

1 Article

2 **On-Line Remaining Useful Life Estimation of Power Connect-**  
3 **ors Focused on Predictive Maintenance**4 **Jordi-Roger Riba <sup>1,\*</sup>, Álvaro Gómez-Pau <sup>2</sup>, Jimmy Martínez <sup>1</sup> and Manuel Moreno-Eguilaz <sup>2</sup>**5 <sup>1</sup> Electrical Engineering Department, Universitat Politècnica de Catalunya, 08222 Terrassa, Spain; jordi.riba-  
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10 **Abstract:** Connections are critical elements in power systems, exhibiting higher failure probability.  
11 Power connectors are considered secondary and simple devices in power systems despite their key  
12 role, since a failure in one of such elements can lead to major issues. Thus, it is of vital interest to  
13 develop predictive maintenance approaches to minimize these issues. This paper proposes an on-  
14 line method to determine the remaining useful life (RUL) of power connectors. It is based on a sim-  
15 ple and accurate model of the degradation with time of the electrical resistance of the connector,  
16 which only has two parameters, whose values are identified from on-line acquired data (voltage  
17 drop across the connector, electric current and temperature). The accuracy of the model presented  
18 in this paper is compared with the widely applied autoregressive integrated moving average model  
19 (ARIMA), showing enhanced performance. Next, a criterion to determine the RUL is proposed,  
20 which is based on the inflection point of the expression describing the electrical resistance degrada-  
21 tion. This strategy allows determining when the connector must be replaced, thus easing predictive  
22 maintenance tasks. Experimental results from seven connectors show the potential and viability of  
23 the suggested method, which can be applied to many other devices.

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## 1. Introduction

Power connectors are critical components, playing a key role for the correct and stable operation of power systems. After a long-time operation, degradation mechanisms can negatively impact the contact resistance, and thus their performance. Severe outages generated because of power connector failure may lead to costly and catastrophic consequences [1].

Medium voltage connectors are copper or aluminum devices designed to provide a low and stable electrical connection between two conductors or bus bars. These electro-mechanical devices are aimed to transmit electrical power with minimum power losses [2,3], thus with minimum voltage drop. The most common materials for medium voltage connectors are copper and aluminum [4] and they are often of compressed type, since compression provides a reduced contact resistance and a reliable electrical connection.

The electrical resistance has two main terms, i.e., the bulk resistance given by its geometry and the resistivity of its constitutive materials, and the contact resistance, which depends on diverse factors such as the pressure of the contact interface [5], the state and roughness of the mating interfaces, or the presence of dirt and debris among others. Connector degradation is often a consequence of an increase of the electrical resistance, which raises its operating temperature. As a result, overheating and consequently a reduction of the useful life are expected [6]. Contact resistance increases as a result of a poor contact

46 between the conductor and connector due to different causes, such as deficient installation  
47 or temperature cycling produced by daily demand cycles, with the consequent expansion  
48 and contraction patterns which lose the contact. When the connector resistance is above a  
49 certain value, it must be substituted to prevent any failure.

50 Health management and prognostics allows assessing the reliability of different ele-  
51 ments in their life cycles, while mitigating risks of sudden breakdowns [7]. Today, health  
52 management and prognostics is evolving from failure management to degradation man-  
53 agement [8]. Reliability engineering is directly related to predict the remaining useful life  
54 of systems by incorporating all available data [9]. The commercialization of low-cost sen-  
55 sors and the development of the Internet of Things (IoT) are facilitating the development  
56 of RUL strategies.

57 The remaining useful life of a power connector is the expected operating time be-  
58 tween the present time and the time when it needs to be replaced [10]. Correct RUL pre-  
59 diction of power connectors is of great interest to ensure satisfactory reliability and safety  
60 of power systems, which provides reference data to develop maintenance plans and  
61 schedules, while allowing to optimize power system operational efficiency, to reduce  
62 costs due to unscheduled failures and to avoid premature connector faults and major  
63 power system failures [11]. Reliability analysis has been typically based on predicting the  
64 failure rate [12]. Power connectors are designed for a continuous operation of several  
65 years, in the order of 30-40 years for substation connectors, although premature failure  
66 modes may happen much before [13]. Accurate RUL estimation is appealing in order to  
67 apply predictive maintenance programs, since it allows determining and planning the  
68 connectors that must be replaced in the short or medium term, thus avoiding their failure  
69 as well as the undesired consequences of these catastrophic faults, while enhancing as-  
70 sessed their operating condition [14].

71 Predictive maintenance is evolving towards data-driven methods and physical mod-  
72 eling due to the widespread use of different types of sensors, communication protocols  
73 and computation systems. Grid reliability can be improved by means of online sensing  
74 technologies based on low-cost sensors [15]. Regardless of the progress in predictive  
75 maintenance methods, hands-on and time-based maintenance are still intensively applied  
76 [16].

77 In case of devices in which the natural ageing under regular operating conditions  
78 requires a long time, accelerated ageing methods are widely applied to analyze their long-  
79 term performance [17]. However, this strategy is very expensive in terms of energy con-  
80 sumed, human labor, required materials and monetary cost, and the attained results are  
81 specific, thus often lacking of generalization capability. Therefore, due to the abovementioned  
82 issues, this work avoids to apply this strategy. In addition, conventional maintenance  
83 strategies are based on failure data of similar devices; however such strategies do  
84 not consider the specificity of the degradation process of each single device [18]. The ap-  
85 proach presented in this paper overcomes this limitation since the predicted RUL is ad-  
86 justed to each particular connector.

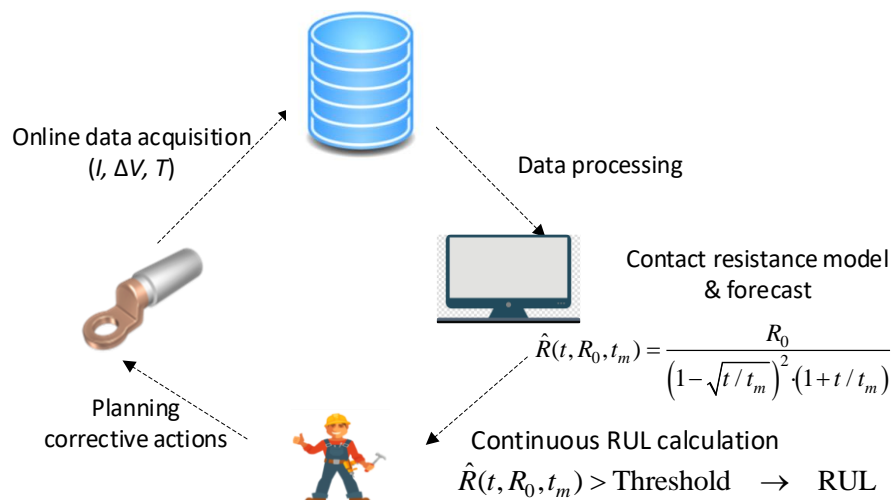
87 This work develops a low-cost method for an on-line monitoring of the electrical resis-  
88 tance of the connector and its evolution over time for a reliable on-line estimation of the  
89 remaining useful life based on voltage drop, current and temperature measurements fo-  
90 cused to improve and facilitate predictive maintenance plans.

