A Prognostic Framework For Electromagnetic Relay Contacts

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ABSTRACT

Electromagnetic relays provide a well proven solution to switching loads in a variety of applications. However, relays are known for their limited reliability due to mechanical wear of internal switching elements, essentially the life of the relay may be determined by the life of the contacts. Failure to trip, spurious tripping and contact welding, can in critical applications such as control systems in avionics and signaling for rail networks, cause significant costs due to downtime as well as safety implications. Prognostics provides a way to assess the remaining useful life of an electromagnetic relay based on its current state of health.

In this paper, the cause of failure and degradation for electromagnetic relays used in avionic power controllers are examined. A first principle model of an electromagnetic relay, including contact wear is proposed. The degradation observations and measurements form the basis for developing a model based remaining useful life prediction algorithm. Our overall aim is to derive a simple but accurate model of the relays contact degradation, and provide prediction of performance changes within the component.

1. INTRODUCTION

The electromagnetic relay has been around for a very long time, approximately 160 years and is essentially an electrically operated switch; the basic principle of most relays is to use an electromagnet to operate a mechanical switching mechanism. Relays are used for the control of circuits via a low power signal and offer a complete isolation between the control and the controlled circuit. Other advantages are their ability to deal with high surge currents and high voltage spikes, as well as having no leakage current. However, their main disadvantage is the life expectancy, which is low compared with their solid state counterpart.

Relays have many applications, amongst the first uses were in telephony and telephone exchanges as well as early computing. Modern uses are still many and varied, with applications such as amplifying a digital signal, switching large amounts of power with a small operating power; industrial control of machine tools, transfer machines, and other sequential control; detection and isolation of faults on transmission and distribution lines by opening and closing circuit breakers (protection relays); isolation of the control circuit from the controlled circuit and logic functions .

Amongst these applications are signaling in the rail network and the main emphasis of this work, the use of relays to control the power to a Full Authority Digital Engine Control (FADEC) on an aero engine. However, relays are known for limited reliability due to mechanical wear of internal switching elements, and **essentially the life of the relay, may be determined by the life of the contacts**. Failure to trip, spurious tripping and contact welding, can, in critical applications such as control systems for avionics and signaling in rail networks cause significant costs due to downtime as well as safety implications.

Prognostics provides a way to assess the remaining useful life (RUL) of an electromagnetic relay based on its current state of health and its anticipated future usage and operating conditions. In this paper, we examine the causes of contact wear on electromagnetic relays used in an avionic power controller. A first principle model of an electromagnetic relay contact wear is proposed. Our overall aim is to derive a simple but accurate model for electromagnetic relay contact degradation.

2. REVIEW OF ELECTRICAL CONTACTS AND FAILURE MODES

The reliability of electromagnetic relays has been the subject of research for many years; however over the last eight years, research has started to appear on the prediction of reliability within relays based on monitoring their dynamic parameters.

The traditional reliability assessment methods for electromagnetic relays are based on censored failure time data; this provides very little reliability information (Fang et al., 2006). In order to predict the life of the relay, a metric of degradation need to be defined, methods explored include dynamic contact resistance, pick-up time, over-travel time, the rebound duration, closing time, the fluctuation coefficient respectively as the predicted variables of the

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abrasion failure, bridging failure and the contamination failure (Qiong et al. & Xuerong et al., 2010).

The effects of the environment on the reliability prediction can be a major contributory factor, the failure process and failure mechanisms of electromagnetic relay may totally change along with the environment.

As well as the environment, influence factors such as material transfer to the contact gap, the combined influence of the arc energy and the contact surface morphology to the degradation rate of the contact gap, and use of fatigue cumulative damage theory has been explored to establish a failure physical degradation model of the electromagnetic relay contacts (Xuerong et al., 2012). Multiple degradation parameters may be required to give an accurate metric of the failure mechanism.

Due to the complexity of defining a model that can predict degradation throughout the electromagnetic relay, most methods of assessing reliability have been based around time series and regression techniques. (Qiong et al., 2010) showed by using time series analysis and by measuring characteristic parameters as predicted variables, the life of relay can be obtained. However, the conclusions showed the predicted accuracy is greatly influenced by the complex variations of characteristic parameters, and as a result it sometimes becomes too low to be accepted. Life prediction based on wavelet transform and ARMA (auto-regression moving average) time series was proposed to improve this (Yu, Q., 2009).

