FAILURE PREDICTION OF ULTRACAPACITOR STACK USING FUZZY INFERENCE SYSTEM

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Abstract:

The failure of the ultracapacitor was significantly accelerated by elevated temperature or increased voltage. Because of the capacitance difference between the capacitor cells, after a number of deep charging/discharging cycles, the voltage difference between cells will be enlarged. This will accelerate the aging of the weak ultracapacitors and affect the output power. So, to improve stack reliability, a correct and timely failure prediction is essential. Based on diverse faults, a fuzzy rule-based inference system, which could approximate human reasoning, was considered. With this method we can reduce uncertainty, inconvenience and inefficiency resulting from the inherent factors. The simulate results under industrial application conditions are given to verify the method.

1 Introduction

Ultracapacitors are widely used to accomplish the electrical power capability of batteries or fuel cells in various applications [1, 2, 3]. Compared with other energy storage components, the main advantages of ultracapacitors are their long lifetime and their facility to accumulate and to supply energy very quickly [4, 5]. In addition, they can be used to meet peak power requirements in power electronic systems. The shortage is that the maximum cell voltage is limited. The reason is that the decomposition voltage of the organic electrolyte is approximately 3V. To obtain higher voltages, the connection of ultracapacitor cells is necessary. The ultracapacitor stack offers huge capacitance, small series resistance, high power density, long lifetime, high recyclability and easy control by power electronic conversion. These particularities make them attractive for numerous applications, such as energy storage, uninterruptible power system (UPS), traction, etc. [6, 7]. For example, in a hybrid vehicle, the ultracapacitor stack will meet peak power requirement in transient state [8, 9]. In some specific applications, the ultracapacitor stack are deeply charged and discharged with high current [10, 11].
The ultracapacitor stack usually has the shortest life span. This will cause degradation of their energetic and power performances. The problem that often appears in the ultracapacitor stack is the capacitance difference. At this point, the voltage equalization circuit might be the current solution. However, some of the voltage balancing operations are slow. The equipment will be running under high voltage in a short period. This situation still results in the capacitance difference. And after a number of deep charging/discharging cycles, the voltage difference between cells will be enlarged. This will accelerate the aging of the weak ultracapacitors and affect the output power. Therefore, to persuade designers to use

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it largely, in this point of view it is essential to give accurate and clear answers to performances and reliability. Nowadays, the most part of the datum is concerned with the reliability of ultracapacitors without application. Indeed, it is difficult to predict the effective state of the cells, which constitute the ultracapacitor stack. In order to avoid breakdowns and intervene at the convenient moment, the detection of the abnormal one in an ultracapacitor stack remains a priority.

The following methods for studying the reliability of the ultracapacitor stack are to be mentioned. At present, the method mainly used to maintain the ultracapacitor is artificial diagnosis. Maxwell Technologies Inc. has explained the way how different physical measurements are used for extrapolating the vital parameters and for estimating the potential operating lifetime of the system. Tongzhen et al. [12] have proposed an online deterioration diagnosis method for using one vital parameter of the ultracapacitor.. Though human operators can handle these complex situations with their hands-on experience, this procedure is time consuming and needs the knowledge of human experts and experienced maintenance personnel.

Another method presented in these papers is to set a threshold of state of ultracapacitors, and when this limit has been reached, a warning signal is emitted. The output is obtained by the comparison between the initial state of the cell and the one obtained by measurement at different stages used. Then, the output is to be compared with the fixed threshold. Uno et al. [13] studied the ultracapacitor by using a charge-discharge cycling method. The aim was to establish a lifetime ultracapacitor model according to the undergone constraints (Arrhenius law). Rizoug et al. [14] presented the evolution of ultracapacitors characteristics with the number of cycles, and studied the aging of ultracapacitors using direct method of characterization. Veit et al. [15] showed a way how to estimate the calendar lifetime and the power cycle lifetime of an ultracapacitor. In these papers, the authors have shown that the prediction of ultracapacitor reliability depend on mathematical methods. The evaluation was performed using electrical and thermal aging experiments. Actually, the failure mode of ultracapacitors is complicated and various. And, one of the deterioration characteristics of ultracapacitors are time-inconsistency. This approach of using empirical formulas cannot give the precise answer to reliability of the actual system.