91 The method proposed in this paper to determine the RUL is based on acquiring on-  
92 line data (voltage drop across the connector, electric current and temperature) to deter-  
93 mine the current value and the evolution of the electrical resistance of the analyzed con-  
94 nector, since it is a suitable indicator of the health status of the connector [19], thus allow-  
95 ing to determine its power efficiency and expected lifetime [20]. Any increase of the resis-  
96 tance implies a raise of the temperature of the connector, which further rises the resis-  
97 tance, thus tending to deteriorate the connector performance and reducing the RUL  
98 [13]. Next, from a mathematical RUL model, the right moment to replace the connector is  
99 calculated, i.e., when the connector will show poor or degraded electrical performance [4].

The RUL model proposed in this work is based on the oxidation multi spot equation which describes the rise of the electrical contact resistance with time due to the growth of oxide films at the contact interface [18]. This on-line method allows predicting and planning the moment to replace the connector based on determining its RUL.

Fig. 1 summarizes the strategy proposed in this work to determine the RUL, which is based on measuring on-line the electrical resistance from the connector temperature, the voltage drop and current flowing across the connector, and the model of degradation of the electrical resistance from which the RUL is determined based on when the electrical resistance surpasses a predefined threshold value.

Electrical connectors reliability has been often characterized by the failure rate in spite of the misleading results and limitations of this approach [12]. Therefore, remaining useful life (RUL) prediction models are required, although there is a scarcity of literature for power connectors. In [21] the joint effect of vibration and temperature stresses on the value of the contact resistance of automotive connectors was evaluated with the aim to determine the minimum vibration amplitude for fretting-corrosion degradation. In [22] the mechanical behavior and fatigue lifetime of micro electrical connectors were estimated based on the effect of fretting wear. In [12] a RUL method for aviation connectors is presented based on high vibration stress, which combines a vibration-induced physical model, a particle filtering data-driven approach and accelerated degradation testing to evaluate the performance of the proposed approach. In [23] the reliability and failure rate of electrical connectors was predicted under particulate contamination and temperature stresses by means of accelerated tests to collect degradation data. A similar approach was applied in [24], where in this case the lifetime distribution was described by a two-parameter Weibull distribution, whose parameters were inferred by applying the maximum-likelihood estimation method from degradation test data. RUL estimation of micro switches based on Bayesian updating and expectation maximization combined with strong tracking filtering was presented in [25], the failure threshold being based on the contact voltage drop between contacts once closed, which is directly related to the contact resistance. In [26] failure indicators based on the change of the electrical resistance of small size socket electrical connectors are applied to predict the RUL of such components based on random vibration tests carried out to produce fretting corrosion degradation. Resistance was measured by applying the resistance spectroscopy technique jointly with phase sensitive detection and a Kalman filter was applied for estimating the health status of the socket connector.



**Figure 1.** Approach applied to predict the RUL of power connectors.

This paper proposes a novel RUL estimation method and a criterion for power connectors based on an on-line monitoring of the electrical resistance of the connector. This approach is focused to ease predictive maintenance plans, thus contributing in this area due to the scarcity of works in the field of RUL estimation methods for power connectors. The proposed criterion has been experimentally assessed by using a contact resistance based degradation model [27], showing promising results. The strategy proposed in this work to determine the RUL of power connectors brings different novelties, since it is based on the on-line measurement of the electrical resistance using low-cost sensors, and on a simple and fast-to-calculate aging model of the electrical resistance based on only two parameters which are identified by applying a generalized least squares fitting based on the Nelder-Mead gradient-free minimization algorithm. Therefore, this process is quite simple, with low mathematical complexity and in consequence, with low computational burden, fact which makes it feasible to be embedded in the field via Internet of Things (IoT) devices or wireless sensor networks. Another advantage of this proposal is that it does not require to perform previous accelerated ageing or degradation tests as in [28], which are time-consuming, expensive and consume high amounts of energy, since it has the ability to continuously update the model from the newly acquired data. It is worth noting that a similar approach can be applied to many other power devices.

## 2. Resistance-based degradation models

### 2.1 Connector's electrical resistance

This section describes the method used for on-line monitoring the electrical resistance of the connectors, which, as explained, is a good health status indicator, although its value depends on its instantaneous temperature value. However, this measurement supposes a challenging task due to the low values of the connectors' resistance, with is in the order of some tens of micro-Ohms.

Connectors are supplied at power frequency, so by measuring on-line the voltage drop between the connector terminals  $\Delta V_{Connector}$  and the AC current  $I$  passing through them, the impedance of the connector  $Z_{Connector}$  is determined instead of the resistance  $R_{Connector}$  [4],

$$R_{Connector} = Z_{Connector} \cdot \cos \varphi = (\Delta V_{Connector} / I) \cdot \cos \varphi \quad (1)$$

$\varphi$  being the phase angle between the voltage drop across the connector and the current waveforms.

Since temperature has a great impact on the connector's resistance, temperature is always corrected to 20 °C to remove or at least to minimize the effect of temperature. This correction is applied as [29,30],

$$R_{Connector, 20^{\circ}C} = \frac{\Delta V_{Connector} / I}{1 + \alpha_R (T - 20)} \cdot \cos \varphi \quad (2)$$

where  $R_{Connector, 20^{\circ}C}$  is the resistance converted to 20 °C reference, and  $\alpha_R$ , is the temperature coefficient, which is 0.004 K<sup>-1</sup> for both copper and aluminum.