A linear regression analysis method has been used to establish the linear degradation model which regards the operation time as the independent variable and the predicted variables of the failure mechanisms as the dependent variable (Xuerong et al., 2012).

The work carried out by (Fang et al., 2012) proposes the analyses of the uncertainty of bounce time of contacts for the relay and its use in predicting operating reliability. It changes the contact bounce time into a symbolic series according to the threshold function. The analysis indicates that series entropy of bounce time for bad contacts descend as time goes on; the law can be used to predict the operating reliability.

The work above has been developed on ascertaining the reliability of relays via various methods, however, very little work has been carried out so far in producing a prognostic solution.

2.1. Failure and degradation modes in relays

The following table outlines the failure modes associated with general relays (Fujitsu Components Engineering Reference: Relays, 2009).

Table1. Failure modes in electromagnetic relays

Parts	Stress	Failure Symptoms	Failure Mode
Contact	Voltage, Current, Temp. Vibration, Humidity, Shock, Dust, Gas	Transfer and wear of contact due to arc discharge Weld and bridging of contact Sticking contact Corrosion (oxidation, sulfurization) Foreign matter (dust etc) Deposits	Poor release Poor contact Increased contact resistance Noise Change in operate/release time Poor dielectric strength
Winding	As above	Corrosion Foreign matter Voltage fluctuation Lead wire vibration	Breakage of coil Burning of coil Poor working release operation Change in operate/release time Change in operate/release voltage Malfunction
Structural parts	As above	Fatigue and creep of spring Abnormal wear Seizure Foreign matter (dust) Deposition of worn contact materials Corrosion	Poor contact Poor release Change in operate/release time Change in operate/release voltage Insulation resistance
Enclosure	As above, Chemicals	Damage by external force Chemical damage	Damage (cracks etc.)

Pursuing manufacturer’s data shows that general relays have a life electrical life expectancy of around 100,000 operations minimum with a resistive loading (this is greatly reduced with inductive loads) and a mechanical life expectancy in the order of one million and in some cases 10 and 100 million operations. The reason the electrical life is so low, compared with the mechanical life is because the contact life is application dependant. The electrical rating applies to contacts switching at their rated loads (Holm, 1967). If however, a set of contacts is used to switch a load less than the rated value, the contact life may be significantly higher. The rated electrical life also takes into account arc destruction of the contacts. Arc suppression may be used to lengthen the life of the contact.

As well as arcing, sparking may cause damage at voltages and currents less than those required for arc ignition. The spark is due to capacitive discharge, and compared to a arc is weak, and contributes less to the damage of the contact.

Contact life is deemed to have reached failure when the contacts stick or weld together, or if excessive material transfer has taken place to either one of both contacts and a good electrical contact make is no longer possible. These failure modes are due to successive switching operations and of material loss due to splattering.

The material transfer takes place as a result of joule heating. As the contact area separates, the area of the contacts diminishes. The load current is then force to flow through an ever more constricted area, and this causes a buildup of heat, which reaches such a point where the contact material is melted and then boils. With a dc load, this liquefied material tends to deposit on the cathode of the contact, simply due to the fact that it is cooler than the anode. Material transfer also occurs as a result of arcing, with the transfer being opposite to above and depositing the molten metal on the anode of the contact.

Material loss due to boiling and arcing is from splattering during contact bounce on the closure of the contacts. Although the amount of material loss is minuscule, over tens or hundreds of thousands of operations it becomes significant.

2.2. Contact bouncing

The making of the contacts is not usually finished at first touch, but as a consequence of bouncing (where the force of contacts impacting together causes them to bounce apart), the members make and break their contact several times before they reach a permanent state of contact. This can have implications due to the many disturbances bouncing brings. The exactitude of contact make is lost, and the material transfer by arcs and bridges is increased, since each bounce is the same as a new switch operation. A contact is particularly vulnerable to damage by re-bounce when the current begins with a high inrush as in the case of inductive loads, such loads may result in current in excess of eight times the normal operating current (McBride, 1991)

2.3. Arcing in a d.c. circuit and material transfer

An arc is produced from stored energy in a circuit due to the inductance L. If the current was to suddenly drop to zero in a circuit by the parting of the electrical contacts, then the stored energy in circuit inductance would result in large over voltages given by

$$\boldsymbol{V = -L\frac{dI}{dt}} \tag{1}$$

In a d.c. circuit the duration of the arcing time is related to the magnitude of the arc voltage V_A compared with the circuit voltage V_C. When $V_A > V_C$ a finite time is required to dissipate the $0.5LI^2$ energy stored in the circuit inductance.