This paper presents a method of failure prediction of the ultracapacitor stack based on the fuzzy inference system. This method allows for measurements to compare the parameters of the cell at different position of the ultracapacitors stack. In this case, we only need to measure the input/output of the cells, which constitute the ultracapacitors stack. Measurements can be done in real time. The diagnostic test can be performed at any time, regardless of the degree of failure. The precedent phenomenon (charge redistribution) has no effect on the used algorithm diagnosis. The simulation experimental results under industrial application conditions are given to verify the method proposed.

The remainder of this paper is organized as follows. Section 2 introduces the failure modes of the ultracapacitor stack. An online health diagnosis method based on fuzzy inference is presented in Section 3. Experiment simulation and results analysis are presented in Section 4. The conclusion and future work are presented in Section 5.

2 Failure modes for an ultracapacitor stack

The lifetime of an energy storage component is the time required to failure. Failure is defined as the lack of ability of a component, sub system, system, or equipment to fulfill its intended function as designed. Failure may be the result of one or more faults. Generally, Ultracapacitor life is predominantly affected by a combination of electrical stress and thermal stress [16, 17, 18]. These stresses can be due to the external conditions, i.e., operating voltage and operating temperature [19, 20]. Considering the factors affecting the performance, the failure modes of the ultracapacitor stack are summed up as listed below:

1. More than 20% loss of capacitance.

The capacitance decreases according to the service time. The reason is that the accessible carbon surface and the ions availability are reduced during the electro-chemical cycling.

2. More than 100% increase of the equivalent series resistance (ESR).

The ESR increases according to the service time. The electrode adhesion on the collector is weakening with time and temperature. The ion availability is reduced.

3. Self-discharge above its specified ultimate value.

The self-discharge as an important parameter for the applications could maintain its state of charge. The voltage drop with the time of a charged capacitor in a floating mode may be due to different discharging mechanisms, which are, e.g., the leakage current and the charge redistribution. The ultracapacitor is chronically working in the violent vibration environment or seal failure, which may result in an increase of the leakage current.

4. Cell container opening due to an internal overpressure [21].

The voltage and the temperature generate a gas pressure inside the cell, which increases with operating time. When the pressure reaches a determined limit, a mechanical weak point designed on the container (a mechanical fuse), generally a groove on the can wall or a pressure relief on the lead, may open softly, avoiding an explosion of the device. In case of opening the component, the main observation is an abrupt increase in leakage current, an accelerated increase in internal resistance and an accelerated decrease of capacitance.

5. Leading wire virtual opening.

The pin of the ultracapacitor may break or corrode when working in a strong corrosive environment. In addition, a strong external force may cause the failure.

The failures referred to above have subtle difference in charging/discharging voltage, which are shown in Figure 1.