It is worth noting that although the temperature can also indicate possible failure modes in the connector, other variables including the electrical current flowing through the connector, vibrations [31], the ambient temperature or different meteorological variables such as wind speed, rain or ice, may produce appreciable changes in the contact resistance. Although the temperature is a key factor affecting the thermal loss of life [32], to use the temperature to indicate the health status, a complete thermal model of the connector is usually required. Although this process is possible to develop, it is much more complex than the approach proposed in this paper due to the inherent complexity of the thermal models, the need to be experimentally validated under different meteorological

conditions (wind speed and direction, fog, rain, ice, etc.) and the fact that the thermal model must be adjusted to each type of connector.

## 2.2 Resistance degradation model

This section details the contact resistance degradation model used to predict the RUL of the connectors, which is a requirement in order to forecast the time-evolution of the resistance.

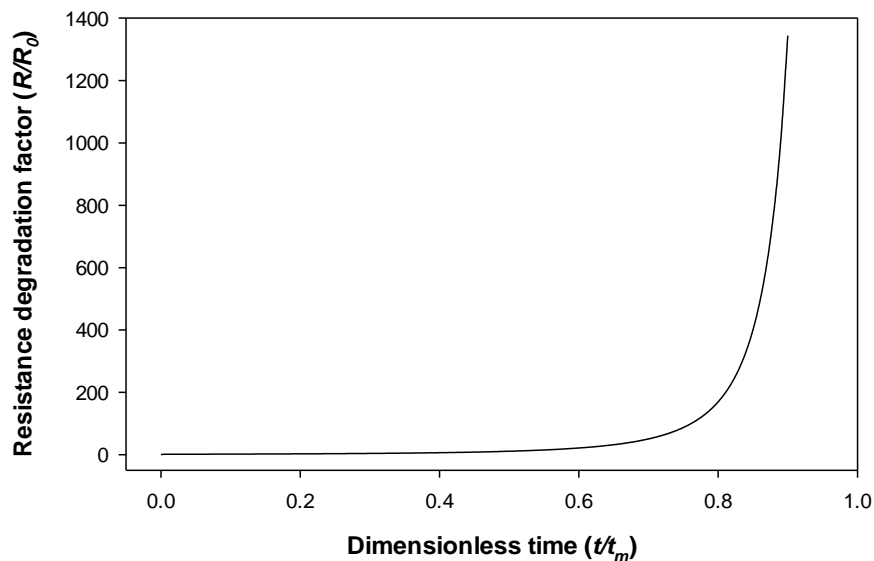
The resistance degradation model analyzed in this paper is based on the increase of the contact resistance with time. According to [27], the contact lifetime is inversely dependent of the diffusion coefficient of the oxidizing agent at the contact interface. It is known that time increases the growth of oxide films at the contact interface under fretting conditions [27], thus increasing the electrical resistance, this effect being boosted with the presence higher temperatures, which in turn increases the effective resistance and the rate of diffusion, thus promoting a faster growth of oxide films at the contact interface.

According to [27], the two-parameter  $(R_0, t_m)$  degradation model of the electrical resistance describing the time evolution of the contact resistance considering the oxidation mechanism for multi-spot contacts can be written as,

$$\hat{R}(t, R_0, t_m) = \frac{R_0}{(1 - \sqrt{t/t_m})^3 (1 + 2\sqrt{t/t_m})(1 + t/t_m)} \quad (3)$$

$R_0$  being the initial resistance of the connector,  $t$  the time elapsed from the installation and  $t_m$  is the so called maximal life time, which corresponds to a vertical asymptote of (3).

Equation (3) applies for multi-spot contacts presenting a beta distribution of the radius of the contact spots [27]. This equation has been chosen since it fits well to the experimental data. Fig. 2 displays the time evolution of the resistance according to (3).



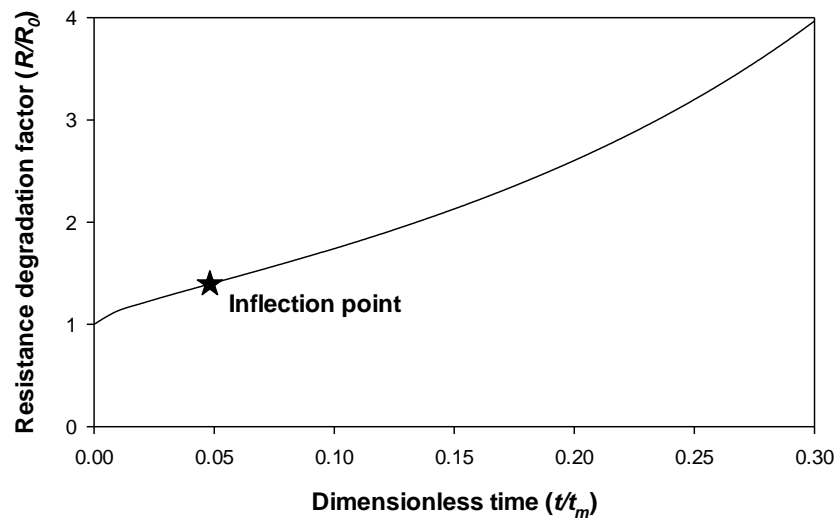
**Figure 2.** Oxidation multi spot contact resistance degradation model. As can be observed, at  $t = t_m$  the model predicts a vertical asymptote.

## 2.3 Parameter identification

Once the model in (3) has been established, parameters  $R_0$  and  $t_m$  must be identified. To this end, the Nelder-Mead gradient-free minimization algorithm is applied from previous or past data (voltage drop, temperature and current) of the connectors. Therefore, once parameters  $R_0$  and  $t_m$  have been identified, by applying (3), which is a simple and fast-to-calculate expression, it is possible to forecast the future values of the connector resistance, which is the basis of the RUL predictive model proposed in this work.

## 2.4 RUL criterion

As previously explained, any increase of the resistance of the connector is traduced in more power losses, heat generation and degradation of the contact interface. Therefore, it is proposed a RUL criterion based on monitoring the time evolution of the resistance. In order to generate a robust and simple RUL predictive model, a simple end-of-life criterion is required. To this end it is proposed to determine the inflection point of the resistance degradation curve expressed by means of (3), this being the point at which the resistance transits from convex to concave, i.e., determining the point in which the increase of the electrical resistance accelerates. After equaling the second derivative of (3) to zero, the inflection point of (3) occurs at  $t = 0.0482t_m$ , corresponding to  $R = 1.395R_0$ , i.e., when the connector's resistance has increased by at least 39.5% with respect its initial value  $R_0$ , as shown in Fig. 3.

