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Methodological Framework for Implementation of a Prediction Reliability Model of IGBT Power Modules Used in Railway Applications

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***Abstract* — The control of critical electronic components reliability is one of the main issues in railway traction applications. Insulated Gate Bipolar Transistors (IGBT) modules are part of these components. They are subjected to high stresses due to severe conditions of use of the train. The increase of requirements in terms of reliability and safety imposes to be able to assess these dependability measures. This paper introduces a methodological framework for predicting reliability of IGBT based on an innovative and structured Bayesian approach.**

Keywords—IGBT power modules; Railway traction applications; Reliability prediction; Bayesian Networks

I. Introduction

The world of electrical railway traction has undergone profound changes in recent decades with the emergence of power electronic modules components made of Transistors IGBT (Insulated Gate Bipolar Transistors). IGBT modules are power switching components equipping converters. They play a very important role in the conversion of the electrical energy captured by the train in a form of energy needed by motors, and this transmission of energy allows the train to move.

The harsh environmental conditions encountered in railway operation and the stringent requirements in terms of system availability and maintainability impose high reliability levels to IGBT modules. The key issue of the proposed work is related to the improvement of the reliability prediction of IGBT modules.

Railway operators are today facing with the lack of failure rate models during useful life of the IGBT. In the first instance, the failure rate is assessed based only on previous experience feedback; this gives an idea of the operational reliability. In the second instance, the lifetime is calculated taking into account only failure mechanisms due to thermal cycling stress specified at early design stages. This last calculation does not give a good visibility related to the real life of the component because it contains a lot of variability and uncertainties.

A methodology is proposed in this paper to assess the reliability of IGBT modules, allowing, on the one hand, to take into account all known failure mechanisms and, on the other hand, to characterize and quantify all existing uncertain data by a probabilistic approach based on Bayesian techniques.

II. State of the art on IGBT module reliability

IGBT modules illustrated in Figure 1 are power semi-conductor devices providing switch function [3]. Used in traction applications, they combine high efficiency and fast switching. Designed to operate under continuous or alternative networks, they cover a wide range of voltage (1700 to 6500V) for currents up to 3600A.

Fig. 1. IGBT power module package

The introduction of IGBT modules in railway traction converters allows a reduction of their volume and weight, a better modularity and a simplification of their circuit diagrams. Some packages as shown in Figure 1 are designed according to a multi-chip configuration involving several materials [3]. Figure 2 presents the structure view of IGBT modules, structured around their electrically active components. The latter are silicon-based power chips. They are mounted on insulating DBC (Direct Bonded Copper) substrates made of a ceramic insulator, alumina or aluminum nitride attached with pure copper.

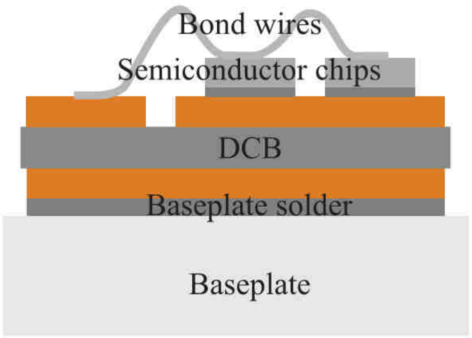

Fig. 2. Cross sectional geometry of IGBT Module [15]

Bond wires in top of chips ensure electrical connection with them. All the constitutive materials of IGBT Modules have to maintain good thermal conduction capabilities, high electrical insulation properties, and high mechanical stability.
Due to the difference of properties of materials inside and the stresses induced by the railway environment, IGBT modules are subjected to different failure mechanisms that can induce failure and affect greatly their reliability.