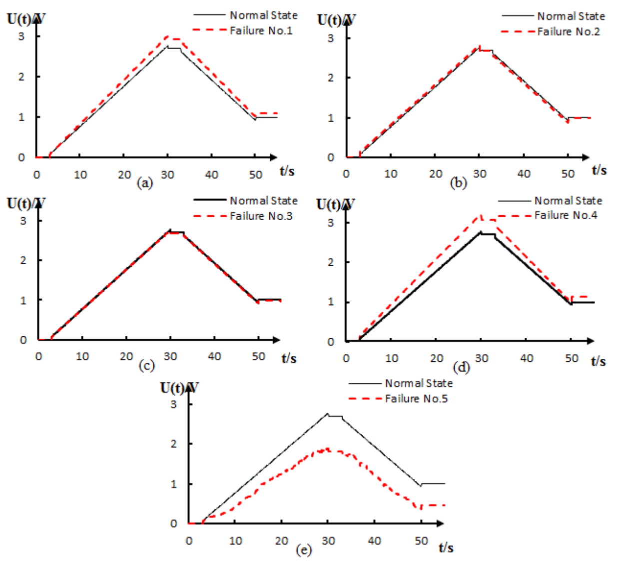

Figure 1. The evolution of voltage as a function of time under different conditions.
(a) The failure mode 1.
(b) The failure mode 2.
(c) The failure mode 3
(d) The failure mode 4.
(e) The failure mode 5.

3 Fuzzy inference system

A correct diagnosis of ultracapacitor failure mode needs to consider many symptoms of operating parameters in practical application. Due to nonlinear, time-varying behavior and uncertainties and ambiguities about the failure causes, it is difficult to deal with ultracapacitor failures with precise mathematical equations. Fuzzy logic provides a precise approach to dealing with uncertainty. Therefore, in this study, the Fuzzy inference system (FIS) gives a proper prediction. FIS is the process of formulating the mapping from a given input to an output with fuzzy logic.

In general, the composition of FIS is the fuzzification, knowledge base, fuzzy inference engine and defuzzification. The structure of FIS is shown in Figure 2. In this figure, x is the input (crisp) value, u(x) is fuzzier output value, u(y) is the result of inference operation and y is the output value. Fuzzification unit converts definite (crisp) data in the input of the classifier to the format of linguistic variables. The Fuzzy knowledge base is composed of the database and the rule base. Database includes the definition of all variables, whereas the rule base covers inspective rules, which are necessary to perform the inference. Inference unit is a platform for performing inference based on fuzzy rules or other operators. This unit performing the operation is similar to the way people think. Finally, defuzzification unit converts the fuzzy values obtained from the output of inference unit to numerical (crisp) values.

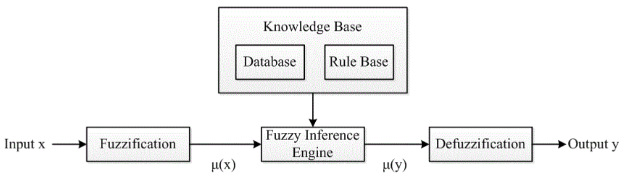

Figure 2. The structure of a fuzzy inference system.

3.1 Fuzzification

Fuzzification is the process of transforming crisp values into grades of membership for linguistic terms of fuzzy sets. Linguistic variables are defined in linguistic terms. The application of classical two-valued logic is not appropriate because fuzzy sets provide a basis for the systematic manipulation of such linguistic variables [22]. A fuzzy inference system uses a collection of fuzzy membership

functions and rules instead of Boolean logic used for the reasoning process.
To carry out this fuzzification process, two decisive factors have to be specified, i.e., the universe of discourse and the membership function. The universe of discourse is the numerical range of the inputs, normally referring to the range of the x-axis in the graph of the fuzzy set. Its range limits the input values, which are constrained within the special range. The universe of discourse is normally divided into several regions, which belong to different predicates. Such as low (L), rather low (RL), normal (N), rather high (RH) and high (H).
Membership function (MF) defines the degree of an elements membership in a fuzzy set:

$$\mathrm{A} = \sum_{i=1}^{n} \frac{u_A(x_i)}{x_i}\,. \tag{1}$$

Equation (1) is the general mathematical expression of fuzzy subset A of X, where X is the whole data set and X_i is an element of subset A and $u_A(x_i)$ is the membership function of element X_i in the universe of discourse when the support set is a finite set:

$$X = \{x_1, x_2, x_3, \dots, x_n\}. \tag{2}$$

Triangles and trapezoids are the most frequently used shapes as they are relatively simpler in terms of calculation. The input fuzzy set comprises several membership values from different fuzzy inputs. Because of the best efficiency point at which the efficiency is highest and all other points to the left or right of the value have a lower efficiency is unique. In this study, the triangular membership functions are used for the inputs. All inputs are expressed as triangular fuzzy numbers, for example, if the values of x lie between 0 and 30. Figure 3 shows how the predicate functions form the composition of the fuzzy set. These predicates have special shape, height and line style to represent their membership function.

