performs its intended function without failure under specified conditions for a specified period of time" [4]. According to their definitions, $R(t) = 1 - PoF(t)$. 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 (*Risk*) is the combined impact of the probability of failure and the consequences or criticality of that failure. The recommended Action (*A*) 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.

D. General Concept

The performance model proposed in this paper is based on the concept of competing failure modes. According to [5] a failure mode can be defined as "the way a piece of equipment fails or a description of what has failed to operate properly". Usually many failure modes can result (as effect) in the failure of an individual device or system, according to the relations among failure modes, effects and causes [6]. 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 [7]. 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. 1*. The failures modes considered here are taken from [8] and represent a comprehensive view of all possible failure modes that can lead to a failure of a MV breaker. Additional failure modes have to be introduced when a MV switchgear is considered. These additional failure modes are not reported in this paper.

According to the concept of competing failure modes, by knowing the failure mode reliability $R(t)_i$ of each failure mode *i,* for $i = 1, 2, \dots, n$, it is possible to determine the reliability of the product or system $R(t)$ by:

$$R(t) = R(t)_1 \cdot \dots \cdot R(t)_i \cdot \dots \cdot R(t)_n \qquad (1)$$

The failure mode reliability $R(t)_i$ is defined here as the probability that a product does not fail due to the failure mode *i* under specified conditions for a specified period of time. After determining the reliability $R(t)$, $PoF(t)$ can be easily determined as $PoF(t) = 1 - R(t)$. By knowing the $PoF(t)$ of the product and given the consequences of failure *C* it is possible to calculate the risk of the asset failure as:

$$Risk(t) = PoF(t) \cdot C \qquad (2)$$

By knowing the remaining useful life RUL_i of each failure mode i, for $i = 1, 2, \ldots, n$, it is possible to calculate the remaining useful life of the asset RUL as:

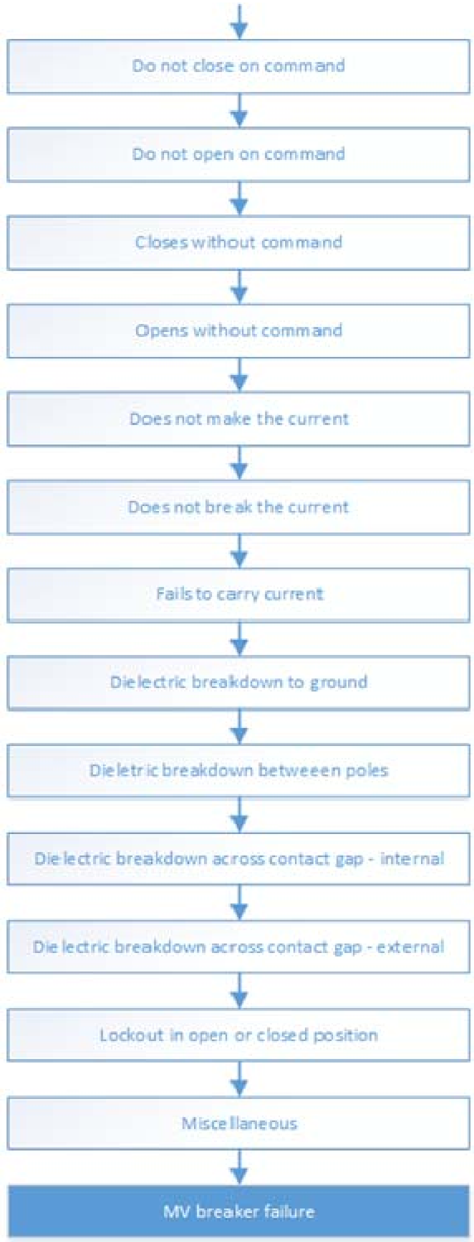

Fig. 1. Reliability block diagram for MV breakers as series of failure modes.

$$RUL = \min(RUL_1, \ldots, RUL_i, \ldots, RUL_n) \qquad (3)$$

The recommended action A is the action associate to the failure mode j characterized by the lowest remaining useful life RUL_j. In the performance model presented in this paper, based on expert knowledge, a recommended action A_i is associated to each failure mode i.

Finally, as illustrated in Fig. 2 (see figures at the end of the paper), by knowing:

- Reliability R_i
- Remaining useful life RUL_i
- Recommended action A_i

of each failure mode i and the consequences of failure C it is possible to assess all the outputs of the performance model as reported in Table 2.

Based on the input data listed in Table 1, the reliability, $R(t)_i$, and the remaining useful life, RUL_i, of each failure mode i can be assessed according to the algorithm illustrated in Fig. 3 (see figures at the end of the paper).

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 the failure mode i. Usually, the health condition is assessed by comparing the actual value of the monitored physical variables to some warning or alarm thresholds. Typical cases of physical variables monitored to assess the health condition of MV equipment are travel times, contact wear, temperature, vibration, and so on. By knowing the historical values of the health condition (i.e. the values of the health condition versus time for the actual product lifetime), it is then possible to determine the failure mode reliability, $R(t)_i$, and the remaining useful life, RUL_i, of the failure mode i, by applying advanced prognostic algorithms. An example is reported in [9], where the reliability, $R(t)_i$, and the remaining useful life, RUL_i, are assessed by applying a Monte Carlo simulation based on a statistical analysis of continuous condition monitoring data.

In the case that continuous monitoring data is not available, the probability of failure, $R(t)_i$, and the remaining useful life, RUL_i, can be assessed after determining the conditional reliability based on internal reliability statistics of the equipment manufacturer and the actual age and use of the MV breaker or switchgear.