One of the most important consequences of arcing is the effect that the arc has on the erosion of the contact material. The contact erosion occurs because with stationary arcs both the cathode and the anode under the arc roots are heated to the boiling point of the contact material (Slade, 1999). The amount of erosion per contact operation depends upon may parameters as summarized by Slade (1999), e.g.,

1. the circuit current
2. the arcing time
3. the contact material
4. the contacts size and shape
5. the contacts opening velocity
6. the contact bounce on make
7. the open gap
8. arc motion on the contacts

Contact erosion is further complicated by mechanical stresses seen by the contact as a result of opening and closing. Slade (1999) defines that in principle the mass lost per operation of contact should be given by

$$\textbf{mass loss = f(total power input into the contacts)} \tag{2}$$

However, this simple equation presents complexities that prevent it ever being established. Firstly, how is mass loss defined? The total mass loss from a contact is a mixture of the following components:

Metal vapor evaporated from the arc roots +
Metal droplets ejected from the arc roots –
Metal re-deposited back onto the contact faces –
Metal deposited from the opposite contact.

As well as the mass loss, calculation of the total power input into the contacts can be difficult, in terms of measurement of arc voltage V_A and circuit current I_C.

Hence calculation of contact erosion is still a topic of research, there is a great deal of literature on contact erosion, but it tends to be application specific and subject to guidance when used for design.

Tables are available giving constant values for example see Holm (1967), for mean values of coefficients characterizing the arc material transfer on making or breaking contact during a long series of operations, ranging from 0.03 to 1.1.

For the relay being used in this work, the contact material is a silver alloy consisting of Silver (Ag) and 40% Nickel (Ni). Hence from the table a material transfer rate γ_p= 0.6 and the loss due to evaporation from arcing is β=0.8.

To conclude, a degree of arcing can be useful to remove oxides and film that collect on the contacts of the relay, but excessive arcing causes reduced life and where arcing suppression is recommended by manufactures, it cannot be eliminated altogether and prediction of how long relay contacts will last.

3. DERIVATION OF DAMAGE AND PROGNOSTIC MODEL FOR ELECTRICAL SWITCHING CONTACTS

A framework for developing a electromagnetic relay contact prognosis takes the form of below.

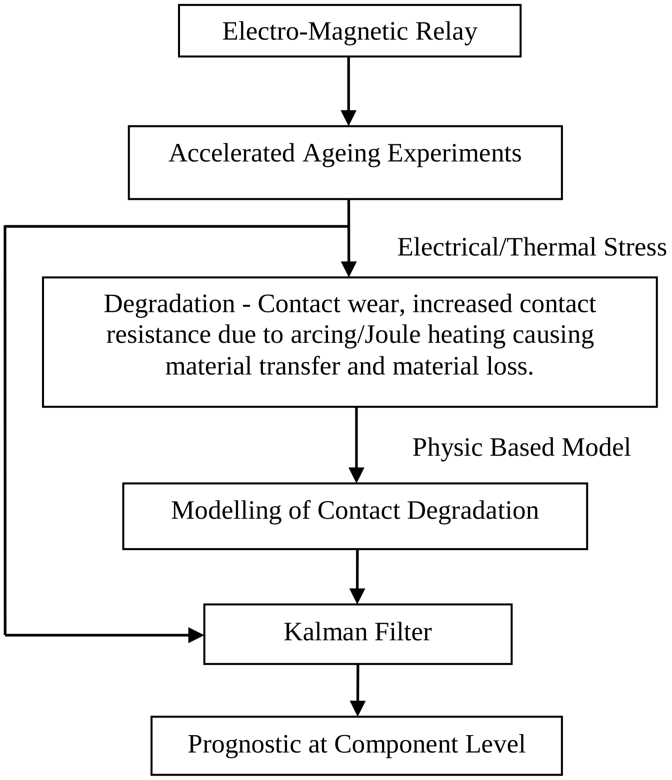

Figure 1. Prognostic framework

3.1. Electrical contact resistance

Any solid surface studied through a microscope will show even the most seemingly smooth finish is in fact undulating. The micro-surface will be composed of peaks and valleys, whose height variations, shape and other geometric considerations vary considerably. When a contact is made between two metals, surface asperities of the contacting members will penetrate the natural oxide and other surface contaminant films, establishing localized metallic contacts and thus, conducting paths. As the force increases, the number and the area of these small metal to metal contact spots will increase as a result of the rupturing of the oxide film and extrusion of metal through the ruptures. These spots, termed a-spots, are small cold welds providing the only conducting paths for the transfer of electrical current. A direct consequence of this is a porous contact where infiltrating oxygen and other corrosive gases can enter to react with the exposed metal and reduce the metallic contact areas. This will eventually lead to disappearance of the electrical contact, although the mechanical contact between the oxidized surfaces may still be preserved (Slade, 1999).