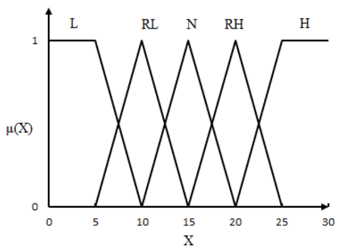

Figure 3. The membership functions of the fuzzy sets.

3.2 Knowledge base

Knowledge base is the aggregation of database and rule base. Database includes the definition of each system variable using fuzzy set. In this study, four kinds of input data and one value of output data were chosen as the input and output of the fuzzy system, as shown in Fig.3. The inputs include: (i) $\widetilde{V_C}$ represents the voltage difference between the single and the average of the array in charge status. (ii) ΔV_C represents the voltage difference of the individual cell in charge status. (iii) $\widetilde{V_D}$ represents the difference between the single and the average of the array in discharge status. (iv) ΔV_D represents the voltage difference of the individual cell in discharge status. (v) The output variable is defined as the FC (Failure Cause).

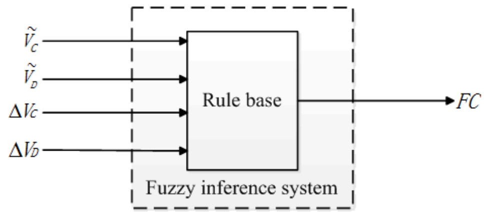

Figure 4. Inputs and outputs of the fuzzy system.

The behavior of a fuzzy system is characterized by a set of linguistic rules, which constitutes a rule base. A fuzzy rule is composed of two parts, namely an IF-part and a THEN-part. Unlike the conventional rule-based mechanism, fuzzy rules allow for the use of imprecise, uncertain and ambiguous terms. A typical linguistic rule takes the following form [23]:
If (a set of conditions is satisfied), then (a set of consequences could be inferred).
The antecedents (statement before "THEN") describes to what degree the rule is applied, while the consequents (statements after "THEN") assigns a membership function to the output variable.
A linguistic fuzzy rule with more premises is of the form of the following example:
If x_1 is A_1 and x_2 is A_2 and … and x_n is A_n; then y is B;
Where x_1 and x_2 and … and x_n are input variables, A_1 and A_2 and … and A_n are input linguistic terms represented by fuzzy sets, y is an output variable and B is an output linguistic term represented by fuzzy sets. Statements in the antecedent (or consequent) parts of the rules may well involve fuzzy logical connectives such as "AND" and "OR". In this case,

the IF-part contains many inputs which are connected with the operator "AND'.
The linguistic rules of this fuzzy system were displayed in Table 1 for ease searching.

Table 1. The linguistic rules for this system

Rule no.	***If (antecedent)***	***Then (consequent)***
Rule 1	$\widetilde{V_C}$ is high and ΔV_C is slightly fast	Capacitance is too low
Rule 2	$\widetilde{V_D}$ is low and ΔV_D is slightly fast	Capacitance is too low
Rule 3	$\widetilde{V_C}$ is slightly high	ESR is too large
Rule 4	$\widetilde{V_D}$ is slightly low	ESR is too large
Rule 5	$\widetilde{V_C}$ is very high and ΔV_C is fast	Cell opening
Rule 6	$\widetilde{V_D}$ is very low and ΔV_D is fast	Cell opening
Rule 7	$\widetilde{V_C}$ is very high	Leading wore turn off
Rule 8	$\widetilde{V_D}$ is very low	Leading wore turn off
Rule 9	$\widetilde{V_C}$ is slightly high and $\widetilde{V_D}$ is slightly low	Self-discharge is too large