In railway traction systems, IGBT modules are facing many requirements: hold high voltages when they are blocked; have a low voltage drop while they are on; switch fast with a minimum of switching losses; exhibit high robustness; operate over a wide temperature range; endure high thermal cycling. In addition, the requirements for 30 years and over of fault-free operation lead to undergo lots of works to improve the reliability of IGBT Modules. Different programs have been devoted to the reliability and lifetime prediction of IGBT Modules. LESIT program (Leistung Elektronik Systemtechnik Informations Technologies) [20] leads to the definition of the power cycling accelerated test and life prediction method for IGBT modules used in railway traction. RAPSDRA program (Reliability of Advanced Power Semi-conductor Devices for Railway traction Applications) [4] extended the power cycling accelerated test to the solder joints reliability. PORTES (Power Reliability for Traction Electronics) [33] uses physics of failure with the aim of predicting their lifetime. Other works also have been undertaken especially [21], [25] to forecast the lifetime of IGBT Modules.

The main particularity of these studies is the fact that they take into account only thermal cycling. The first research question is then addressed: what is the impact of other failure mechanisms on the reliability of the IGBT?
Response surface methods coupled with finite element analysis also are used to assess the reliability of power electronic modules [2], [7]. These methods aim at approximating the function of failure through its assessment at different points in the region followed by a regression over these points. The knowledge of the function of failure is required for the method to be adequate. This constitutes a limit for failure mechanisms that are not nowadays quantified mathematically. It is then difficult to use this method to quantify them. The second research question is then addressed: how can we deal with failure mechanisms that are not mathematically quantified?

All these studies rely on a lot of assumptions, uncertainties and variability. For example, different criteria of failure result in different values of lifetime predicted. This introduces the third research question: how these uncertainties could be quantified?

To answer all these previous questions a probabilistic approach is proposed. It allows the assessment in terms of probability of all known failure mechanisms, the quantification of uncertainties and the assessment of the impact of each failure mechanisms on the reliability. The model will be implemented with Bayesian networks.

III. Proposed Framework Methodology

Currently, it is difficult to collect data on the evolution of the operating variables directly at IGBT level. This leads to carry out analyses at different levels. The proposed work is then integrated into a new approach that we will refer to as the "U" cycle illustrated in Figure 3.
These analyses are prior to the implementation of the Bayesian model.

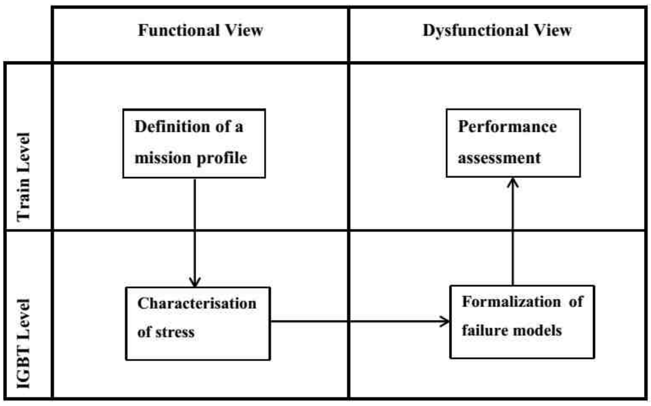

Fig. 3. Proposed cycle in "U"

Functional view consists of knowing the functions realized by the system or the component in its direct or indirect environment. The dysfunctional view is used to complete the first one in order to take into account the possible operating drifts or abnormalities.

A. Functional view: Train Level

The performance of a component can be characterized by the performances both related to the component itself but also to the system to which it belongs. The operating of IGBT modules greatly depends on the environment performance of the train. Train level functional view consists of defining a mission profile to characterize the set of relevant conditions in which the train works. The analysis allows the definition of train operational variables (voltage, speed), environmental variables related to the itinerary of the train (vibration frequency, shock frequency, total distance covered, absolute altitude above sea level between start station and end station), environmental variables related to climate (ambient temperature, ambient humidity, ambient air pressure), operational requirements (in service operation mode, out of service mode, stop/stations), operation phases (start, acceleration, braking).

