Effect of Operating Conditions on Condition Monitoring of Power Electronic Converters and a Review of Normalization Schemes

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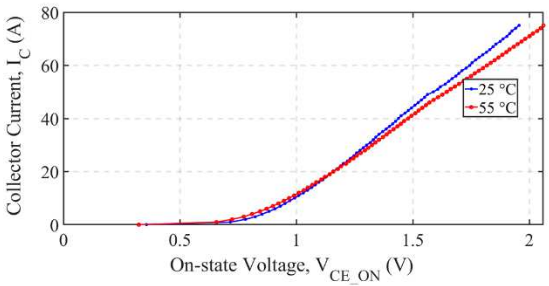
***Abstract*-- Power electronic converters have changed the way in which electrical energy is converted from one form to another form. They are widely used in many critical applications because of their efficient and precise control of electric power. However, they suffer from failures which may lead to loss of revenue and even threaten the safety of human life in certain safety critical applications. Power devices and capacitors are the major sources of failures in power converter. Therefore, condition monitoring methodologies are developed for these components and a vast majority of those methods are based on failure precursor parameters like on-state voltage drop, case temperature, capacitance, equivalent series resistance (ESR), etc. These failure precursor parameters are sensitive to operating conditions which makes normalization techniques that eliminate the influence of operating conditions very important in condition monitoring methodologies. However, this normalization process is often overlooked during implementation. Therefore, this paper presents a review of normalization schemes and analyses the effect of operating conditions on some of the most widely used failure precursor parameters.**

***Index Terms*—Condition monitoring, power electronics, failure precursors, normalization schemes.**

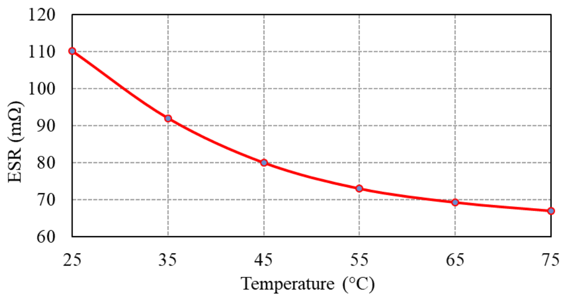
I. Introduction

The global shift towards sustainability is reflected in all walks of life with electric power systems becoming more efficient and sustainable [1]. Power electronics play a pivotal role in this transition by enabling the integration of renewable energy sources and transformation of transportation industry from fossil fuels-based vehicles to electric vehicles (EV) [2]-[4]. With power electronic converters playing such a critical role, reliability-oriented design and condition monitoring of power electronic converters are gaining importance [5]-[7]. Power electronic converters are a synergistic combination of multiple components like passive magnetic components, capacitors, printed circuit boards, power semiconductor devices and their associated components like gate driver, snubber, connectors, etc. This paper focuses on insulated gate bipolar transistors (IGBT) and capacitors as they are not only indispensable but also the failure prone components in a power converter [8]. Several condition monitoring techniques are discussed in literature and the most popular techniques are usually based on the monitoring of parameters that are sensitive to device degradation called failure precursor parameters [6], [9, 10], [13]-[38]. The most popular failure precursor parameters for IGBTs are on-state voltage drop (V_{CE_ON} or V_{CE_sat}), on-state resistance (r_{CE}) and thermal resistance (R_{th}) [6], [9]-[11] whereas for capacitors, it is capacitance value and equivalent series resistance (ESR) [12]-[14]. Fig. 1 illustrates the influence of operating conditions on failure precursor parameters. The on-state voltage of an IGBT varies with load current and junction temperature as shown in Fig. 1. (a). Similarly, the ESR and capacitance vary with operating temperature and frequency. The temperature characteristics of ESR is shown in Fig. 1. (b).