3.3 Fuzzy inference engine

Based on fuzzy concepts, fuzzy inference engine imitates the reasoning process of the domain experts to seek information and relationships from the rule base and to provide answers, predictions and suggestions. Fuzzy outputs are inferred by using fuzzy implication and rules of inference in fuzzy logic. The inferred fuzzy output of the system is the aggregated result derived from all individual fuzzy rules. This refers to the THEN-part of the rules using the results of composition with different implication operators such as the Mamdani operator, Larsen operator and Zadeh operator, etc. Different operators generate different implication results involving various mathematical calculations and expressions. The Zadeh operator is used by the intersection operator, whilst the Mamdani operator and Larsen operator are used by the union operator. Union aggregation maximizes all the fuzzy sets generated in implication, and intersection aggregation maximizes the same parts of all the fuzzy sets. Since the main feature of Mamdani-type fuzzy inference system is that the rules are explained in linguistic variables, and as a consequence it is more compatible with the reasoning process of human operators. In this study, a Mamdani-type fuzzy rule-based inference system is used. Mamdani-type fuzzy inference system used Classic max-min compositional operation method to dispose the fuzzy relation and fuzzy set.
Premise: x is X;
Rule: if x is A, then y is B;
Consequence: y is Y.
The procedure of The Mamdani inference algorithm is as follows:
Calculate the degree of fulfillment of the antecedent for each rule i:

$$w_i = u_{A_{i1}}(x1) \wedge u_{A_{i2}}(x2). \quad (3)$$

Use the minimum t-norm for each rule to derive the output fuzzy set:

$$u_{B_i{}'}(y) = w_i \wedge u_{B_i}(y)_j. \quad (4)$$

Take the maximum (union) to aggregate the output fuzzy sets:

$$u_{B'}(y) = \vee_{i=1,2,\ldots n}(u_{B_i{}'}(y)), \quad (5)$$

where n is the number of rules, A_i and B_i are the fuzzy sets, x is antecedent variable representing the inputs in the fuzzy system, y is the consequent variable related to the output of the fuzzy system, and $u_{B'}(y)$ is the output fuzzy set resulted from the fuzzy inference mechanism.

3.4 Defuzzification

This is the final stage in the fuzzy system. In the defuzzification process, the output fuzzy set stemmed from the fuzzy inference mechanism is mapped to a crisp value or linguistic values. There are many defuzzification methods for performing defuzzification, including center of the area, maximum possibility, the mean of maximum possibilities, the center of mass of the highest intersected region, etc. One of the common techniques for performing difuzzification is the maxima method, which returns a point with the highest degree of membership in the fuzzy output. However, in most practical cases there might be many points having the same maximum degree of membership in the output fuzzy set. In this study, due to discrete feature of the output variable (failure cause), and descending order of the failure causes in the output space (based on the probability of the failure causes), and the simplicity and speed of the maxima method in the calculation, the maxima method with threshold is used. The threshold is determined by the practical application.

4 Experiment

In this section, the proposed fuzzy inference approach is applied to the ultracapacitor stack. The actual operation includes fault simulation presented in Saber (Saber is a simulation program that simulates physical effects in several engineering domains such as mechanical, hydraulic, thermal and electric), and fault diagnosis in MATLAB. The equipment being studied in this research is one kind of K2 series ultracapacitors made in Maxwell.

4.1 Fault Simulation

The test circuit developed for this study is shown in Figure 5. The ultracapacitor stack is composed of 8 Maxwell elements (BCAP 1200/1200F/2.7V). This stack has a controlled charge/discharge current. The choice of the cycles is based on the kind of the application.

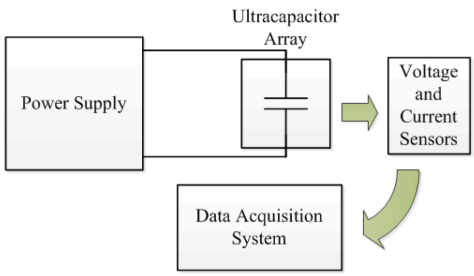

Figure 5. Synoptic of the test circuit.