B. Functional view: IGBT Level

IGBT Modules perform the following functions [3]:

- Cut the current: the modules consist of the active elements which are the semiconductor power chips which perform the electrical function of the module.
- Evacuate losses; the substrate allows the evacuation of losses dissipated in the chips. The transfer of losses is done through the baseplate.
- Isolate the chips: the isolating substrate DBC (Direct Bond Copper) allows the electrical insulation between the potential at the chips level and the potential at the cooler level.
- Connect components: chips are connected to the external environment by bond wire. Substrate acts as a mechanical support for electrical connections.
- Protect components: the module is protected by a packaging adapted to the electrical connections. A silicone gel is generally added to avoid the appearance of electrical arcs and to protect the module from impurities.

This analysis includes also translating the mission profile of the train into a mission profile of the IGBT. The mission profile of the IGBT is not that of the train for functional and architectural reasons.

C. Dysfunctional view: IGBT Level

From the knowledge of the stresses undergone by the component, it is necessary to determine the level of resulting damage. This damage is quantified in terms of cumulative fatigue or strain for example. This analysis includes the definition of stress (thermal, electrical, hygrometric, mechanical…) associated with each elemental phase of the train mission profile. It consists also in defining intrinsic behaviour laws and deterioration thresholds by using Physics of failures. All information about failure modes, causes, mechanisms, and effects are gathered through this analysis.

The IGBT power modules undergo various failure mechanisms that may be related to their operating conditions or their environment. The causes of faults can be due to [13]:

- constraints applied to the component during its normal operation (voltage, temperature swings, environmental stress, vibration, shock ...); these causes are called external. It is also referred to as degradation or ageing mechanisms and may force the component to operate outside its safety area.
- defects of the component arising from errors in the manufacturing processes, bad quality of the raw material (malformation of the gate oxide, defects in the purity of the silicon crystal, Packaging) and poor controls. They are known as mechanisms of strong ageing.

The state of the art identifies about twenty failure mechanisms that lead to failure of IGBT modules. Some of these failure mechanisms have been deeply investigated in the literature and lifetime models have been developed. Others are identified but no model exists yet.

For instance, the bond wire lift-off represented in Figure 4 is one of the failure mechanisms of IGBT modules well studied [12], [19]. It is due to thermal cycling and the mismatch of CTE (Coefficient of Thermal Expansion) between materials composing the chips and the bond wire.

Accelerating tests had been investigated to model the lifetime of IGBT modules submitted to these failure mechanisms. As results, Coffin-Manson laws [18] model the number of cycles to failure N_f as (1):

$$N_f = A\,\Delta T^{-n} \tag{1}$$

where A and n are parameters obtained after regression of experimental data.

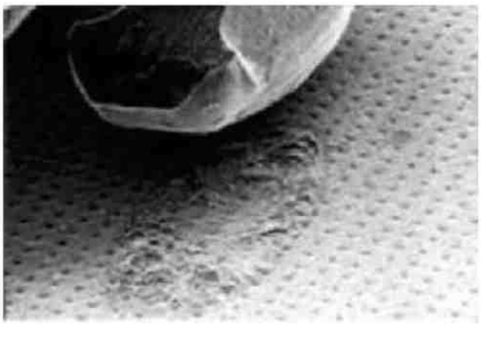

Fig. 4. Bond wire lift-off [18]

Other failure mechanisms encountered in IGBT modules are: bond wire crack [11],[19], reconstruction of metallization [18], corrosion [19], solder fatigue [31], electromigration [23], cristal defects [22], long term DC stability due to cosmic rays

[1], [6], [10], latch-up [32], vibration, mechanical shock, Time Dependant Dielectric Breakdown (TDDB) [8], Hot carriers [28], Ion contamination [28], brittle cracking, crack in the packaging, electrochemical migration [40], static avalanche [14], dynamic avalanche[14].

All these failure mechanisms will have to be considered in the model.

D. Dysfunctional view: Train Level

This analysis allows the assessment of the impact of the IGBT failure probability onto the train performance. It consists in aggregating all information from analyses, combinations and interpretation of performance according to the stresses measured at each level of the system nomenclature. The aggregation of the information on the use of the train, its impact on the operation and the dysfunction of the IGBT, will feed the model.