Since electrical current passes only where the small contact spots (also known as a-spots) are electrically conducting (e.g., where electrically insulating films on the contact surfaces are displaced), electrical current is highly constricted as it passes across the interface, as illustrated in Figure. 2. Current constriction gives rise to a *contact resistance* very much like constriction of a water hose increases resistance to water flow. For a circular constriction of radius a, the constriction resistance R_C is given as

$$R_C = \frac{\rho}{2a} \tag{3}$$

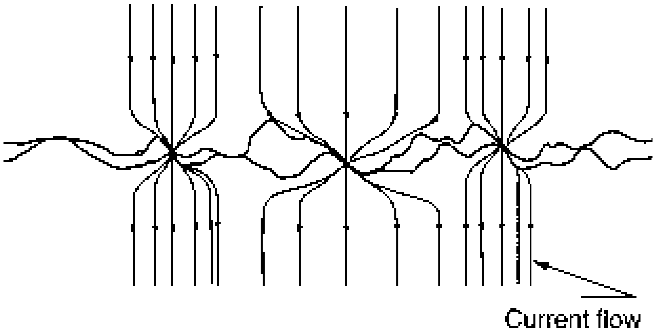

Figure 2. Schematic diagram of contact a-spots and current flow in an electrical contact

The contact resistance R_C between two conductors of resistivity ρ_1 and ρ_2, held together with a force F, is given as (Holm, 1967; Slade, 1999; Braunovic et al., 2006)

$$R_C = \frac{(\rho_1 + \rho_2)}{4}\sqrt{\frac{\pi H}{F}} \tag{4}$$

where H again, is the Vickers' micro-hardness of the softer of the two materials and F is the contact force.

Because the metals are not clean, the passage of electric current may be affected by thin oxide, sulphide, and other inorganic films usually present on metal surfaces. Consequently, the total contact resistance of a joint is a sum of the constriction resistance (R_s) and the resistance of the film (R_f)

$$\mathrm{R_c = R_s + R_f} \tag{5}$$

$$\mathrm{R_f} = \frac{\sigma}{\pi \mathrm{a}^2} \tag{6}$$

where σ is the resistance per area of the film.

The contact resistance is the most important and universal characteristic of all electrical contacts and is always taken into account as an integral part of the overall circuit resistance of a device. Therefore, although it is significantly smaller as compared with the overall circuit resistance, the changes in the contact resistance can cause significant malfunctions of the device. This is because the contact resistance can vary significantly with the changes in the real contact area, contact pressure variations, resistive film non-uniformity, and other factors (Braunovic et al., 2006).

3.2. Effects due to switching

As we are only interested in the switching of direct currents, phenomenon related to this is considered here. In the case of d.c., the arc has no natural weak phase like a.c., where the arc passes through zero, therefore the switch has to extinguish the un-weakened arc at full current.

The function of the switch arc can be described as the generation of an emf V_a (the arc voltage) and a current I_a both of opposite direction to the emf E and current I of the system. If t_a is the life time of the arc, the available energy, W, of the system shall be consumed by the arc during this time with the consequence that, at $t=t_a$, the current through the switch is zero.

$$W = \int_0^{t_a} V_a\, I_a dt = \frac{1}{2} L I^2 + \int_0^{t_a} (EI - RI^2) dt \tag{7}$$

where $\frac{1}{2}LI^2$ is the inductive energy of the system, $\int_0^{t_a} V_a\, I_a dt$ is the energy that the system produces during t_a and $\int_0^{t_a} RI^2\, dt$ is the energy consumed in the resistance, R, of the system as discussed in Holm (1967).

3.3. Modelling of contact degradation

In order to derive a model of the contact wear the heating due to arcing (Holm, 1967) from above is as $W = \int_0^{t_a} V_a\, I_a dt$

Differentiating this equation gives:

$$\frac{dW}{dt} = V_a I_a \tag{8}$$

This equation gives what is termed the Joule heating through the contact.