The cycle duration is 50 s with two steps of current of 120A during 17 s (Tch = Tdech = 17 s). These specifications obtain rms current of 99A. Furthermore, the voltage varies between the maximum (21.6 V) and the minimum (8 V). These cycle specifications allow for the elements temperatures up to 25℃. Figure 6 shows the current and the voltage obtained during the cycling process. And numerous electrical data should be selected in order to analyze the behavior of each element in the module.

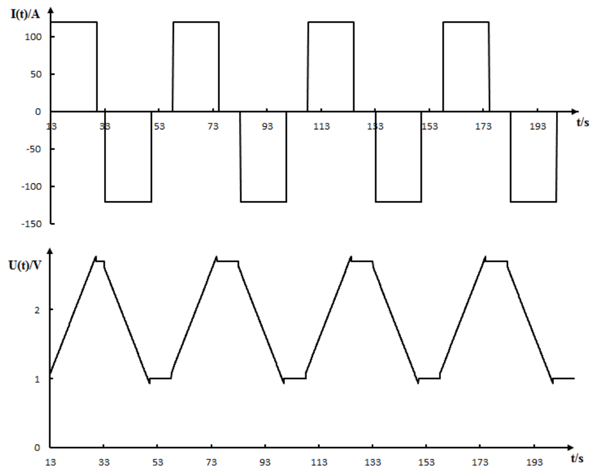

Figure 6. The current and voltage during the cycle.

4.2 Fault Diagnosis

The fault diagnosis system consists of the signal processing and the fault inference implemented in MATLAB. In the signal processing using the information monitoring (which includes the voltage and current of the single cell) mathematic calculation is done. Fault inference utilizes the fuzzy logic approach to classify faults under different operating conditions. In this work, the voltage and current of every component in the array were preserved during the circle. By using the current datum, the current state of charge, discharge and standing are distinguished. Then, when calculating the value of symptoms difference methods are used. $\widetilde{V_C}$ and $\widetilde{V_D}$ are obtained by calculating the voltage difference between single and the average of the array in 0.5 seconds. ΔV_C and ΔV_D are obtained by calculating the rising (descending) voltage value in 1 second. The time period is the trade-off between computational efficiency and accuracy. After extracting the features in the signal processing, the fuzzy logic inference approach is used in the proposed fault diagnosis. First, the triangular membership functions are used for the inputs. The four inputs are modeled into different fuzzy sets as shown in Figure 7.

Input 1. The voltage difference between the single and the average of the array in charge status:

$$\widetilde{V_C} = \sum_{i=1}^{n} \frac{u_{\widetilde{V_C}}(\widetilde{V_{C_i}})}{\widetilde{V_{C_i}}}, \qquad (6)$$

where $\widetilde{V_C}$ is the fuzzy set, $\widetilde{V_{C_i}}$ is an element in the data set, $u_{\widetilde{V_C}}(\widetilde{V_{C_i}})$ is the membership function and

$$\widetilde{V_C} = \{SH, H, VH\}, \tag{7}$$

where SH is slightly high, H is high and VH is very high.

The mathematical expressions of the rest inputs were similar to the input 1. Furthermore, the finite sets were different:

$$\widetilde{V_D} = \{SL, L, VL\}, \tag{8}$$

where SL is slightly low, L is low and VL is very low.

$$\Delta V_C = \{SF, F\}, \tag{9}$$

where SF is slightly fast and F is fast.

$$\Delta V_D = \{SF, F\}, \tag{10}$$

where SF is slightly fast and F is fast.

