Towards Self-aware and Environment-aware Power Converters

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ABSTRACT

This paper develops the vision of power converter as a sensor for D&P (Diagnostic & Prognostic) of electrical energy systems. Such power converter would rely on available on-board intelligence & sensors. The converters are capable of monitoring components within the converters themselves, i.e. self-awareness and also the systems to which they are connected (e.g. motor, cables…), i.e. environmental awareness.

This vision is supported in this paper by an analysis of the literature. For a selection of components and systems prone to failure, key methodological steps are outlined. They include analysis of failure modes, of their cause and consequences. Then, stressors and precursors to failure are listed in a context of observability at the converter level. Means for processing this measurable data and extracting the useful information such as state of health, remaining lifetime and fault location are exemplified.

1. INTRODUCTION

Power Converters are nowadays used in a multitude of application from mW (e.g. energy harvesting) up to GW (e.g. HVDC energy transmission). Their primary function is to control and shape the electrical energy. They constitute the intelligent part of electrical energy systems, by including sensors (e.g. voltage, current, temperature), actuators (e.g. power semiconductor devices) and intelligence (e.g. micro-controller) as presented in Fig. 1. This hardware architecture is often valorized to provide secondary functions. This existing hardware architecture make them good candidates for embedding additional features benefitting the performances of the whole energy system, at a controlled cost.

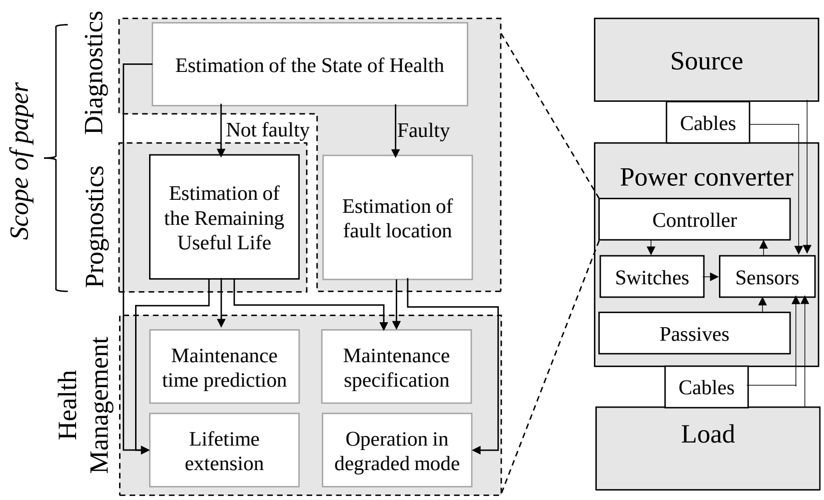

Figure 1. Illustration for the self-aware and environment-aware power converter

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Performance is typically defined in terms of cost, availability, efficiency, volume or mass, with different weights according to the application. In a life-cycle approach, cost and availability can be improved with Condition-Based Maintenance (CBM). Maintainability imposes several requirements on the product design (e.g. dismounting), and needs to be supported by a circular business model. The most important technical challenges are Diagnostic and Prognostic (D&P) technologies to estimate and indicate the State Of Health (SOH), the Remaining Useful Lifetime (RUL), and perform fault location as illustrated in Fig. 1. Operation in degraded mode and lifetime extension are additional health management features enabled by D&P technologies. In this paper, the following definitions will be used:

- Diagnostic: estimating the state of health (e.g. healthy, degraded, faulty…), and the location of the degradation.
- Prognostic: predicting the time and type of future faults

Prognostic is closely linked to diagnostic in that state estimation is required prior to state forecasting. With D&P technologies, maintenance could be anticipated, predicted, and improved.

Power converters, as heterogeneous electrical systems handling high power densities, are subject to high electro-thermal constraints, and can be subject to reliability and robustness issues. For example, it is reported in (Spinato et al., 2009) that electrical system failures account for up to 30% of the total failures, most of them concerning the power electronic converters. A self-aware power converter would be able to auto-diagnose and predict failure of its most critical active and passive components such as power semiconductors and capacitors. Beyond that, the power converter is electrically connected (e.g. with cables) to other devices classified in sources (e.g. photovoltaic panels) and loads (e.g. motor) as in Fig. 1. These components are generally passive in that they do not contain sensors, actuators and intelligence, and they rely on the power converter to manage their operation. An environment-aware power converter would be able to diagnose and predict failures of the devices it is directly or indirectly connected to.