The $R(t)_i$ 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 $R(t)_i$ is available, the $PoF(t)_i$ can be simply calculated as $PoF(t)_i = 1 - R(t)_i$. 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 assessed easily by the actual reliability of the product or system and can be expressed in different ways (i.e. integer value between 0 and 10, percentage value between 0% and 100%, and so on).

3. 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 reliability, probability of failure, remaining useful life, failure risk and recommended action, it represents the foundation of any 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 equipment knowledge and can be applied to any class of MV breakers and switchgears.

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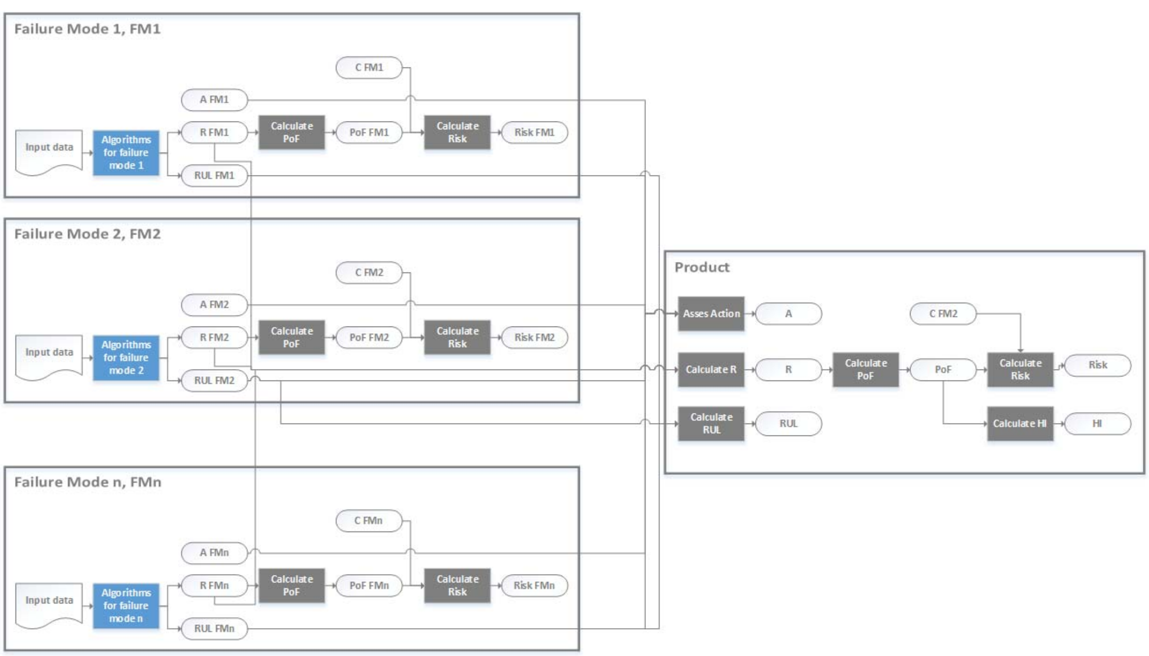

Fig. 2. Calculation of the outcomes of the performance model based on the reliability R_i, remaining useful life RUL_i and recommended action A_i of each failure mode i.

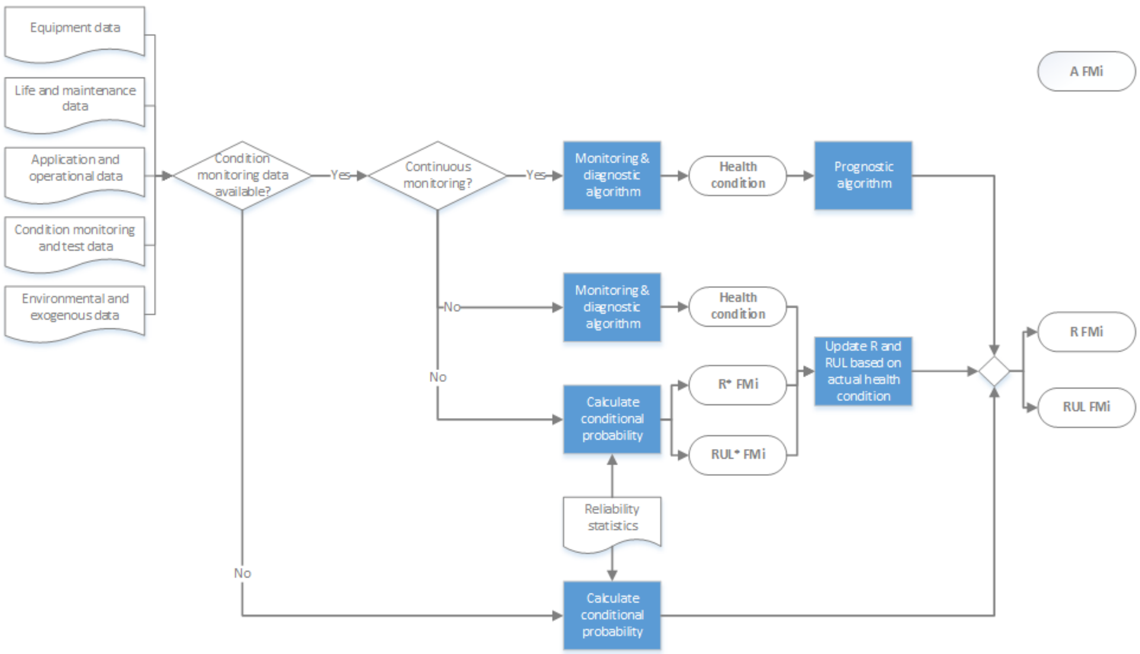

Fig. 3. Algorithm for the determination of the reliability R_i, remaining useful life RUL_i and recommended action A_i of each failure mode i.