The temperature and frequency of the IGBTs and capacitors in a power converter may vary during operation and therefore, it is necessary to fully understand the effect of operating conditions on failure precursor parameters to design a reliable condition monitoring system. Also, it is important to understand the ageing related variations in their relationship with operating conditions. However, the vast majority of existing research in this field focuses on the estimation of failure precursor parameters and only a handful of them discuss the normalization schemes for condition monitoring. Therefore, this paper presents a review of normalization schemes from the literature for the most widely used parameters such as V_{CE_ON}, capacitance and ESR followed by the analysis of proposed methods with respect to ageing through accelerated ageing tests. This paper is organized as follows: Section II presents a review of normalization schemes for capacitance and ESR from literature, Section III presents the analysis of ageing related changes in the relationship between operating conditions and failure precursors (capacitance and ESR) to validate the normalization schemes, Section IV and V present the review and analysis for on-state voltage (V_{CE_ON}) of IGBTs and finally, section VI presents conclusion with directions for further research.



(a)



(b)

Fig. 1. (a) Effect of temperature and current on on-state voltage of IGBT and (b) Temperature characteristics of ESR

II. Normalization Techniques for Capacitance and ESR in Electrolytic Capacitors

A scheme for normalising the influence of operating temperature on capacitance and ESR is presented in [15, 16] for condition monitoring of electrolytic capacitors in adjustable speed drives (ASD). The temperature and frequency characteristics of capacitance and ESR for capacitor samples are taken when they are new and after they are aged. The analysis of these characteristics showed that the effect of ageing is more pronounced at low temperatures. Therefore, it is proposed in [15, 16] to estimate the capacitance and ESR at low operating temperatures. In order to ensure that, the ESR and capacitance measurements taken right after the converter is turned on, after sufficient idle time for the converter to reach thermal equilibrium with the surroundings, is used. As the thermal capacitance of electrolytic capacitors is large, the measurements taken right after long idle time can be safely considered as measurements at ambient temperature. Apart from these findings, an ambient temperature estimation method based on stator resistance of the ASD is presented which can be used to study the temperature effects on ESR and capacitance.

In [17], the ESR and capacitance values of dc-link capacitor in adjustable speed drives are estimated whenever the motor is stopped. The temperature characteristics of ESR and capacitance are modelled as in (1) and (2).

$$ESR(T_a) = a + b \cdot e^{\frac{-T_a}{c}} \quad (1)$$

$$C(T_a) = d + e \cdot T_a \quad (2)$$

where T_a is the ambient temperature, *a, b, c, d* and *e* are the parameters specific to the capacitor used. The model parameters are estimated using the recursive least squares method on ESR and capacitance values at different temperatures when the drive is stopped and cooling down. The estimated model can be used to generate ESR and capacitance value at a standard base temperature. In [17], it is assumed that the motor and capacitor are in thermal equilibrium and stator resistance is used to estimate the temperature. However, this may not be the case in most applications and core temperature must be estimated using other methods. In [18]-[23], the capacitance and ESR values estimated at operating temperature is compared with initial values at the same operating temperature. As ageing related variations in ESR is more pronounced at low temperatures, it is possible that the proposed method may identify degraded capacitors as healthy which can lead to secondary failures.

In [24], the capacitance and ESR values estimated at any operating temperature is normalised by multiplying with C_{Ta} and ESR_{Ta} to represent estimates at a standard base temperature based on the physics-based equations in (3) and (4) governing changes in permittivity and conductivity. However, this method does not consider the complex RC ladder like structure of electrolytic capacitor which affects both ESR and capacitance at higher frequencies. Therefore, it cannot be used if the parameters are estimated at higher frequencies. Also, the ESR is made up of multiple components like foil resistance, electrolyte resistance and dielectric loss which cannot be accurately normalised using (4).

$$C_{Ta} = e^{\left(\frac{B}{T2} - \frac{B}{T1}\right)} \quad (3)$$

$$ESR_{Ta} = \frac{1}{1 + D(T2 - T1)} \quad (4)$$

The findings of the above discussion are summarised in Table I.