This paper organizes and presents the scientific researches on D&P that contribute to the vision of self-aware and environment-aware power converters. The D&P method and reachable performances depend on the considered component, and failure mode. For instance, when considering the random electrical failures of an integrated circuit, the state of health is binary (operational or faulty). When considering the wear-out electrolytic evaporation of a capacitor, the evolution of precursors to failure can be monitored and the state of health can be evaluated more finely. Prognostic can be performed based on stress-based models (e.g. estimation of the evaporation based on the time spent at certain temperatures) or condition-based methods (e.g. evolution of the measured precursor to failure). This paper is organized by critical internal (i.e. power semiconductors, capacitors, converters) and external (i.e. cables, motors) components. For each, the major failure modes are described, and a selection of D&P methods (including condition monitoring) are classified and examples are given. Overall, this paper presents the most popular types of D&P methods, and the reader will understand that a method presented for a component may be adapted to another component.

2. SELF-AWARENESS: D&P OF THE INTERNAL COMPONENTS

2.1. Power modules

Power modules include several power semiconductors, terminals, thermal conducting and insulation material. Some power modules called IPM (Intelligent Power Modules) also integrate gate driving and protection circuits. Power modules are one of the critical building blocks in power converters because they are active component switching at several kHz to control high voltage and high current. Power modules are designed in a multi-layer structure as shown in Fig. 2 where reliability is ensured by a proper thermomechanical stability, heat dissipation capability and isolation.

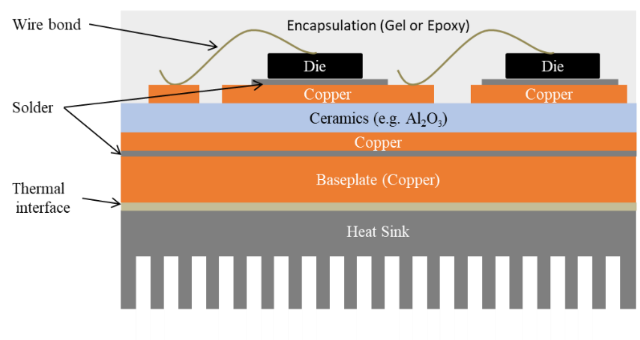

Figure 2. Illustration of the structure of a typical power module

Failure modes of power modules are categorized using famous bathtub curve such as, early failure, random (or incidental) failure and wear out failure (Mitsubishi Electric, 2019a). Table 1 summarizes the major failure modes and root causes.

Table 1. Summary of major degradation mode of power module

Failure Mode	Problem Classification	Diagnostic Method
Early	Electrical screwing issue	--
	Mechanical screwing issue	Measure initial junction-to-case thermal resistance
	TIM issue	“
Random (incidental)	Cosmic ray	--
	Gate signal issue (overvoltage, ESD)	--
	Short-circuit failure	Adding short-circuit detection circuit
Wear out	Thermo-mechanical stress	Stress counting
	Wire bonds lift off	Measuring electrical resistance
	Wire bonds heel-crack	„
	Metallization degradation	Measuring sheet resistance
	Solder degradation	Measuring thermal resistance
	Time dependent dielectric break-down	Measuring gate leakage current
	Humidity	Measuring leakage current between C-E (or D-S)

The early failure mode is mainly related to semiconductor process-induced failure or module manipulation error. Nowadays semiconductor process-related failures are almost eliminated thanks to the state of the art quality control of the commercial products. Application notes (Mitsubishi Electric, 2019b) provide guidelines for screwing and choosing TIM. In random failure modes, the main root cause is considered as single event burnout (Titus, 2013), especially in high voltage devices. The only way to avoid this effect is to reduce the internal electric field strength, i.e. de-rating of the applied voltage (Lichtenwalner et al., 2018). Other than that, one may face some failures during operation. However, it is more often related to the overvoltage, overcurrent or overheating due to the improper design of the circuit, cooling system or failure of the other components connected to the module (e.g. short circuit in the load, high speed switching with large stray inductance…). Wear out failures are considered as the unavoidable end of life of the module. The main failure mode of wire-bonded power module (Fig. 2) is considered as wire bonds lift-off or heel crack. Both of them increase the internal resistance of the current path and finally lead to the catastrophic failure of the module (Ciappa, 2002). In addition to that, we can often see the degradation of electrodes of semiconductor dies (Ciappa, 2002), as well as die solder degradation or the base solder layer degradation (Lutz et al., 2011). There, all degradation mechanisms are originated from thermo-mechanical stress.

Several testing methods are used to accelerate those degradation modes. Power cycling is a popular method to trigger wear-out failures and estimate the lifetime of modules. It accelerates the thermomechanical stress on the wire bonds and die solder by applying the cyclic loss generated by DC current or PWM operation (Choi et al., 2018; Degrenne & Mollov, 2018). Several research indicate that lifetime model depends on the maximum temperature of the die, temperature swing of cycles, on-duration and current density (Bayerer et al., 2008).

As we know the degradation mechanism of the power modules, it may be possible to estimate or forecast the lifetime of the modules depending on the usage.