IV. Bayesian Network Modelling

Bayesian Networks formalism is used to model complex systems, [35], [36], [37], [38], [39] through graphical representation [17] and reasoning with complete or incomplete data. They provide a way for integrating data from various sources and generate a coherent interpretation of that data.

A. Definition and semantics

Bayesian networks are probabilistic graphical models used to represent knowledge about a complex or uncertain system. The nodes in a Bayesian graph represent random variables and arcs the existence of direct relations between them. The nodes may contain a description of the variables in the form of probability distributions functions, probability tables or deterministic equation of parent's nodes. In the case of probability tables, one could distinguish prior probability tables for root nodes and conditional probability tables for nodes with parents. The links may represent the influence or causal relationship between variables. Figure 5 shows an example of a risk bayesian network used for PSS (Public Safety and Security) mobile [42]. Its consists of fives nodes such as Trigger, Control, Event, Consequence and Mitigant and their relationships .Bayesian networks greatly relies on probabilty theory. The semantics of Bayesian networks allows the assessment of the joint probability [24] as (2):

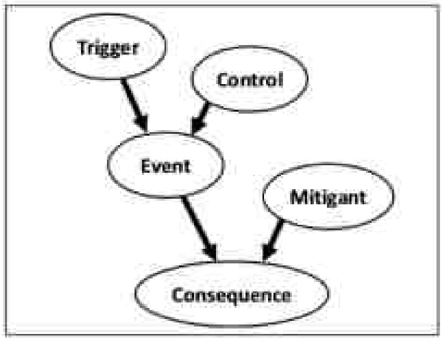

Fig. 5. Example of bayesian network [42].

$$P(X_1, X_2, \dots, X_n) = \prod_i P(X_i | Pa(X_i)) \quad (2)$$

where $(X_1, X_2, \dots X_n)$ are the variables contained in the graph and $Pa(X_i)$ are the parents of X_i.

Knowledge represented by Bayesian networks can be obtained from experience feedback, observations, expert's judgements, manufacturer's documents. The principle of Bayesian networks is to introduce information or observations in the network that spreads and updates the probability associated with each variable [35]. Bayesian networks are used to answer probabilistic queries [5], [9], for example update the knowledge of the state of a variable when other variables are observed. This process is called inference [5] and consists in computing the posterior distribution of variables given evidence.

The modelling with Bayesian approach relies on three main steps [41]:

- Descriptive step describing all interesting and influential variables of the system.
- Structural step setting up the graph of the Bayesian model.
- Relational step allowing the determination of CPT (Conditional Probability Tables) for each variable.

Learning approaches may be used to determine the internal structure of a system either by identifying interactions between its components known as structure learning; or by determining the strength between them known as parameter learning [38].

Bayesians networks have been extended in other to model continuous and time dependent variables (Dynamic Bayesian Networks) [16]. Dynamic Bayesian networks may be used to take into account temporal dimension in the model.

B. Deployment of the Bayesian approach for train system reliability assessment

The translation of the knowledge gathered from different analyses through the previous proposed "U Cycle" based methodology will help feeding the Bayesian model presented in Figure 6.

The proposed modelling follows the same steps as the implementation of a Bayesian model.

Step1: Identification of variables

Each relevant condition of the mission profile at the train level will be represented by a variable in the network for example ambient temperature, ambient humidity, voltage, altitude, train speed, vibration frequency, shock frequency. At the component (IGBT module) stress level, the identified variables have a potential influence on the appearance of failure mechanisms on IGBT modules.