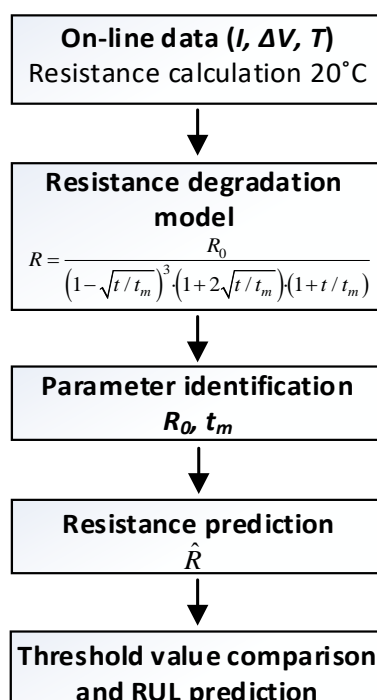


**Figure 3.** Detail of Figure 2 up to  $t/t_m = 0.3$  together with the proposed RUL criterion, corresponding to the inflection point of (3).

The proposed RUL criterion based on the time instant of the inflection point found in model (3) makes sense, since it is the point from which the derivative of the contact resistance starts to increase. Therefore, above this point, the resistance increases with the consequent higher chance of being quickly degraded.

### 3. Tested connectors and experimental setup to determine the RUL of the analyzed connectors

This section presents the method applied in this paper to assess the proposed on-line connector RUL estimation method from experimental data. Fig. 4 summarizes the steps required to determine the RUL of the connectors according to the approach proposed in this work. The first step corresponds to the acquisition of experimental data when the connector is operating under the conditions which will be further specified. The acquired data is the current that flows through the connector, the voltage drop across connector's terminals, the phase difference between current and voltage, and finally the working temperature of the connector. According to (2), the resistance is transformed to 20 °C. As mentioned earlier, resistance data is fitted to model (3) by means of the generalized least squares and Nelder-Mead minimization algorithm. Such procedure allows to infer the model parameters  $R_0$  and  $t_m$  and thus, predicting the future behavior of connector's resistance. From such prediction, the RUL criterion can be applied and compared against the threshold value to yield the actual RUL estimation.

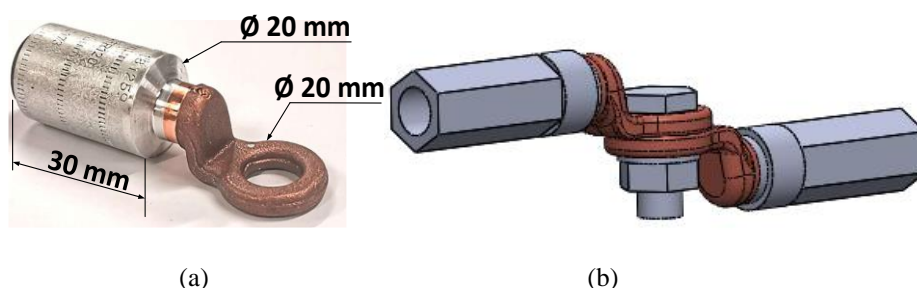


249  
250 **Figure 4.** Steps required to determine the RUL of the connectors.

251 It is worth noting that the approach proposed in this paper, including the experi-  
252 mental results, are focused to confirm the viability of applying this method to determine  
253 the RUL of substation connectors. This implies to add an energy harvesting unit, different  
254 sensors (current, voltage drop and temperature) and wireless communications, through  
255 the *SmartConnector* project [33].

### 256 3.1 Electrical connectors

257 This section describes the bimetallic friction-welded copper-aluminum ICAU120 Al-  
258 Cu compression connectors from the catalogue of SBI Connectors, for aluminum conduc-  
259 tors size 120 mm<sup>2</sup>. They are intended for low- and medium-voltage and are shown in Fig.  
260 5. The aluminum material is EN AW-1050A aluminum according to the EN 573-3:2014  
261 standard [34], whereas copper material is Cu-ETP according to the EN 13601:2014 stand-  
262 ard [35]. To optimize the contact between the connector and the conductor, the barrel is  
263 compressed by means of a hexagonal crimping tool (69 MPa BURNDI EP-1HP) [36] and  
264 the inner surface of the aluminum barrel is covered with contact grease withstanding 140  
265 °C.



266  
267  
268 **Figure 5.** ICAU120 Al-Cu connectors. (a) Before compression. (b) CAD drawing after compression including the bolting  
269 elements.

270 It is noted that the results presented in this work are planned to be applied in substa-  
271 tion connectors by means of the *SmartConnector* project [19]. Apart from the substation  
272 connector, the *SmartConnector* includes a thermal-based energy harvesting system, the  
273 sensors unit (temperature, current and voltage drop) and the wireless data transmission  
274 system. Therefore, the connectors described in this section serve as a previous stage to  
275 validate the feasibility of the proposed approach to estimate the RUL in a faster and eco-  
276 nomical way since due to their geometrical dimensions the current required is lower com-  
277 pared to that required by the substation connectors, thus consuming much less power,  
278 whereas the duration of the heat cycle tests is much lower.