At present, power cycling lifetime is mainly discussed. Main diagnostic methods are summarized in Table 1. The traditional way to estimate the state of health is to use stress counting method, like rainflow counting algorithm. In this case, the temperature is monitored during operation and the temperature swings equivalent to thermo-mechanical stress on the wires are extracted. Since the several electrical parameter of power semiconductor are temperature dependent, various methods are proposed to monitor temperature based on TSEPs (Temperature Sensitive Electrical Parameters). The review on several TSEPs are summarized in (Avenas et al., 2012).

Alternatively, the degradation extent can be estimated by measuring DSEPs (Damage Sensitive Electrical Parameters). For instance, electrical resistance or on-state voltage V_{on} at a given current is widely used, because it is directly related to the resistance increase due to the crack propagation of wire bonds and degradation of surface electrode on the dies. However, in general, semiconductor has a non-linear and temperature dependent characteristics. So a calibration is necessary to isolate the impact of degradation from other dependences. At the same time electrical sensor should withstand high voltage as well as have good precision at the low voltage region. For the on-line monitoring, several voltage sensors are proposed (Degrenne and Mollov, 2019). The other parameter is thermal resistance or impedance, this is related to the degradation of heat dissipation path, in other words, degradation of die attach, baseplate solder or TIM. Thermal resistance is calculated from the temperature difference and dissipated power.

Relating DSEPs to SOH is another technical challenge. Ideally, the relation should be based on PoF (Physics of Failure), in other words, degradation mechanisms modeled by physical (or structural) parameters, which cannot be measured during testing. In (Degrenne & Mollov, 2018a), DSEP and SOH is related through modeling of resistance increase based on the sum of crack length of wire and linear increase of the resistivity of the metallization. Once DSEP is related to structural parameters, it is possible to integrate the effect of mechanical stress into electrical parameter more accurately.

Prognosis of power modules can be achieved by extrapolating the SOH. Traditionally, RUL (Remaining Useful Life) of power module can be estimated using stress counting method and given power cycling lifetime curve. However, as aforementioned, power cycling lifetime depends on many conditions. The empirical models and methods established during accelerated ageing are difficult to extrapolate and validate to field operation (Dornic, 2019). Thus it is necessary to correct the estimate using other measureable parameters, such as DSEP. Several pioneering research has been published (Celaya, 2010; Degrenne & Mollov, 2018b; 2019), however, even in the state of the art research, it is hard to forecast the precise mission profile of individual application. The estimation of mission profile may be a key technique to estimate the reasonable RUL.

2.2. Capacitors

Next to power modules, electrolytic (EL) capacitors are amongst the major component prone to fail in a power converter. Despite their intrinsic weaknesses they remain massively used for their low cost and high power density. Their major stressor, source of ageing, is the temperature which accelerates the wear out due to drying out of electrolyte. Electrolytic capacitors usually present some ageing signs before failure, except for random, thus unpredictable failure. Main sources of failures are: over-voltage, over-current (ripple creates self-heating due to internal ESR (Equivalent Series Resistance)), or assembly issues (weak screwing, over-heating during soldering process, mechanical damages due to improper handling, reverse polarity, etc). Most of these latter problems can be avoided by ensuring proper quality during manufacturing process. In this we focus here on unavoidable ageing of EL capacitors and associated D&P methods.

Table 2. Summary of major failure modes, limited to electrolytic capacitor type (Gupta et al., 2018)

Root cause	**Major Failure Mechanism**	**Major Failure Modes**
High Ambient Temperature	Electrolyte evaporation: increase in pressure inside the capacitor	Capacitance loss, ESR increase; vent opening in case of excess internal pressure
Over Voltage Stress	Degradation of oxide film, anode foil capacitance drop	Increased leakage current flow, capacitance loss, ESR increase
Excess Ripple Current	Electrolyte evaporation	Capacitance loss, ESR increase
Continuous Charge/Discharge Cycle (Pulsed Discharged)	Cathode foil capacitance decrease due to formation of additional dielectric layer; electrolyte evaporation	Capacitance loss, ESR increase; vent opening in case of excess internal pressure due to gas generated during oxide layer formation

2.2.1. Diagnostics of electrolytic capacitors

During ageing, the ESR increases while the capacitance C decreases. Monitoring the evolution of these precursors of failure is the basis of many studies to determine the SOH of capacitor. The goal is to detect the end of useful life before potentially catastrophic failure (explosion for instance due to excess internal pressure as a consequence of thermal over-heating). Globally the diagnostic aims at detecting that at least one of the ageing sensitive parameters of the capacitor has evolved beyond a threshold value with respect to its initial healthy state. This is the case for instance when capacitor has lost 20% of its initial capacitance, or ESR has been multiplied by a factor two with respect to initial ESR value. The exact value of the threshold is of course dependent of the type of component considered (limits given by manufacturer for safety), and of the application (degradation of desired function). Appreciation of the current SOH, or reciprocally degradation level, of capacitor is determined by the diagnostic algorithm (100% lifetime at beginning, 0% when C_{EOL} (end of life) is reached for instance).