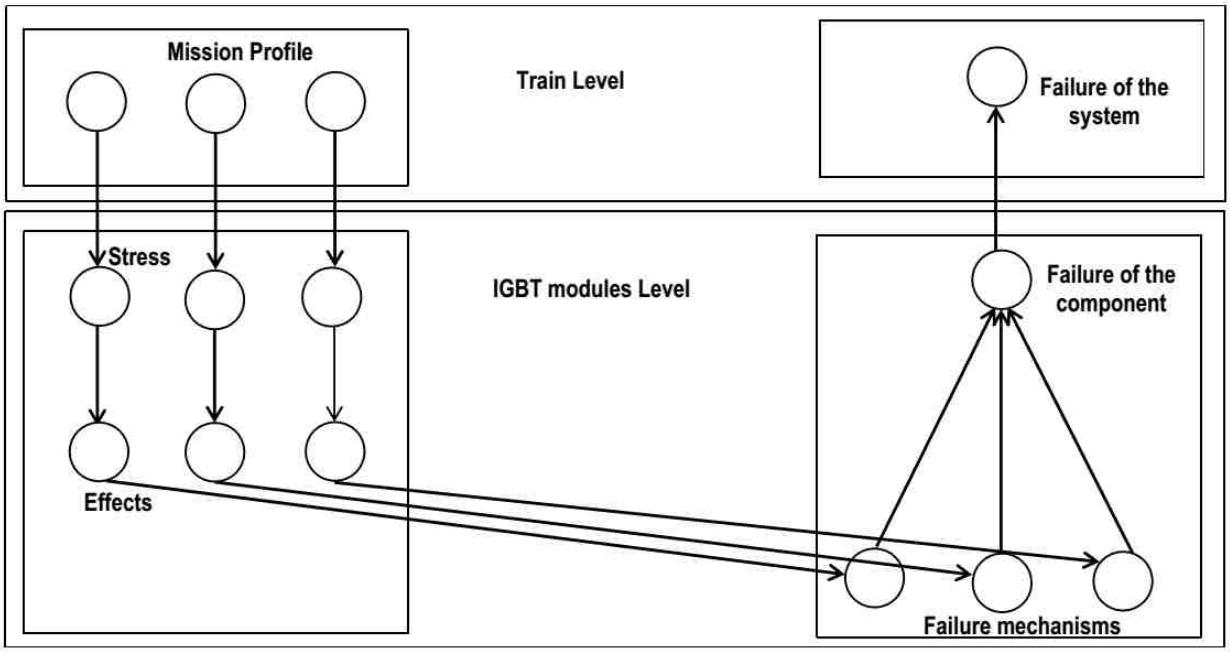

Fig. 6. Bayesian model of IGBT reliability

The influential parameters identified through the dysfunctional view are: temperature, temperature swing, current, voltage, current covered by wire bond, vibration frequency, and shock frequency. The effects represent the damage cumulated by the stress. The known failure mechanisms identified by the previous analysis are described by introducing the corresponding variables in the model. The failure at the component level and the failure at the train level are also represented by a node in the model.

Step 2: Implementation of the Bayesian graph

The previous proposed methodology allows not only the identification of variables but also the establishment of causal relationships between them. Relationships are represented by links in the graph. The links between the variables at Train level and IGBT module level characterize the breakdown structure and establish the connection both on the functional and dysfunctional views. The links between failure mechanisms and the failure of the component permit the computation of the probability of failure due to one or all failure mechanisms identified.

Step 3: Determination of probability tables

Supervised learning techniques consisting in learning parameters from a given structure (the variables of influence are already known) may be also used to identify the various CPT (Conditional Probability Tables).They can be expressed through analytical expression characterizing the behaviour laws or when there is a lack of knowledge by expert judgement. This a priori knowledge will be progressively completed by experience feedback.

The model assesses the reliability both at IGBT and train levels. This transition is made by aggregating all informations combinations, and interpretations of performances over the time. It also considered elementary components, subsystems and finally system according to the characteristics of each level of decomposition.

V. Conclusions

A conceptual framework has been proposed in this paper to set up a prediction model of complex systems made of various modules with distinct nomenclature levels. It results in different analysis relying on a new methodology called "U-Cycle" associated with the analysis of functional and dysfunctional behaviors on different levels of a system breakdown structure. This methodology is implemented onto a train system and deployed down until its elementary components and in particular onto IGBT modules. After having described the functional and dysfunctional parts both at train and IGBT levels a modelling approach based on the use of Bayesian network has been introduced with the goal to predict the reliability of railway systems.

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