### 279 3.2 Connector degradation stress by applying heat cycle tests

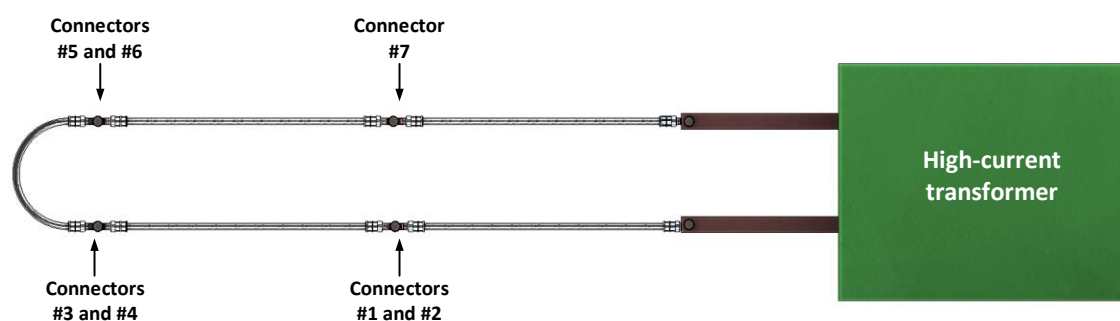
280 In order to acquire on-line experimental data of the degradation of the connectors,  
281 they were degraded by applying heat cycle tests according to the IEC 61238-1-3:2018 in-  
282 ternational standard [37]. Heat cycle tests are commonly used to characterize the thermal  
283 behavior of power connectors and to accelerate the thermal ageing process [38]. Heat cycle  
284 tests generate thermal expansion and contraction cycles, because of the heating and cool-  
285 ing effects, thus affecting the contact spots at the interface and tending to increase the  
286 contact resistance. To this end, an AC (alternating current) electrical current is forced to  
287 flow through the loop so that the conductor reaches the thermal equilibrium at 120 °C.  
288 The IEC 61238-1-3:2018 standard defines the equilibrium as the time instant at which the  
289 temperature of the connector and the reference conductor do not change by more than  $\pm 2$   
290 °C for 15 min. Next, the current is disconnected in order to cool down the loop using  
291 forced ventilation, to bring the loop to a temperature  $\leq 35$  °C. At this point the next heat  
292 cycle starts. A total of 140 heating-cooling cycles according to the requirements of the IEC-  
293 61238-1-3:2018 standard were carried out at the AMBER-UPC laboratory. Experimental  
294 tests were performed at 20 °C and the temperature, the voltage drop and current flowing  
295 through the connectors were measured during the tests. It is noted that the heat cycles are  
296 applied to obtain experimental data for testing the suitability of the RUL approach pro-  
297 posed in this paper. In a real application using the *SmartConnector*, the data from the heat  
298 cycle tests will be no longer required since the on-line data provided by the *SmartConnector*  
299 installed in a real substation will be used instead.

300 The data obtained through the heat cycle tests are used to emulate real service life  
301 data. To this end, an electrical loop consisting of seven ICAU120 Al-Cu connectors and  
302 aluminium alloy conductor with a cross-section of 120 mm<sup>2</sup> was mounted to apply the  
303 heat cycle tests, as shown in Fig. 6. Wire equalizers were used to equalize the voltage at  
304 the measurement terminals and to improve the accuracy of the contact resistance meas-  
305 urement.

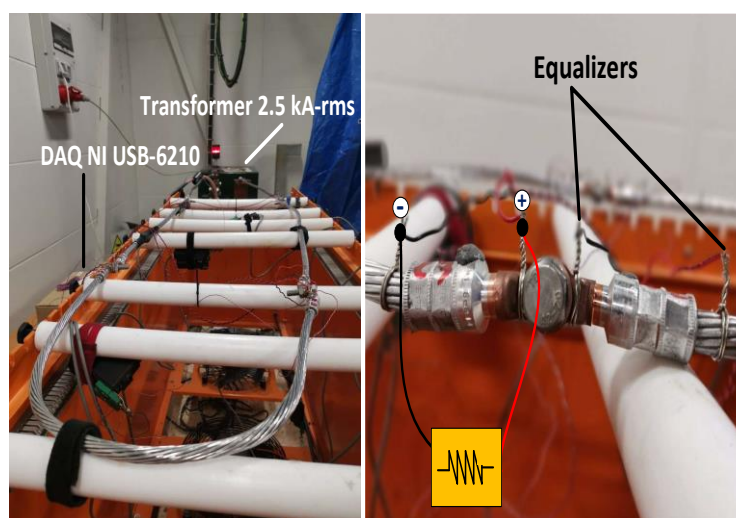
306 Before running the heath cycle tests, the initial DC contact resistance of all connectors  
307 was measured by means of the four wire method in order to have a reference value. Next,  
308 the heat cycle tests were started so that a total of about 140 heat cycles were completed.  
309 Such tests lasted about 92.5 h, during which the temperature, current and voltage drop in  
310 the seven connectors were acquired every 6 seconds. To accelerate the degradation pro-  
311 cess and to reduce the time required to perform the heat cycle tests, the temperature of  
312 the reference conductor during the tests was set to 120 °C, which corresponds to an electric  
313 current between 330 A<sub>RMS</sub> and 380 A<sub>RMS</sub>, but the recommended working temperature is  
314 below 90 °C.

315 The electrical loop during the heat cycle tests was supplied by means of a high-cur-  
316 rent variable transformer (400 V<sub>RMS</sub>/6 V<sub>RMS</sub> with a rated output current of 2500 A<sub>RMS</sub>), as  
317 shown in Figure 6.





(a)



(b)

(c)

**Figure 6.** (a) Schematics of the electrical loop. (b) Loop used in the heat cycle tests. (c) Measurement of the contact resistance.

#### 4. Sensors and equipment used

This section describes the equipment and sensors used to determine the contact resistance, which is the main parameter to determine the performance and the RUL of the connectors.

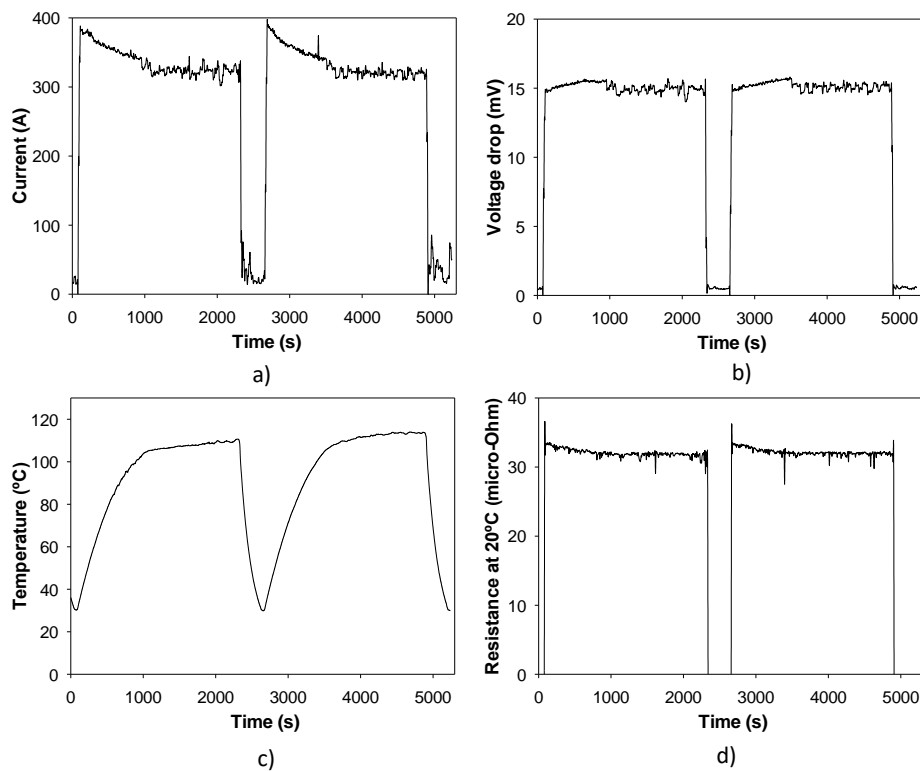
As explained, before running the heat cycle tests, the initial DC contact resistance of all connectors was measured by means of the four wire method, using a calibrated digital micro-ohmmeter (10–200 A,  $0.00\ \mu\Omega$  to  $5\ \Omega$ ,  $\pm 0.1\%$ ,  $0.01\ \mu\Omega$ ; model Micro Centurion II from RayTech GmbH, Bremgarten, Switzerland). This is the reference measurement of the contact resistance, which is used to check that the connector is properly installed before running the degradation heat cycle tests.