Many capacitor diagnostic methods, including condition monitoring, are available in the published literature. We present thereafter an overview of a few popular methods applicable in the context of self-diagnostic of the converter i.e. that can be evaluated by the converter itself, a summary of these methods can be found in Fig. 3

The simple model of a capacitor composed of ESR and C in series is often used for identification of actual capacitor parameter. With the knowledge or estimation of capacitor's current, it is possible to estimate its impedance, or to more or less directly determine the internal parameters (ESR, C). The problem of the identification of these parameters can be addressed by many different methods. For observer based methods operating in time domain, different algorithms such as RLS (recursive least squares), Kalman filter, etc, can be used to adjust the parameters. Alternatively, ESR & C can also be estimated by considering the impedance of capacitor in a range of frequency (typically low frequency for estimation of C, where impedance is dominated by capacitive effect and at higher frequency for estimation of ESR, near the resonance frequency of the capacitor, usually close to the switching frequency or of one of its harmonics).

Other methods rely on the study of the charge or the discharge of capacitor (integration of capacitor current) or study of ripple (HF ripple proportional to ESR, or low frequency ripple more related to capacitance value).

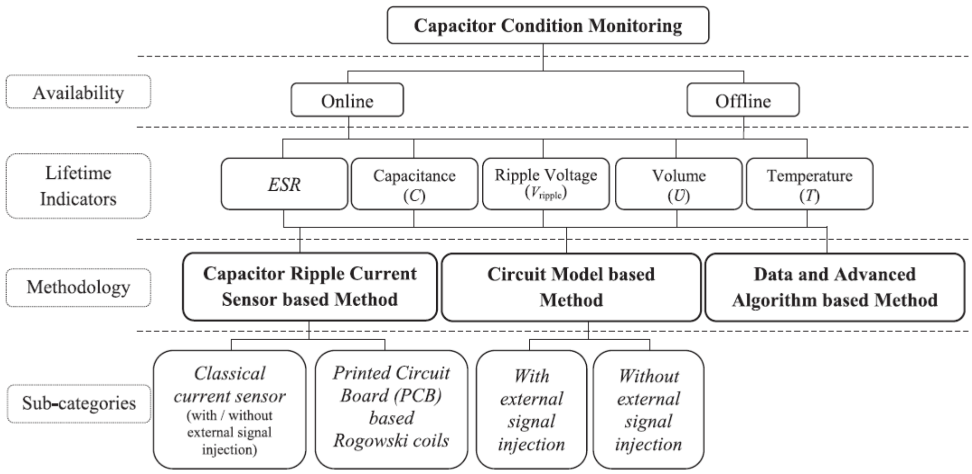

Figure 3. Classification of capacitor condition monitoring technology and their indicators, (Soliman et al., 2016).

In (Soliman et al., 2016) the authors present a classification of capacitor condition monitoring technologies and a significant number of references. Following this classification, methods are either “online” or “offline” depending on availability, i.e. when and how it is possible to proceed to diagnostic. “Online” designate normally methods that operate during normal operation of converter, ideally non-intrusively i.e. by creating a minimum of disturbance. Note that the term “offline” here might be called “pseudo-online” to designate methods requiring a particular operating condition of converter to operate, in opposition to true “offline” terminology reserved for methods implying the test of capacitor outside the converter (using impedance analyzer for instance).

The authors distinguish the following lifetime indicators: ESR, capacitance, the ripple voltage (subject to increase with ageing). We could also add the estimated volume of electrolyte and the capacitor’s temperature (at a given current ripple, the self-heating of capacitor due to ESR losses increases with ageing).

The authors propose to classify the methodology in three main categories, by descending number of publications: capacitor ripple current sensor based method, circuit model based method (equation based, using existing sensors to estimate capacitor current, such as for instance in (Wechsler, 2012)), data and advanced algorithm based method (machine learning, support vector machine, artificial neural networks, Particle Swarm Optimization-Based Support Vector Regression, etc). For this latter class of methods, different features of system might be analyzed together to provide information on the SOH of the system. For instance, the level of a particular DC bus voltage harmonic, combined with output current, DC bus ripple level to finally derive the capacitance state. This kind of algorithms typically require some training phase to learn the state of the system, i.e. what distinguishes a healthy from an aged state. A few examples of such methods can be found in (Abo-Khalil et al., 2019), (Soliman et al., 2017), (Wang et al., 2017), (Abo-Khalil, 2012), (Hammam et al., 2015) for instance.

Capacitor ripple current sensor based method ((Venet et al., 2002), (Foube & Mollov, 2017)) can be further classified in two sub-categories depending on current sensor type, for example Rogowski based (Vogelsberger et al., 2012), and methods creating artificial disturbances to perform diagnosis (voltage or current injection). First sub-category typically performs analysis based on naturally present disturbances (harmonics created by rectifier, or by commutations of switches for instance). The second one typically creates disturbance that can be more easily analyzed because of its particular frequency (and sufficient amplitude) that can be distinguished from other disturbances caused for instance by grid unbalance, control sub-harmonics, etc.