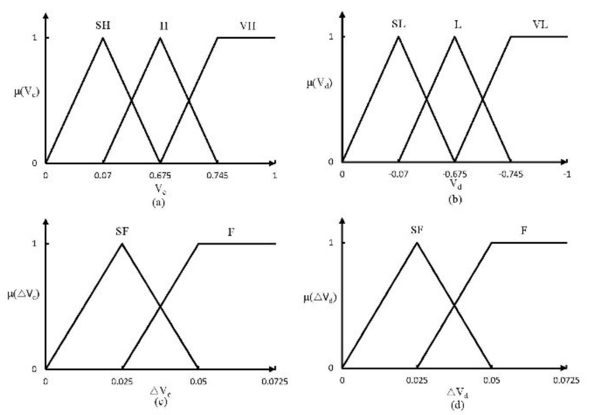

Figure 7. The fuzzy sets of those inputs are shown in (a–d). (a) The fuzzy set u($\widetilde{V_C}$). (b) The fuzzy set u($\widetilde{V_D}$). (c) The fuzzy set u(ΔV_C). (d) The output fuzzy set u(ΔV_D).

According to the situation analysis, the universe of discourse for:(i) $\widetilde{V_{C_i}}$ in fuzzy set $\widetilde{V_C}$ is 0-1 V. (ii) $\widetilde{V_{D_i}}$ in fuzzy set $\widetilde{V_D}$ is -1-0V. (iii) ΔV_{C_i} in fuzzy set ΔV_C is 0-0.0725 V. (iv) ΔV_{D_i} in fuzzy set ΔV_D is 0-0.0725 V.

The output variable is defined as the ‘‘Failure cause”, and since the output is a discrete choice, the singleton membership function is employed for representation of the output variable. The discrete elements were {1,2,3,4,5}, which represent the failure mode number.

The membership functions including $u_{SH}(\widetilde{V_C})$, $u_H(\widetilde{V_C})$ are converted into mathematical form as shown below.

$$u_{SH}(\widetilde{V_C}) = \begin{cases} \widetilde{V_C}/0.07; & \widetilde{V_C} \in [0, \quad 0.07] \\ (0.675 - \widetilde{V_C})/0.605; & \widetilde{V_C} \in [0.07, 0.675] \end{cases} \tag{11}$$

$$u_H(\widetilde{V_C}) = \begin{cases} (0.675 - \widetilde{V_C})/0.605; & \widetilde{V_C} \in [0.07, 0.675] \\ (0.745 - \widetilde{V_C})/007; & \widetilde{V_C} \in [0.675, 0.745] \end{cases} \tag{12}$$

Let’s take the membership function of an element as an example.

Substituting $\widetilde{V_C}$ = 0.55 into Eqs. (11) and (12), the crisp value intersects with the predicates function of SH and H and the resultant membership values are: $u_{SH}(0.55) = 0.21; u_H(0.55) = 0.79$.

The same is valid for the element $\widetilde{V_C}$. Substituting $\widetilde{V_D}$ = -0.58, ΔV_C = 0.036, ΔV_D = 0.035 into the membership function, the resultant membership values are: $u_{SL}(-0.58) = 0.16$, $u_L(-0.58) = 0.84$, $u_{SF}(0.036) = 0.56, u_F(0.036) = 0.44$, $u_{SF}(0.035) = 0.6$, $u_F(0.035) = 0.4$.

After the fuzzy sets and membership values are determined, only part of rules can be set up in the rule block. The linguistic rules are extracted as it was displayed in Section 3.2. In this example, there are five firing rules: Rule 1, Rule 2, Rule 3, Rule 4 and Rule 9.

Then, the activated rules are processed to determine the output fuzzy set by a Mamdani operator, which is discussed in Section 3.3. In the inference engine, the purpose is to determine the fuzzy relationship between the inputs and the output. The fuzzy relationship was based on the experimental result and experience.

For the given input data, the output variable FC can be: $u_1 = 0.6, u_2 = 0.21, u_3 = 0.16$.

Finally, Crisp values or linguistic values can be obtained through the defuzzification process according to the maxima method with threshold: FC (1) = 0.6.