TABLE I
Summary of Normalization Methods for Capacitors

Methodology	Equation / Explanation	Pros and Cons
Ambient temperature-based method [15, 16]	Always carry out parameter estimation right after the power converter turns ON after long idle.	Pros: 1. Simple and easy to apply without additional cost. 2. Ambient temperature estimation without additional sensor. Cons: 1. Suitable only for applications where there is sufficient idle time. 2. Ambient temperature may vary and all estimates are not available at standard temperature. 3. Effect of frequency is not considered.
Empirical model-based methods [17]	$ESR(T_a) = a + b \cdot e^{\frac{-T_a}{c}}$ $C(T_a) = d + e \cdot T_a$	Pros: 1. Ageing related effects on temperature characteristics is considered. 2. All estimates are available at a standard temperature. 3. Temperature estimation without any additional sensor (may not work for other

		applications). Cons: 1. Estimation is possible only when the motor is stopped. 2. Effect of frequency is not considered.
Temperature based threshold [18]-[23]	Compare ESR and capacitance estimated to initial values at same temperature.	Pros: 1. Only a look-up table for initial values is required. Cons: 1. Needs core temperature estimation. 2. Possible errors at high operating temperatures.
Physics-based method [24]	$C_{Ta} = e^{\left(\frac{B}{T2}-\frac{B}{T1}\right)}$ $ESR_{Ta} = \frac{1}{1+D(T2-T1)}$	Pros: 1. New approach which converts all estimates to represent values at a standard temperature. Cons: 1. Model is oversimplified which can lead to poor accuracy.

Based on the review presented, the following conclusions can be derived:

1. The comparison of ESR and capacitance estimated at a given operating temperature to its initial values at the same temperature may lead to poor results at high operating temperatures as ageing is more pronounced at low temperatures.
2. Some of the methods need core temperature measurements which can be solved either by embedded temperature sensor and better methods to estimate core temperature.
3. The ageing-related effects of frequency on ESR and capacitance must be studied in detail to ensure the effectiveness of current methods.

Considering these issues, the following section presents a study on the effect of temperature and estimation frequency on the failure precursors for capacitors through ageing tests to establish a standard normalisation procedure.

III. Analysis of Frequency and Temperature Characteristics of Capacitance and ESR Through Ageing Tests

A. Accelerated Ageing Tests

A thermal chamber is used to perform aging tests on 560 µF, 250 V aluminium electrolytic capacitors where a combination of voltage and temperature is used as stress factors. Fig. 2-5 presents some characterization results taken for the analysis of temperature and frequency characteristics.

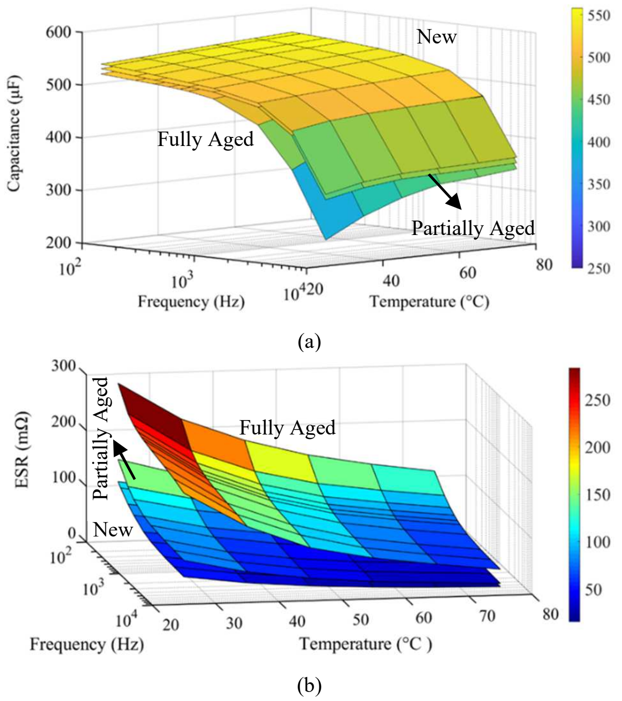


Fig. 2. (a) Effect of ageing on temperature and frequency characteristics of capacitance and (b) ESR

B. Effect of Frequency and Temperature on Degradation Indicators

Fig. 3 shows the temperature effects on capacitance is linear when measured at low frequency like a few hundred Hertz whereas the relationship becomes non-linear at high measurement frequencies in the range of kHz. This non-linear relationship will lead to higher complexity and uncertainty, if the capacitance values are required at a standard base temperature. Fig. 4. (a) and (b) presents the ESR values measured at different temperatures and frequencies for five capacitor samples at different degradation levels. The percentage increase in ESR is always more for the ESR measured at a higher frequency as summarized in Table II as it does not include dielectric loss component. Therefore, if the failure threshold of twice the initial ESR is used irrespective of the frequency, then the condition monitoring system which uses higher frequency for ESR estimation will report failure earlier than the ones which use a lower frequency. This is a critical issue in the power converter system where the capacitor voltage and current have more than one frequency component. Therefore, to avoid confusion, it is better to estimate the ESR at a lowest dominant frequency (e.g. 100 Hz in single-phase full-wave rectifier fed inverter applications) in capacitor voltage and current.