Similarly, circuit model based method might be further divided according to the use or not of signal injection. Some data and advanced algorithm based methods might be similarly classified: for example with signal injection (Abo-Khalil, 2012), or without like in (Hammam et al., 2015).

Note that localization of fault (degraded capacitor) depends on monitoring method. Indeed, with capacitor ripple current sensor i.e. “individual” monitoring, it is possible to determine accurately the SOH of a particular component and thus to locate it. Alternatively, global monitoring of parameter of a bank (without individual capacitors’ current sensors) does not allow localization of particular faulty component, but rather detects an averaged ageing state of the whole bank.

2.2.2. Prognostics of electrolytic capacitors

The goal of prognostics is to estimate the remaining useful life of the capacitor. We present thereafter a short overview of a selection of prognostic methods.

In (Kulkarni et al., 2013) the authors perform prognostic by using a stress-based model (physics based degradation model used for estimation of the evaporation based on the time at certain temperatures). This supposes to estimate the evaporation rate of electrolyte, determine the initial volume of electrolyte as well as a few other parameters. The model parameters are then further adjusted by using real data obtained from accelerated ageing tests.

Other methods rely on empirical models (e.g. Arrhenius based lifetime model). Their main advantage is the simplicity. However, these are based on population statistics and are not expected to be very accurate for a particular capacitor.

Other authors, e.g. (Abdennadher et al., 2010), use condition-based methods for prognostics (evolution of precursor to failure, i.e. ESR or capacitance). The prediction of the future evolution of the trajectory of C and ESR as function of time allows to determine with some uncertainties the remaining useful lifetime. This kind of method is investigated in (El Hayek et al., 2018).

In (Rigamonti et al., 2016) the authors develop a Particle Filter-based (PF) prognostic model for the estimation of the remaining useful life of aluminum electrolytic capacitors, working under variable operating conditions. The ageing parameter monitored is the variation of ESR adjusted to be independent of temperature.

2.3. Converter-level approaches

During the last few years, the advancement in the field of semiconductors have led to the improvement of the conversion efficiency and the control of the electrical power together with a reduction of the cost of the power systems, resulting in an increase of power electronics converters in various industries (power transmission, renewable power generation, automotive, motor drives systems, uninterruptible power supply (UPS),etc.). However, power electronics converters still suffer from a relatively high failure rate, this in one of the reasons why research in effective CBM system for power electronic converter is currently of high interest. CBM new technologies are continuously improving thanks to the increase knowledge of the ageing mechanisms (before complete failure) of power components and the development in sensor technologies and signal processing.

Reliability-critical components are integrated in a power electronic converter, which constitute a system assembly. D&P at system level either complements the approaches at the component level (e.g. by detecting/generating D&P instants/sequences), or permits implementation of specific D&P methods. Each converter type and application have particularities. It is impossible to address all converters in this paper, as a result on the following section the HVDC (High Voltage Direct Current) converter is proposed as an example.

HVDC systems are worldwide increasingly deployed and represent an essential part of the electricity grid. They assure bulk power transmission over long distances and connection between the offshore wind farm and the onshore grid with quality and reliability. The HVDC transmission system is critical as any loss of the link can lead to forced outage or even the black-out of part of or the complete electricity grid. In that context, HVDC converter stations need to be monitored.

Most HVDC converter stations consist of a Voltage Source Converter (VSC) based Modular Multilevel Converter (MMC) with cooling and auxiliary components. The typical structure of a three-phase MMC is presented in Figure 4(a) and includes six arms (two arms per phase), and each arm is composed of N submodules (typically in the order of hundreds) and one arm inductor Ls. Each submodule is composed of two (or four) IGBTs connected in series and one capacitor. Figure 4 (b) shows the ith half bridge submodule of the upper arm of phase A composed of two IGBTs..

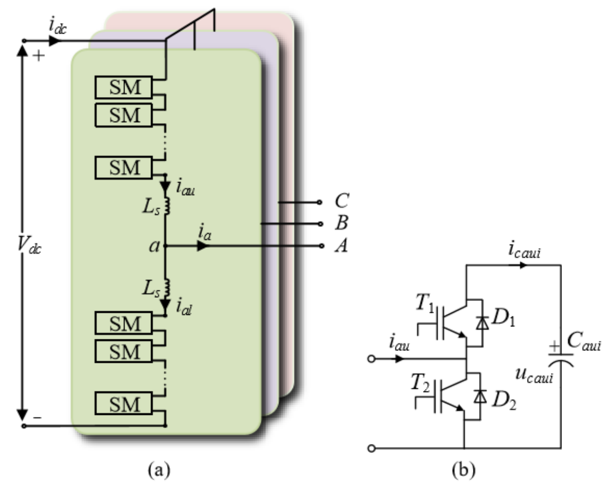

Figure 4: (a) Structure of a three-phase MMC. (b) Structure of the ith Submodule (Deng et al., 2020)