The value in the bracket represents the failure mode, and the 0.6 represents the extent of the damage. So the conclusion was that this capacitor broke down because the capacitance decreases.

With reference to the ultracapacitor stack, the hypothesis was that one component was broken and the other next to useless in the fault simulation. The voltage of each ultracapacitor was shown in Figure 8. In the figure, the red line represents the one next to useless and the black line represents the broken one. In the fault diagnosis, the inferred outputs are shown in Table 3. From the table, we can see the Ultracap.uc2 and Ultracap.uc5 which are about to break down. Compared to the practical matters, the result is suitable.

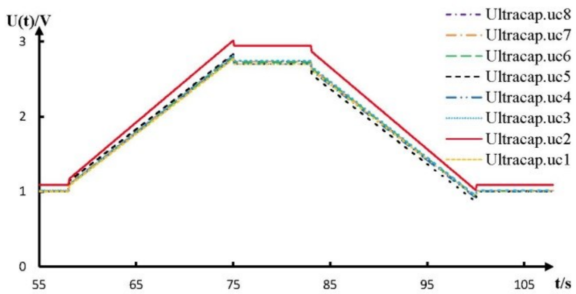

Figure 8. The voltage of 8 elements in the fault simulation.

Table 2. The result in the fault diagnosis

Element no.	***Failure cause diagnosed***
Ultracap.uc1	FC(0)
Ultracap.uc2	Capacitance decrease(0.53)
Ultracap.uc3	FC(0)
Ultracap.uc4	FC(0)
Ultracap.uc5	Series resistance increase(0.86)
Ultracap.uc6	FC(0)
Ultracap.uc7	FC(0)
Ultracap.uc8	FC(0)

4.3 Results and discussion

To validate the proposed FIS, eight random failures of the ultracapacitor under studyare selected from the previous field failure reports. The application state and fault types of the tested ultracapacitor obtained from experimental and the estimated results are presented in Table 3. The difference between two methods for determining the fault is due to the fact that the methods implemented the FIS. The abnormal parameters are represented in the table with the red markers. As demonstrated in Table 3, he results also show that the proposed fuzzy inference system is well capable of diagnosing the correct failure causes.

Table 3.The result in the fault diagnosis

Failure mode no.	**Parameter setting**				**Failure cause diagnosed**
	C(F)	***ESR(mΩ)***	***(mA)***	***Leading wire***	
1.Normal	1200	0.58	0.25	Y	FC (0)
2.Abnormal	1000	0.58	0.28	Y	FC (1)
3.Abnormal	1200	1.1	0.35	Y	FC (2)
4.Abnormal	670	23	0.46	Y	FC (4)
5. Normal	950	0.75	0.36	Y	FC (1)
6.Abnormal	1150	0.65	0.8	Y	FC (3)
7. Normal	1050	1.2	0.54	Y	FC (2)
8.Abnormal	1150	0.6	0.4	N	FC (5)

5 Conclusion

In this paper, due to nonlinear, time-varying behavior and imprecise measurement information of the systems, a FIS was proposed for failure diagnosis of the ultracapacitor module. Firstly, some failure modes of the ultracapacitor were acquired through experiments. And, some electrical characteristics were observed when it failed. Secondly, the FIS was designed based on the observation. Finally, the proposed approach was tested and applied to the ultracapacitor array. The diagnoses in the running state show an acceptable performance.

The implementation of the proposed approach in the industry would result in: (1) Reduction of repair time by eliminating the long time needed for human operators to find out the failure reason. (2) Reduction of human error. (3) Creation of expert knowledge which could be used for training. (4) Reduction of unnecessary expenditures for upgrades by providing the earlier diagnosis of the faults. (5) Improvement of the reliability and safety of the system by enhancing the maintenance strategies.

Furthermore, we intend to implement the FIS in experiments. And, in order to improve the fuzzy rules and fuzzy system intelligence, we will use the learning and prediction capability of neural network.

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