Further to this, the consideration of material loss and transportation need to be considered. The loss factor ϒ depend upon the latent heat of evaporation and the factor β indicates how many bonds of a molecule are lost (Holm, 1967; Weißenfels &Wriggers, 2008). This factor depends on the choice of the materials and also on the temperature and can range from 0 to 1. Lower values have to be used, if each of the contact member possesses different materials. If the difference of the heat of evaporation between both materials is very high, the factor β decreases. If both members have the same material the value is around 0.2, and if the temperature is very high, at arcing for instance, the factor is close to one.

Equation 8 now becomes

$$\frac{dW}{dt} = \frac{\beta}{\gamma} VI$$

This is now the equation for the computation of wear, $D_{surface}$

$$\frac{dW}{dt} = \frac{\beta}{\gamma} D_{surface} \tag{9}$$

This wear is equivalent to the damage occurring due to the contact resistance changing through degradation. Introducing a new variable to represent the damage

$$\alpha^{contact} = V_{contact} \times I_{contact} \tag{10}$$

The resistance across the contact can be related to Ohms law, where $I_{contact} = \frac{V_{contact}}{R_{contact}}$, where $V_{contact}$ is the voltage measured across the contact and $I_{contact}$ is the current flowing through the contact.

Substituting for $R_{contact}$, $R_C = \frac{(\rho_1 + \rho_2)}{4} \sqrt{\frac{\pi H}{F}}$ an equation for the rate of damage due to Joule heating may be derived and can be determined by the relation.

$$\begin{aligned} \frac{d\alpha^{contact}}{dt} &= \Delta V_{contact} I_{contact} \\ &= (V_{contact} - V_{open}) \times \frac{V_{contact}}{\frac{(\rho_1+\rho_2)}{4}\sqrt{\frac{\pi H}{F}}} \end{aligned} \tag{11}$$

where V_o is the voltage across the contact when it is open.

The above equation now gives the Joule heating equivalent to the voltage appearing across the contact given a derived theoretical contact resistance for the contact. This equation will form the basis for modeling of how the degradation will occur across the contact given a measurement of contact voltage, due to Joule heating. The degradation will increase in proportion to the voltage increasing across the contact.

A dynamic model may now be derived to enable a physical model of contact wear to be estimated.

$$\frac{dW}{dt} = \frac{\beta}{\gamma} D_{surface}$$

can be re-written as a discrete equation by introducing the first order approximation for the change in wear the above equation may be written as

$$\frac{W_t - W_{t-1}}{\Delta t} = \frac{\beta}{\gamma} D_{surface}$$

which gives

$$W_t = W_{t-1} + \frac{\beta}{\gamma} D_{surface}\, \Delta t \qquad (12)$$

similarly, the same procedure may be applied for the degradation equation.

$$\frac{d\alpha^{contact}}{dt} = (V_{contact} - V_{open}) \frac{V_{contact}}{\frac{(\rho_1 + \rho_2)}{4}\sqrt{\frac{\pi H}{F}}}$$

$$\frac{\alpha_t^{contact} - \alpha_{t-1}^{contact}}{\Delta t} = \left(V_{contact} - V_{open}\right) \frac{V_{contact}}{\frac{(\rho_1 + \rho_2)}{4}\sqrt{\frac{\pi H}{F}}}$$

which gives

$$\alpha_t^{contact} = \alpha_{t-1}^{contact} + \left(V_{contact} - V_{open}\right) \frac{V_{contact}}{\frac{(\rho_1+\rho_2)}{4}\sqrt{\frac{\pi H}{F}}} \Delta t \qquad (13)$$

following the framework in figure 1.,this now allows a state-space dynamic model to be formed, this is needed for the Kalman filtering (Grewal & Andrews, 2008). The general discrete state space model takes the form of below:

$$\begin{aligned} x_k &= A x_{k-1} + B_k u + v \\ y_k &= C_k + D_k + w \end{aligned} \qquad (14)$$

where *x* is the state vector, *y* is the measurement vector, *u* is the input or 'control' vector, *A* is the "state (or system) matrix", *B* is the "input matrix", *C* is the "output matrix" and *D* is the "feed through (or feed forward) matrix", if the system does not incorporate feed thorough this is usually zero. Furthermore, *v* and *w* are normal random variables with zero mean and Q and R variance. Q is the model noise variance and is estimated from the model regression residuals and was used for the model noise in the Kalman filter implementation. The measurement noise R, is computed from experimental results.