For proper operation of the MMC, the voltage between the submodules should be well balanced, which is done by a voltage balancing algorithm that controls the switching states of the IGBTs. If a disturbance in the HVDC systems occurs, it can lead to inconsistency in the conduction and firing sequences of the IGBTs, thus increasing the stresses on the MMC arms. The IGBT power modules and the capacitors are the weakest components in MMCs. Condition monitoring not only enables the estimation of the SOH of the component itself but it can also contribute to the estimation of the converter's SOH. To date, few studies have been proposed for the monitoring MMCs and can be classified as follows:

- Methods based on "normal" operation. Most of the methods are based on information available during the voltage balancing control: (Chen, et al., 2018) proposes an on-state voltages based method to estimate the SOH of the submodules IGBTs, (Ronanki, et al., 2018; Wang et al., 2019) propose methods to estimate the submodules capacitor capacitance.

- Methods that change the normal operation regularly for the purpose of monitoring. In (Jo et al., 2014), a controlled current is injected into the circulating current inducing higher current and voltage ripples on the submodules capacitors for capacitance estimation.
- Methods where the system is optimized for performing component-level condition monitoring. In (Zhang et al., 2019) a dedicated sorting scheme with reduced switching frequency compared to the conventional scheme is proposed for condition monitoring. It enables the collection of sufficient data samples during the on-state without changing the normal operation and results in an accurate estimation of capacitor parameters. (Deng et al. 2020) propose a sorting-based monitoring strategy which monitors on the capacitor with the smallest capacitance and the biggest ESR.

Online diagnostic is challenging for MMCs, as the fault has to be detected and localized amongst the large number of submodules in a short time. However, the redundancy offered by the modular structure allows isolation of a failed submodule under certain conditions. Diagnostic for MMCs has recently been addressed and is based on distinguishing the dynamic characteristics of the faulty submodules from those of the healthy ones for various types of faults. (Deng et al., 2015 ; Li et al., 2016 ; Yang, et al., 2016 ; Zhou et al., 2019).

3. ENVIRONMENT-AWARENESS: D&P OF THE EXTERNAL COMPONENTS

3.1. Condition monitoring of motors

Motor Condition Monitoring (MCM) is a process of systematic continuous or periodic monitoring of properties/performance of motors to identify damage or fault before the machine complete failure. The condition monitoring of motors is an important task on the industry to planning maintenance and reducing down time at the plants. This section focus on the MCM of induction machines since they are the most used on the industry plants (approximately 90%) (A. Sumper & A. Baggini, 2012), because of the self-starting capability and the low maintenance cost.

A number of signal can be used to identify the motor fault including electro-magnetic (voltage, current, and leakage flux), mechanical (vibrations), thermal and audio.

MCM has a long history with first MCM methods for detecting stator winding condition being developed, implemented and reported in 1940’s (G. L. Moses et al., 1945). The MCM is based on measuring, collecting and analyzing large amounts of data from motors and connected mechanical components (transmission, load). Consequently, the introduction of digital automation manufacturing concepts that provided techniques/infrastructure for collecting and handling of such data (i.e Industry 4.0), has also facilitated larger scale implementation of MCM methods in industrial environment. Today MCM based preventive maintenance planning is one of the basic functionalities of modern manufacturing industrial solutions (Siemens, 2020) and (ABB, 2017). Commercially available MCM products are available even for low-cost motors. For example, for monitoring of low-voltage motors MEMS based multi-sensor just needs to be mounted on the motor’s housing (ABB, 2020; Siemens, 2019). Often the solutions come with included service for cloud data storage and analysis.

Further, dynamic motor analyzers are available on the market that can detect some motor faults. Such analyzers are portable devices mostly used for periodic MCM. The analyzer is at the same time measurement device, data storage and data analyzer therefore it provides results of the analysis on the spot (SKF, 2020).

Very recently also first commercially available frequency converter with embedded condition monitoring functions for motor has been released (Danfoss, 2020). The solution promoted as ‘inverter as a sensor’ is used for condition monitoring of stator windings and monitoring of vibrations (Dannehl J. et al., 2019).

In this section an overview of methods that are based on analysis of electrical signals is presented. Such methods can be implemented on motor control centers for grid-connected motors and directly on the inverter processor for inverter-fed motors.