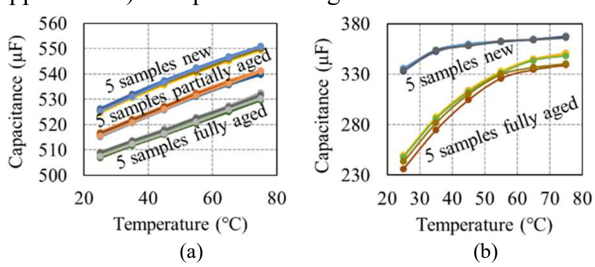


Fig. 3. (a) Effect of ageing on capacitance measured at low frequency (300 Hz) and (b) capacitance measured at high frequency (10 kHz)

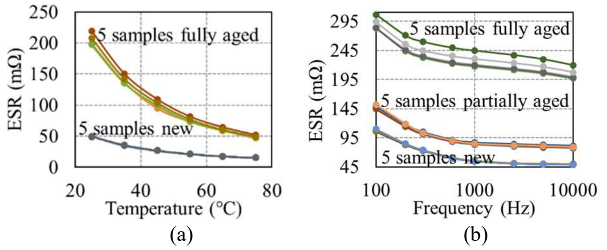


Fig. 4. (a) Effect of ageing on ESR measured at 10 kHz and (b) Effect of ageing on frequency characteristics of ESR

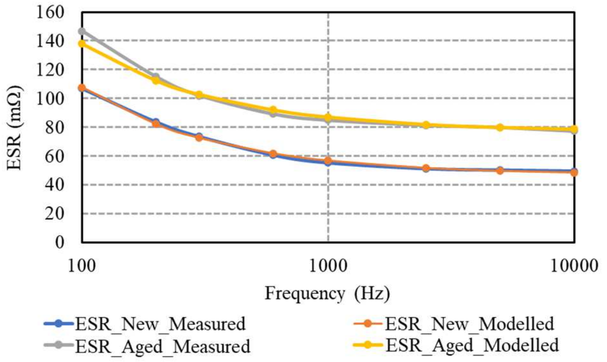


Fig. 5. Frequency characteristics of ESR using proposed method

TABLE II
EFFECT OF FREQUENCY CHARACTERISTICS OF ESR IN CONDITION MONITORING APPLICATIONS

S. No.	ESR measured at 100 Hz (mΩ)		
	New	**Partially Aged (% Change)**	**Fully Aged (% Change)**
1	107	146.7 (37.1%)	283.4 (164.9%)
2	108	146.5 (35.6%)	283.3 (162.3%)
3	106.2	144.5 (36.1%)	284.1 (167.5%)
4	106.5	149.6 (40.5%)	306.9 (188.2%)
5	110.1	151.8 (37.9%)	293.8 (166.8%)
S. No.	**ESR measured at 2.5 kHz (mΩ)**		
	New	**Partially Aged (% Change)**	**Fully Aged (% Change)**
1	51.1	81.4 (59.3%)	213.6 (318.0%)
2	51.3	79.9 (55.8%)	211.2 (311.7%)
3	51	81 (58.8%)	212.9 (317.5%)
4	50.7	84 (65.7%)	236.9 (367.3%)
5	50.5	82.1 (62.6%)	223.5 (342.6%)

Most of the existing condition monitoring systems estimate ESR at higher frequencies because it is difficult to estimate the ESR online at low frequencies as the capacitor's impedance is dominated by the capacitive reactance at low frequencies. In order to solve this issue, a conversion procedure is proposed based on the power model for frequency characteristics of ESR. The frequency characteristics of the ESR of a new capacitor can be modelled as a power equation in (5).

$$ESR = a * f^b + c \qquad (5)$$

If electrolyte evaporation is the dominant failure mechanism as in most cases, the frequency dependent component of ESR can be safely assumed as a constant, and the model after ageing can be determined from the model in (6) as follows:

$$ESR = a * f^b + c + (esr_{aged} - esr_{new}) \qquad (6)$$

where esr_{aged} and esr_{new} are the ESR values measured at high frequency when the capacitor is aged and new respectively. The results obtained using the model in (6) is shown in Fig. 5 and the maximum error is less than 6% which is much better than current assumption to use ESR measured at high frequencies.