The voltage drop AC waveforms across the terminals of every connector were measured during the heat cycle tests by using a DAQ instrument (absolute accuracy  $88\ \mu\text{V}$ , sensitivity  $4.8\ \mu\text{V}$ , 16 bits, 250 kSamples/s; model USB-6210 from National Instruments, Austin, Texas, USA), which includes 8 differential inputs. The 50 Hz waveform of the electric current flowing through the loop was measured with a calibrated Rogowski coil ( $0.06\ \text{mV/A}$  sensitivity,  $\pm 0.05\%$  linearity; model CWT500LFxB from Power Electronic Measurement Ltd, Nottingham, UK) connected to the DAQ. The 50 Hz voltage drop and current waveforms were acquired at a rate of 5 kS/s. This setup ensures a measuring accuracy of the initial electrical resistance better than  $1\ \mu\Omega$  by applying (2).

The first differential input of the DAQ was used to measure the current, whereas the remaining 7 inputs were used for measuring the voltage drop across the connectors. The sample acquisition frequency used in this experiment was 6 samples/second for the cur-

rent and voltage measurements, thus allowing to calculate the resistance of every connector once each 6 seconds. The temperature of the connectors and reference conductor was also measured by using T-type thermocouples and an USB thermocouple data acquisition module (accuracy better than 1 °C, 20 bits, 0.2% ± 0.5°C accuracy, 0.1°C sensitivity; TC-08 from Omega, Bienne, Switzerland).

Figure 7 shows the current, voltage drop, temperature and resistance of connector # during two heat cycles.



**Figure 7.** Measurements done in connector #2 during two heat cycles. (a) Current. (b) Voltage drop. (c) Temperature. (d) Resistance.

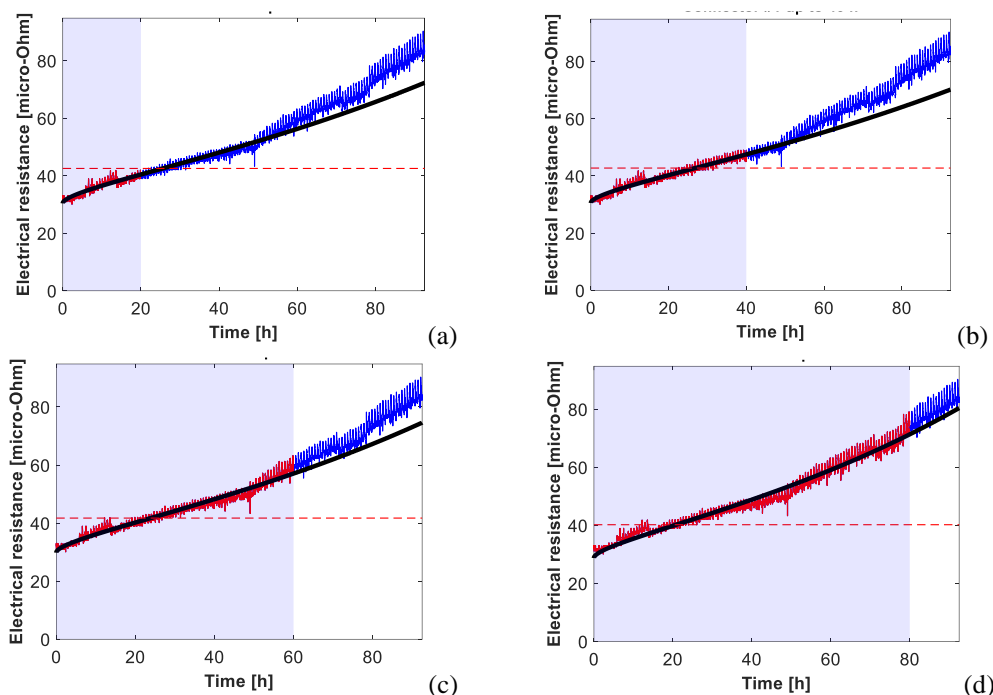
## 5. Experimental results and RUL model assessment

### 5.1 Experimental assessment of the electrical resistance degradation model (ERDM)

This section assesses the suitability of the multi-spot resistance degradation model described by (3). The full set of experimental values of the electrical resistance of the seven connectors dealt with in this work obtained from the heat cycle tests is adjusted by means of (3).

As an example, Fig. 7 shows the experimental evolution of the connector's #1 resistance and the fitting values from (3) and the proposed threshold value to determine the RUL. The experimental connector resistance is calculated from the instantaneous electrical current, voltage drop, phase shift and temperature, according to (2). Results presented in Fig. 7 show that the heat cycles (heating and cooling cycles) are reflected in the instantaneous values of the resistance, since its profile is not smooth since it contains peaks and valleys corresponding to the heating and cooling phases. Results presented in Fig. 7 also show that despite the irregular profile of the resistance evolution with time, the degradation model described by (3) is able to produce a good fitting of the experimental data. To determine the accuracy of the multi-spot model of the electrical resistance in predicting the degradation of the connectors, the coefficients of determination  $R^2$  obtained by fitting (3) to the experimental data are summarized in Table 1. Results summarized in Fig. 7 and

Table 1 evidences the appropriateness and accuracy of the multi-spot resistance degradation model.