3.1.1. Motor current signature analysis and other fault detection methods based on electrical signals

Motor current signature analysis (MCSA) is used to detect a number of faults in motor such as such as broken rotor bars, bearing damage, stator winding turn-to-turn short circuits and eccentricity of the rotor axis. For grid-connected motors and steady-state operation conditions it usually relies on Fast Fourier Transform (FFT) analysis of the stator current. Each failure results in harmonics at the specific frequency, which also depends on the motor slip, motor construction (number of poles for induction motor). The amplitude of the specific harmonic also reflects the severity of fault. In the case of detecting broken rotor bar (Bellini A., et al., 2008) the peak in spectrum indicating fault is at low torque very close to the fundamental current frequency, which makes the analysis more difficult. Signal demodulation or filtering for removing of fundamental current frequency from the current spectrum can be used to address this problem (Garcia-Calva T. A., et al., 2019).

For detection of bearing faults due to the wear-out traditionally vibration-based monitoring is used. However, it has been shown that bearing can be monitored and reliably detected also with MCSA (J. Jung et al., 2017). In some approaches the MCSA is used as a basic method and vibration analysis is additionally applied to confirm MCSA's findings (S. Sin et al., 2017)

One of the most common problem on induction machines is eccentricity (Faiz, J. et al., 2016). Eccentricity is a type of fault where the airgap between the stator and the rotor is uneven. The result of this fault is can cause a friction between the stator and the rotor, finally damaging the rotor. Three different forms of eccentricity are known: static eccentricity (SE), dynamic eccentricity (DE) and a combination of both, which is called mixed eccentricity. SE is the problem when the rotor is displaced from the stator center and turns around its own center. With DE, the rotor is also displaced from the stator center, but the rotor rotates around the stator center. Normally these problems happen at the same time, which means that the center of the stator, the center of the rotor and the rotation axis are displaced with respect to each other (Faiz, J. et al., 2009) and (Li, D.Z. et al., 2017). Theoretical models show that spectral components related to eccentricity can be located (Saucedo-Dorantes, J.J. et al., 2016). A method was proposed in (Kun Tian et al., 2018) for the decomposition of the apparent power in order to extracts the characteristic component. In this paper (Kun Tian et al., 2018) we also have a definition of the faulty severity factor to evaluate the severity of the eccentricity.

Analytical methods used for detection of open and short circuits in the stators' windings are based on measured currents and in some cases also voltages. Negative sequence current monitoring (Gou B., et al., 2019) and negative impedance monitoring (Bouzid M. B. K., et al., 2013) is used to detect asymmetry in the stator windings.

3.1.2. Condition monitoring and fault detection in inverter-fed motors

MCSA is a well know technique used for many years. It works really well in numerous cases, yet, drawbacks of the techniques do not allow it to be a global solution for an online condition-monitoring technique.

Nowadays the induction machine (often squirrel cage) gained a lot of popularity with the new inverter drives that appeared on the market (J. Cusidó et al., 2011). The inverter drives allow the induction machines to work with variable speeds and loads. Induction machines do not operate with a constant low torque and at constant speed, which is the condition used for most of the MCSA techniques presented in the literature.

FFT analysis is performed in frequency domain and provided information is average value of the signal. Time information is in frequency domain lost so there is no information about the changing speed. Further, the fault information that is present in frequency spectrum can be masked by the control action when closed-loop control is implemented (Bellini A. et al., 2000). Additionally, the drives introduce additional harmonics and common mode voltages in the system. The additional signatures excited by the inverter harmonics on the stator current spectrum have been theoretically and experimentally analyzed in detail in (Akin B., et al., 2008). Therefore, conventional MCSA combined with FFT as well as analytical methods have limited application.

For non-stationary conditions therefore time-frequency methods are used instead of FFT. For example, torque oscillations caused by mechanical faults in induction machines were investigated by stator current time-frequency analysis in (Blodt M., et al., 2006).

Some new methods which take advantage of the current regulating effect of the motor controller have been developed instead (Cheng S., et al., 2011). Further the methods have been developed that are based on time-frequency methods such as for example Discrete Wavelet Transform (Bouzida A., et al., 2011).

Another possibility are signal injection techniques that are well known on the field of sensorless control for machines. We also know from the literature that double frequency injection techniques can be used for the temperature evaluation of stator windings. Some works were done in the direction of using supplementary injection on the control of the machine for the mitigation of the previously mentioned drawbacks imposed by the inverter drives.

The work made on (J. Cusidó et al., 2011) proposes a signal injection technique that would ensure a proper result for the MCSA fault detection, especially at low torque. The technique is based on an anti-clockwise injected frequency, which introduces additional slip on the motor. This allows the detection of faults with a better dynamic resolution. The composed frequencies analysis, shows an increase in their values in case of fault. However, it is not possible to differentiate the faults e.g. rotor misalignment and broken bars. The fault condition can be distinguished by the analysis of the current spectral distribution of both injected and composed harmonics but, the value of the slip must be known in order to do so, which is impossible in a variable load condition.