IV. Normalization Techniques for Temperature and Current Dependency of IGBT Parameters

The on-state voltage of an IGBT is dependent on the operating temperature and collector current as shown in Fig. 1. (a). Several condition monitoring methods have been discussed in literature for IGBTs using its on-state voltage as the failure precursor [30]-[37]. In [30], an innovative circuit that is both simple and inexpensive has been proposed to extract the on-state voltage of IGBTs in three-phase full-bridge. However, the dependency of on-state voltage on device current and temperature is not discussed. In [31], a circuit has been proposed to extract the on-state voltage of all the IGBTs in back-to-back converter. To avoid the influence of current and temperature, it is suggested to make comparison at specific temperature and load current. A real-time monitoring method for bond wire ageing in IGBTs using on-state voltage is discussed in [32]. The dependency of on-state voltage on operating current and temperature is considered and solutions were proposed. For the estimation of junction temperature, on-state voltage measured at 100 mA using a specially designed circuit is proposed as temperature sensitive electrical parameter (TSEP). The on-state voltage measured at 100 mA has a linear relationship with negative slope as shown in Fig. 6. The current value of 100 mA is selected to avoid self-heating and to minimize the effect of various connection resistances. Also, the load current is maintained at zero by turning off all the other switches. Each of the temperature estimation period is followed by on-state voltage measurements at device currents close to 100 A. The measured samples of on-state voltage at operating conditions close to 100 A and 125 °C are used to estimate the on-state voltage at an operating current of 100 A and temperature of 125 °C using interpolation technique to monitor ageing. A similar method which uses on-state voltage measurements at low currents as TSEP for junction temperature estimation and at normal operating currents for condition monitoring of EVs is proposed in [33]. The measured values of on-state voltages are compared with healthy baselines at the same temperature.

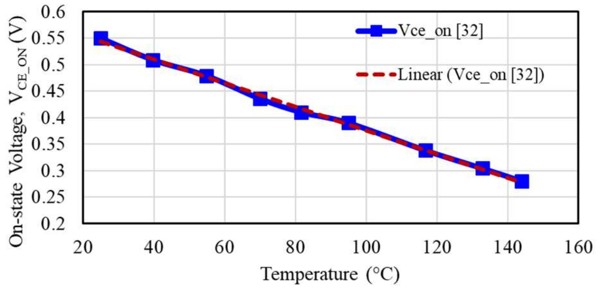


Fig. 6. Relationship between on-state voltage measured at 100 mA and junction temperature [32]

In [34], on-state voltage at inflection point is proposed to solve the issues caused by changes in operating current and temperature. At inflection point, the on-state voltage is independent of operating temperature and the current value is fixed as shown in Fig. 1. (a). For a predetermined gate voltage, inflection point occurs at a fixed collector current value which can be determined through characterization experiments. Another condition monitoring scheme based on on-state voltage measurement has been proposed in [35]. This article also discussed online measurement strategies based on operating conditions. For converters operating in fixed load conditions, it is suggested to use the on-state voltage measured at same current level and angle in order to eliminate the effect of operating current and its influence on junction temperature. For converters operating in varying load conditions, it is suggested to use the on-state voltage measured at inflection point to avoid the influence of operating temperature. In [36], a condition monitoring method has been presented for IGBTs based on on-state resistance. The use of on-state resistance instead of on-state voltage eliminates the need to normalize for changes in operating current. An empirical model-based method has been proposed to model the influence of junction temperature on on-state resistance as shown in (7).

$$r_{CE}(T_j) = r_{CE} * (b_1 * T_j^2 + b_2 * T_j + b_3) \quad (7)$$

where r_{CE} is on-state resistance, T_j is junction temperature, and b_1, b_2 and b_3 are model parameters. A thermal impedance and power loss-based method has been discussed for junction temperature estimation of the IGBT. There are several methods available for the estimation of junction temperature of IGBTs which are discussed in [37]-[40]. A summary of normalization methods for IGBTs is presented in Table III.