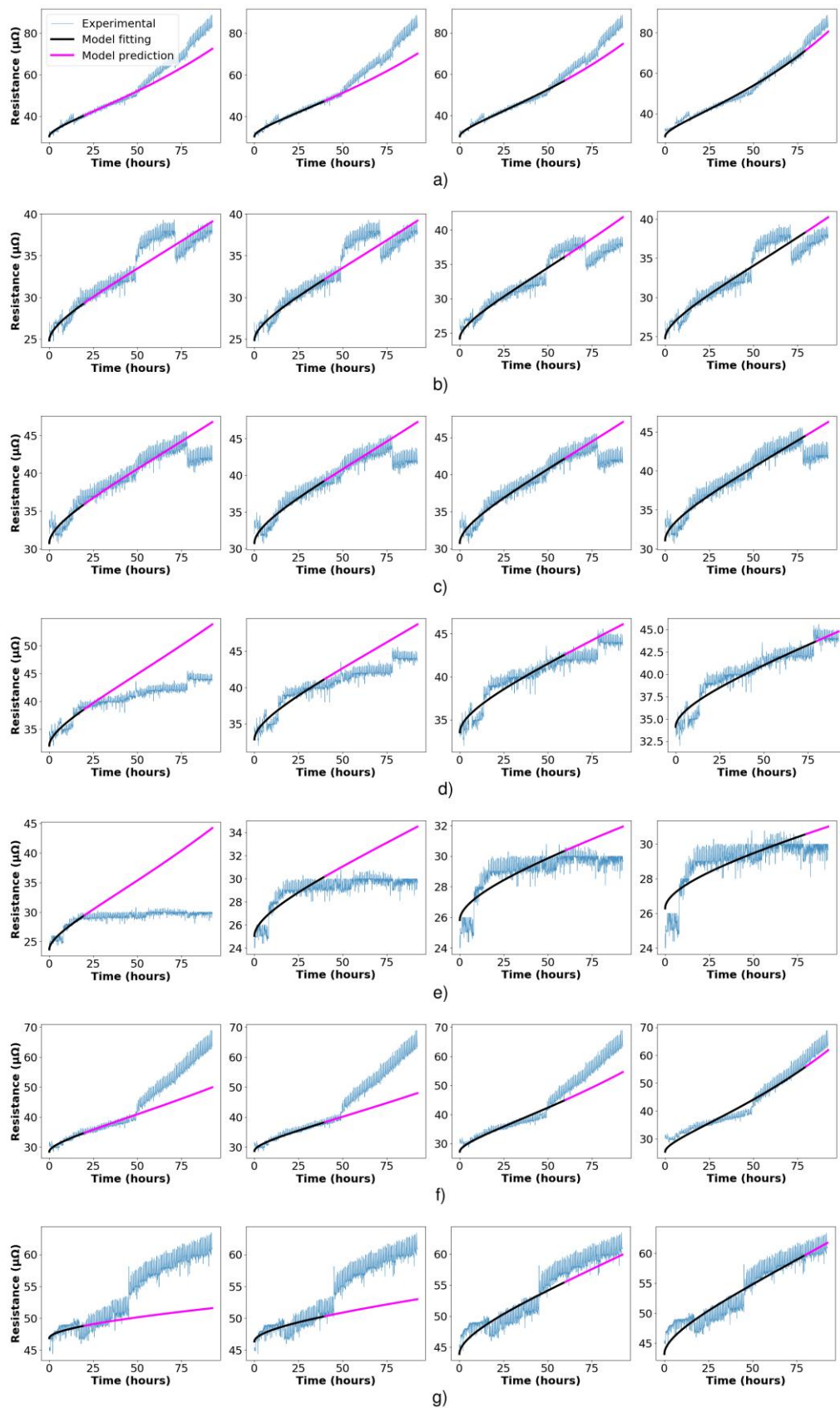
**Figure 7.** Detail of the fitting of the multi-spot electrical resistance models during the 92.5 h of the heat cycle tests for connector #1. Experimental (red-blue) and fitted (black) values of the electrical resistance versus time and threshold value settled by the inflection point of (3). (a) 20-72 model, where 20 refers to the data collected during the first 20 h to fit the model, and 72 refers to the prediction done for the next 72 h ( $R^2 = 0.874$ ). (b) 40-52 model ( $R^2 = 0.967$ ). (c) 60-32 model ( $R^2 = 0.972$ ). (d) 80-12 mode ( $R^2 = 0.981$ ).

**Table 1.** Fitting results of the experimental evolution of connector's resistance according to (3)

Connector	#1	#2	#3	#4	#5	#6	#7
$R_0$ ( $\mu\Omega$ )	28.0	25.3	32.0	34.2	24.4	24.9	43.3
$t_m$ (h)	398.2	1281.8	1936.3	2645.7	5582.7	471.7	1754.4
$R^2$	0.988	0.895	0.882	0.918	0.893	0.967	0.913

### 5.2 On-line RUL prediction based on different prediction horizons

This section describes the experimental results attained through the heat cycle tests and the RUL estimation obtained through the approach shown in Fig. 4. The experimental data is split in two sets, i.e., past and future data like in Fig. 7, in order to simulate a real case in which it is supposed to have the current and past values of the connector's variables (temperature, voltage drop and current), from which the RUL must be determined. The data acquired during the heat cycle tests and labeled as future data, are used to assess the performance and accuracy of the RUL model. The data acquired during the first 20 test hours is used to predict the evolution of the connectors' resistance during the remaining 72 h (20-72), the same for the 40 first hours to predict the remaining 52 h (40-52) and also the 60-32 and 80-12 data models are analyzed. In a real case, this estimation could be done in an hourly basis or whatever suitable interval. Since the data is acquired on-line, the RUL estimation evolves with time according to the contact resistance profile. Sometimes it requires some time before stabilizing, so it is better to have a minimum amount of experimental data collected before applying the RUL prediction, about 20 h in this case. Fig. 8 shows the RUL estimation for the 20-72, 40-52, 60-320 and 80-12 prediction horizons for all connectors #1 to #7.



**Figure 8.** Fitting of the multi-spot electrical resistance models during the 92.5 h of the heat cycle tests until the conductors reach the thermal equilibrium at 120 °C for the seven connectors (#1 to #7) considering four models (20-72, 40-52, 60-32 and 80-12 models). a) #1. b) #2. c) #3. d) #4. e) #5. f) #6. g) #7.

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Table 2 summarizes the main parameters of the RUL estimation using the already mentioned prediction horizons. The RUL values are referred to time zero (installation time). Results shown in Table 2 clearly indicate that the predictive capability of the proposed model evolves with time, so that the model provides a different RUL value at each time instant.