Other works as in (Briz et al., 2003), introduces a high-frequency injection method for detecting winding faults and also on a second work (Briz et al., 2004), focused on the rotor faults. The papers use a low-magnitude and high-frequency voltage superimposed on the fundamental excitation voltage, with the measurement of the negative-sequence carrier signal currents. The results show a reliability in the detection on the stator windings faults and broken bars on the rotor. The effects of frequency composition and behavior under double frequency (injected plus fundamental) are not clearly shown in this paper and should be further analyzed.

New control techniques are presented in many papers in order to reduce the instability, to raise the efficiency and also to eliminate sensors (sensorless). However, in doing so the task of identifying faults on the motor becomes more difficult since the signals are hidden by the control. It is important that control engineers think about new techniques in order to evaluate the condition of the motor working together with the control algorithms. This is the reason why the injection of supplementary signal maybe a possibility to establish a relationship between new control algorithms and condition monitoring of the motors.

3.2. Cables

From industry to domestic applications, cables play an important role in the systems as they are responsible of the communication and the power flow between the subsystems and/or components. As an example, in power systems, HVDC cables are used for long distance.

The typical lifetime for a power cable ranges from a few years up to well over 50 years. In HVDC, external aggressions are the main cause of power cables faults, for subsea cables it is represent more than 90 % of the faults (Heggås, et al., 2018). A large percentage of in-service cable faults occur within the first three years of service. These failures typically occur at the cable accessories (cable joints and terminations) and are usually the consequence of their incorrect installation. Furthermore, mechanical and vibration effects of subsea cables moving with the tides and currents can lead to degradation and damage on the cable insulation.

Detection of cable faults are of most importance as they can lead to the breakdown of the total power transmission system.

In addition, maintenance and repair costs of power cable system equipment are high, especially for subsea systems. Reliable D&P methods with preventive maintenance is therefore necessary to avoid excessive expenses.

For condition monitoring of power cables, different technologies exist and can be applied to HVDC cables in the submarine as well as in the land cable section. The on-line condition monitoring methods are (Heggås, et al., 2018):

- Partial discharge (PD) monitoring: PD monitoring is used to observe defects, in homogeneities in the cable insulation. On-line PD monitoring can be done with high-frequency current transformers (HFCT) sensors and acoustic sensors.
- Temperature monitoring: Thermal stress is a major aging phenomena of insulated HV cables under service conditions as it changes both electrical and mechanical properties and alter the dielectric performance of the insulation. Distributed temperature sensors (DTS) with an optical fiber are used for temperature monitoring along the subsea cable.

As it is not always possible to prevent the fault, HVDC systems are equipped with protection relays at the end of the cables.. Protection relays together with protection strategies enable to detect, localise, discriminate the faulty cable from adjacent healthy cables and finally extinguish the fault very quickly. The system in the defined protection zone in which the fault has occurred can thus be isolated from the healthy part of the HVDC network, thus preventing the whole network to collapse. With the deployment of HVDC lines together with the increase penetration of renewable energy sources, it is of utmost important to define robust protection strategies and advanced converter controls in order to detect and isolate the fault as fast as possible and to assure that there is no loss of stability in the whole network that would lead to its breakdown.

Protection methods for HVDC are distance, differential or more recently based on traveling wave for faster fault detection with higher sensitivity (Muzzammel, R., 2019).

Once, the faulty section of the cable is detected it is disconnected from the system with safety rules. Off-line condition monitoring is used to locate and classify the fault in order to either repair or replace the faulty cable section.

The off-line condition monitoring methods are:

- Dielectric response (DR): DR measurements can be done on site and assess the insulation properties of the cable (i.e. capacitance, dielectric loss factor, insulation resistance...). It is widely used as a routine and after-installation test as it requires the transmission to be turned-off.
- Time domain reflectometry (TDR) (Bawart et al., 2016): TDR is used when the fault cannot be located by visual inspection.

The diagnostic consists of classifying the fault type: low, high resistance faults, intermittent fault that becomes active above the operating voltage.

Regarding prognostic, recently a system for predicting damage and life expectancy of subsea cables in (Dinmohammadi F et al., 2019) is based on mathematical models developed from accelerated ageing data.

Furthermore, considering the vision of converters being aware of the state of health of their environment, HVDC cable faults, which are the most severe, can be detected and protection can be achieved with fault blocking converters such as full bridge MMCs.

4. CONCLUSIONS

In this paper the condition and health monitoring techniques for internal (power modules, capacitors) and external components (motor, cables) of a power converter are reviewed. The purpose is to state on the current techniques applicable to power electronics systems.

This paper shows that research work converge towards the integration of sensors, intelligence, and communication means at the converter level.

The vision of a self-aware and self-environment converter is a converter that has the ability to state on its health and its neighboring and based on them has the intelligence to decide on the actions to take to enhance reliability and avoid unscheduled maintenance.

It is expected that the market demand will increase steadily for high-value niche applications where high-availability is required. In the context of high-volume markets, such as the Industry 4.0, the cost-control will favor software solutions as much as possible, including virtual sensors, advanced control, and digital twins.

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