TABLE III
SUMMARY OF NORMALIZATION METHODS FOR IGBTS

Methodology	**Equation / Explanation**	**Pros and Cons**
Fixed operating condition-based method [31, 32]	Always estimate parameters at specific load current and junction temperature. For example, estimation of V_{CE_ON} at 100 A and 125 °C [32].	Pros: 1. Simple and easy to implement as this method doesn't need complicated models/methods to account for changes in temperature and current. Cons: 1. Need junction temperature to carry out required on-state measurements. 2. Difficult to have continuous monitoring in applications with highly dynamic load conditions. 3. Failure threshold should be selected according to selected operating condition for monitoring.
Temperature based threshold [33]	Compare estimated on-state voltage to initial values at same temperature.	Pros: 1. Only a look-up table for initial values is required. Cons: 1. Need junction temperature to decide appropriate failure threshold.
Inflection point-based method [34, 35]	Estimate on-state voltage at inflection point.	Pros: 1. Junction temperature estimation is not needed. Cons: 1. On-state voltage measurements need to be carried out at predetermined collector current (Inflection point).
Empirical model-based methods [36]	$r_{CE}(T_j) = r_{CE} * (b_1 * T_j^2 + b_2 * T_j + b_3)$	Pros: 1. Allows conversion of on-state resistance estimates to values at a predetermined standard temperature. Cons: 1. On-state voltage measurements need to be carried out at predetermined collector current (Inflection point).

V. ANALYSIS OF AGEING EFFECTS ON CONDITION MONITORING OF IGBTS

The on-state voltage of IGBTs measured at low currents in range of 50 mA to few hundred mA is commonly used as a TSEP for junction temperature estimation. Any error in junction temperature estimation would lead to error in normalization and false condition monitoring signals. Fig. 7 shows the shift in on-state voltage characteristics with ageing. Therefore, using the same equation to estimate the junction temperature after ageing would give higher temperature than actual values and calibration of TSEP is required to maintain the accuracy of junction temperature estimation with ageing.

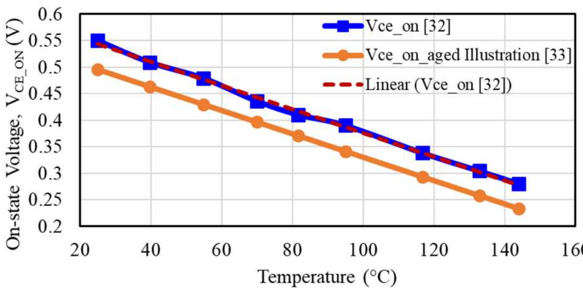


Fig. 7. Shift in TSEP characteristics with ageing [33]

The on-state voltage of IGBTs measured at inflection point is another commonly used failure precursor as it eliminates the need for junction temperature measurements. However, the effect of ageing on collector current value at inflection point must be considered. Based on the results presented in [41], the shift in collector current at inflection point caused by ageing can be neglected as it in the range of few tenths of mA. Therefore, on-state voltage measurement at inflection point can be considered as calibration free failure precursor for bond wire degradation. However, it must be further analyzed for other failure mechanisms.

VI. Conclusions

This paper presented a detailed review of normalization schemes for capacitors and identified underlying issues in the existing normalization process regarding measurement frequencies and a method has been proposed to rectify the same. The proposed method is verified using the data from ageing tests. The analysis and results have proved the importance of using dominant low frequency harmonic for ESR estimation. A similar review of normalization scheme for IGBTs is presented along with analysis of ageing effects on condition monitoring schemes. The on-state voltage at inflection point is identified as a reliable indicator which does not need calibration for ageing related changes in collector current. Based on the above findings, it is clear that a standard practice is needed for selection and implementation of condition monitoring using failure precursors. Further research is necessary to understand the influence of operating conditions on failure precursors.

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