**Table 2.** Fitting parameters and RUL estimation for different connectors using several prediction horizons (time in hours, resistance in  $\mu\Omega$ )

Connector		#1	#2	#3	#4	#5	#6	#7
20-72	$R_0$ ( $\Omega$ )	30.4	24.8	30.8	32.0	24.9	28.4	46.90
	$t_m$ (h)	519.3	1219.8	1369.0	1010.1	11549.6	905.7	14306.3
	RUL (h)	25.0	58.8	66.0	48.7	557.1	43.7	690.1
40-52	$R_0$ ( $\Omega$ )	<b>30.6</b>	24.9	30.8	32.9	24.8	28.6	46.4
	$t_m$ (h)	<b>548.3</b>	1218.3	1321.1	1502.4	8933.4	1023.7	8144.4
	RUL (h)	<b>26.4</b>	58.8	63.7	72.5	430.9	49.4	392.8
60-32	$R_0$ ( $\Omega$ )	<b>29.8</b>	<b>24.2</b>	30.8	33.5	24.8	<b>27.2</b>	43.9
	$t_m$ (h)	<b>486.0</b>	<b>938.9</b>	1339.9	2056.2	9408.6	<b>683.9</b>	2129.4
	RUL (h)	<b>23.4</b>	<b>45.3</b>	64.6	99.2	453.8	<b>33.0</b>	102.7
80-12	$R_0$ ( $\Omega$ )	<b>28.7</b>	<b>24.8</b>	<b>31.1</b>	34.1	24.5	<b>25.4</b>	43.2
	$t_m$ (h)	<b>424.6</b>	<b>1117.1</b>	<b>1481.1</b>	2595.7	6451.3	<b>505.5</b>	1725.6
	RUL (h)	<b>20.5</b>	<b>53.9</b>	<b>71.4</b>	125.2	311.2	<b>24.4</b>	83.2

Bold numbers indicate that the connector has reached its RUL

Results in Table 2 show that each connector has its own RUL evolution profile as a consequence of its particular change of the electrical resistance with time. It is important to note that some of the results presented in Table 2 (marked in bold) would not have been computed in a real life scenario because the RUL prediction has yielded to an early end-of-life and consequent replacement of the connector. See for instance connector #1, for which the fitting and RUL estimation carried out at 20 h predicts that it will last only up to hour 25, so it should be replaced at hour 25.

Table 3 compares the RUL results attained with the electrical resistance degradation model (ERDM) proposed in this work against the widely used autoregressive integrated moving average model, ARIMA ( $p,d,q$ ), where  $p$  is the AR order,  $d$  is the differencing order, and  $q$  is the MA order. Table 3 only analyzes connectors #1-3 and #6 because they reached the end of life (EOL) during the experiments. In addition the ARIMA(2,1,2) model showed better accuracy than other combination of the ( $p,d,q$ ) orders. Results presented in Table 3 shows the better accuracy of the RUL predictions made by the ERDM proposed in this work compared with the ARIMA model. It is worth noting that ERDM is appealing because it combines physical knowledge and data driven approaches, whereas ARIMA only relies on a data driven approach. It is noted that data driven approaches usually include three stages, i.e., data acquisition, health index calculation and RUL prediction [39]. In addition, predictions made by ARIMA highly rely on the and the difficulty to set a priori the ( $p,d,q$ ) orders. The proposed ERDM based RUL estimation strategy presents a considerably low computational effort, since the average computation time required for fitting and estimating the RUL for each of the 28 calculations summarized in Table 2 is about 5 ms when executed over an Intel Core i7-7700HQ CPU running at 2.8 GHz with 8 Gb of RAM, whereas ARIMA requires about 1100 ms to perform the same task.

**Table 3.** RUL estimation for different connectors using ARIMA(2,1,2)\* and the ERDM proposed in this work

Connector	#1	#2	#3	#6	Error [h]	
20-72	Measured	32.7	53.1	72.2	50.8	-
	ERDM	25.0	58.8	66.0	43.7	26.7
	ARIMA	30.8	54.6	55.6	56.8	26.0
40-52	Measured	32.7	53.1	72.2	50.8	-
	ERDM	-	58.8	63.7	49.4	15.6
	ARIMA	-	82.4	> 92	73.1	> 51.6
60-32	Measured	-	-	72.2	50.8	-
	ERDM	-	-	64.6	-	7.6
	ARIMA	-	-	83.6	-	11.4
Total error				ERDM	49.9	
				ARIMA	> 89.0	

## 6. Conclusions

Power substations are commonly inspected by means of visual inspections using thermal infrared cameras, ultraviolet solar blind cameras or drones equipped with different types of cameras. However, these inspection methods cannot be applied very often, since they are expensive and difficult to carry out under adverse weather conditions [40], and do not provide a sufficient amount of numerical data to develop mathematical RUL models, thus this paper contributing in this area. However, the implementation of a *SmartConnector* in a real high-voltage environment is not fully developed, being a challenging task due to the complex systems involved, including energy harvesting, sensing systems and wireless communications. The main drawbacks of this system are related to the use of extra components (the *SmartConnector* itself) and the extra cost, which can be offset by several advantages, since it allows applying predictive maintenance tasks and to minimize the possibility of sudden faults and the associated costs.

This paper has developed a simple approach with very low computational burden to determine the remaining useful life (RUL) of power connectors while in the field. An appealing feature of this approach is that it does not require to perform previous degradation tests on the connectors, which consume high amounts of electrical energy, are expensive and time-consuming. Its main application is found in predictive maintenance plans, since the proposed on-line strategy allows anticipating and planning the moment in which the connector must be replaced based on determining the evolution of its RUL based on the available data. To this end the voltage and the current flowing drop across the connector, as well as its temperature must be acquired on-line and processed to determine the instantaneous value of its electrical resistance. Due to the large number of power connectors installed, their extended service life that is longer than that of the electronics required for an on-line monitoring, only some connectors deserve to be instrumented, those that are in critical links and those that have greater electrical loads, as a poor operating condition could jeopardize the proper operation of critical parts of the system. By using a simple but accurate analytical model of time evolution of the resistance, i.e., the degradation model, the RUL can be easily predicted. This model depends on two parameters which are identified by fitting the equation describing such degradation model to the experimental data by means of a generalized least squares algorithm. The proposed criterion for determining the RUL is based on the inflection point of the equation describing the degradation of the electrical resistance. To validate the proposed approach to determine the RUL, experimental tests performed on seven connectors have been conducted, proving the potential and viability of this method in determining and anticipating when the connector must be replaced before presenting a major failure. It is worth noting that a similar approach can be applied to many other power devices.

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