3.4. Prognostic prediction process

The prediction process is concerned with how the estimate $\hat{x}_k$ will vary when time changes from t_k to $t_{k+1}$is predicted.

$$\begin{aligned} \hat{x}_{k+1}^{-} &= A\hat{x}_k \\ P_{k+1}^{-} &= A P_k A^T + Q \end{aligned} \qquad (15)$$

where the first equation predicts the estimate and the second equation predicts the error covariance.

The equations of state are:

$$W_t = W_{t-1} + \frac{\beta}{\gamma} D^{contact} \Delta t$$

$$D_{surface} = \alpha_t^{contact}$$

$$\alpha_t^{contact} = \alpha_{t-1}^{contact} + \left(V_{contact} - V_{open}\right) \frac{V_{contact}}{\frac{(\rho_1+\rho_2)}{4}\sqrt{\frac{\pi H}{F}}} \Delta t \qquad (16)$$

The state model is given in matrix form as below:

$$\begin{bmatrix} W_t \\ \alpha_t^c \end{bmatrix} = \begin{bmatrix} 1 & \frac{\beta}{\gamma}\Delta t \\ 0 & 1 \end{bmatrix} \begin{bmatrix} W_{t-1} \\ \alpha_{t-1}^c \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{(V_c - V_o) V_c}{R_c} \Delta t \end{bmatrix} \begin{bmatrix} 0 \\ 1 \end{bmatrix} + \begin{bmatrix} v \\ w \end{bmatrix} \qquad (17)$$

where R_c replaces $\frac{(\rho_1+\rho_2)}{4}\sqrt{\frac{\pi H}{F}}$ and α^c is $\alpha^{contact}$. Inserting values for H, ρ, β, γ and using the maximum contact force allows a plot of the contact resistance and damage to be produced to verify the model

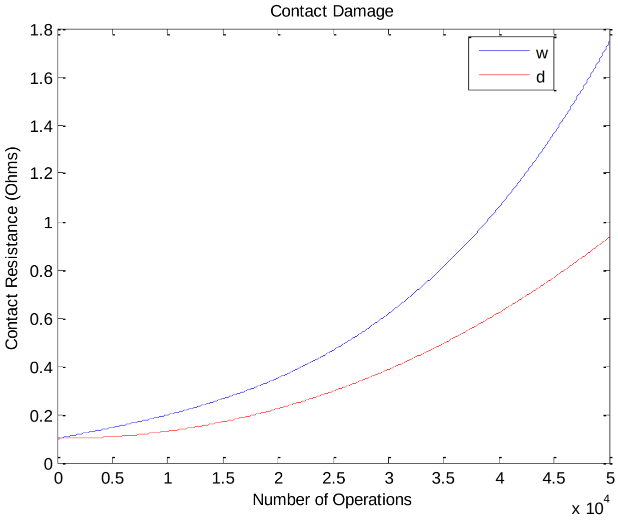

Figure 3. Output from model

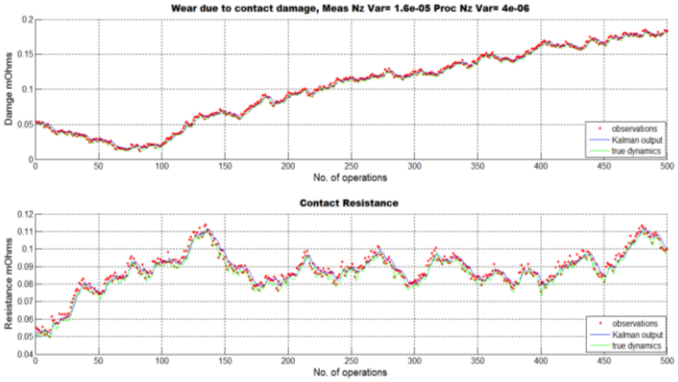

Figure 4. Kalman Filter prediction of damage and contact resistance

In order to produce a forecast of the RUL, the Kalman filter forms a prediction of damage in terms of the future contact resistance from a present resistance measurement (figure 4). Manufactures literature gives the contact resistance when the contact operation is deemed unacceptable. The forecast of RUL, is the number of operations left to reach this point.

4. CONCLUSION

A great deal more work needs to be carried out to model failure modes in order to get a accurate prognostic model of relay contact failure. As well as this, other components in the relay need to be explored and their involvement in the process of the predicting the remaining useful life.

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