

Assessing Circuit Breaker's Electrical Contact Condition through Dynamic Resistance Signature Using Fuzzy Classifier

M. Khoddam*, J. Sadeh^(C.A.) and P. Pourmohamadiyan*

Abstract: Circuit Breakers (CBs) are critical components in power system for reliability and protection. To assure their accurate performance, a comprehensive condition assessment is of an imminent importance. Based on dynamic resistance measurement (DRM), this paper discusses a simple yet effective fuzzy approach for evaluating CB's electrical contacts condition. According to 300 test results obtained from healthy and three defected electrical contacts, the authors describe the special effect of common failures on DRM characteristics and propose seven deterioration indicators. Using these parameters, a fuzzy classifier is suggested to accurately determine contact sets condition. The salient advantage of the proposed model is its capability to recognize the type of contact failure. The feasibility and effectiveness of the proposed scheme has been validated through 40 real life recorded data of some electrical contacts.

Keywords: Condition assessment, Circuit Breaker (CB), Electrical contact, Dynamic Resistance Measurement (DRM), Fuzzy logic, Fuzzy classifier.

1. Introduction

Circuit breakers are extremely important components in power system reliability, control and protection. Fast and secure fault interruption are very vital as it involves isolating faulty part of power system to prevent possible cascading outages, which may lead to a blackout [1, 2]. Modern high voltage puffer type SF₆ gas CBs are designed based on switching two parallel contact sets. First, the main contacts are designed to carry the load current without any excessive temperature rise. Second, the arcing contacts operate at breaker opening following the main contacts part [3]. Since the main contacts are just expected to pass the load current, they usually do not degrade by the effects of arcing current. On the other hands, the arcing contacts are subjected to the arcing discharge and thus faced to arcing effects [3, 4]. In fact, interrupting large fault currents at high voltages involves high thermal stresses being placed on arcing contacts. The energy released by the electric arcing has the ability to induce rapid material erosion at the arcing contacts [3-5]. This erosion and its effects such as changing contact geometry, directly

reflects on a significant decrease in the breaking capacity and working condition of the CB and associated electrical circuit [4-8]. So, it is considered necessary to develop condition monitoring technique which can assess healthiness of main and arcing contacts of CBs. Dynamic resistance measurement (DRM) is a simple, effective and appropriate method to evaluate the contacts condition. This method is performed when the breaker is out of service and consists of applying high DC current through the contact system, measuring the voltage drop across the contact and calculating the resistance [3-4, 9]. DRM has been investigated from various perspectives in the recent literature. For instance, Ref. [3] reports effects of metallic products produced during arc quenching on contact resistance in SF₆ circuit breaker. Authors of [10-12] observed several spikes in the resistance curves which could be the result of a partial contact part during the contact separation. Ref. [4] suggests that the DRM test should carry out at low contact speed (0.002-0.2 m/s) in case of reproducible resistance curve to be obtained, but authors of Ref. [13] find that this method is instructive for some breaker mechanisms. Since an adjustment to the operating mechanism is required, there is a potential risk of damaging the operating mechanism when restoring it back in service. One of the difficulties with DRM is that interpretation of its data is acutely depended on the operator knowledge, which might result in an incorrect condition assessment of the contact performance. To overcome this

Iranian Journal of Electrical & Electronic Engineering, 2017.

Paper received 5 December 2016 and accepted 17 March 2017.

* The Authors are with the Department of Electrical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Mashhad, Iran. E-mails: marya.khoddam@stu.um.ac.ir, sadeh@um.ac.ir and pourmohamadiyan@um.ac.ir.

Corresponding Author: J. Sadeh

drawback, Ref. [14] describes the use of Arduino platform as a solution for measuring the dynamic contact resistance curve. This platform is an open source electronic prototyping one which can receive analog or digital input from a variety of sensors. However, it has some limitations such as the sampling rate. Ref. [15] proposes a software solution for analyzing the dynamic resistance measurement results for high voltage circuit breaker. This software is capable to calculate the main contact resistance, time difference between main and arcing contact separation (which is called overlapping time) and contact travel using dynamic resistance and motion waveforms instantly. However, this software does not reveal the normal/abnormal status of the contacts and interpretation of the results is still depending on operator's knowledge. Some DRM indicators that can assist in the contacts diagnosis are introduced in [4, 16]. Their results suggest that the evolution of the curve area is directly proportional to the wear level of the main and arcing contact. But according to Ref. [17], curve area is increased in other contact failures and then it could not be considered as a unique sign for contact wear defect. The correlation between the various levels of contact degradation and DRM properties is scrutinized in Ref. [17], five DRM indicators including maximum and average of main/arcing contact resistance and overlapping time are extracted, then using scoring and weighting techniques, health index is applied to classify contact performance as healthy, need caution and risky.

As it is briefly reviewed, large number of previous works tried to modify the DRM test but none of them was

successful in finding type of contact failure through its DRM signature. This paper presents a new DRM approach to prepare an intelligent decision-making strategy for identifying healthy versus different faulty conditions of electrical contacts. The proposed failure detection technique is based on the results of exploring the characteristics of DRMs corresponding to various healthy and some faulty conditions. Seven eminent features of DRM are extracted and their changes during three faulty conditions are investigated to precisely detect different defects in CBs and distinguish between them correctly. In the following step, the overlap margins of selected features are recognized and then a fuzzy classifier is implemented to assess condition of contact sets.

Worthy to note is that for obtaining a greater accuracy in the level of contact degradation and DRM characteristics, monitoring of the process since the initial stage until advanced stage of the defect is suggested. For failure modes, weld spotted contacts, eroded arcing contacts and misaligned contacts are taken into account. Results of this study will provide a powerful diagnostic tool for CB's electrical contacts health management.

2. Experimental setup

Fig. 1 shows a schematically drawing of the break apparatus and arrangement of other necessary items used in the experiments. A regular 12V/220 Ah car battery is used as a power source for high current injection. The current passing the contacts is measured via a 1 mΩ non-inductive shunt resistance. All signals are recorded with a digital storage oscilloscope with 50 GHz bandwidth.

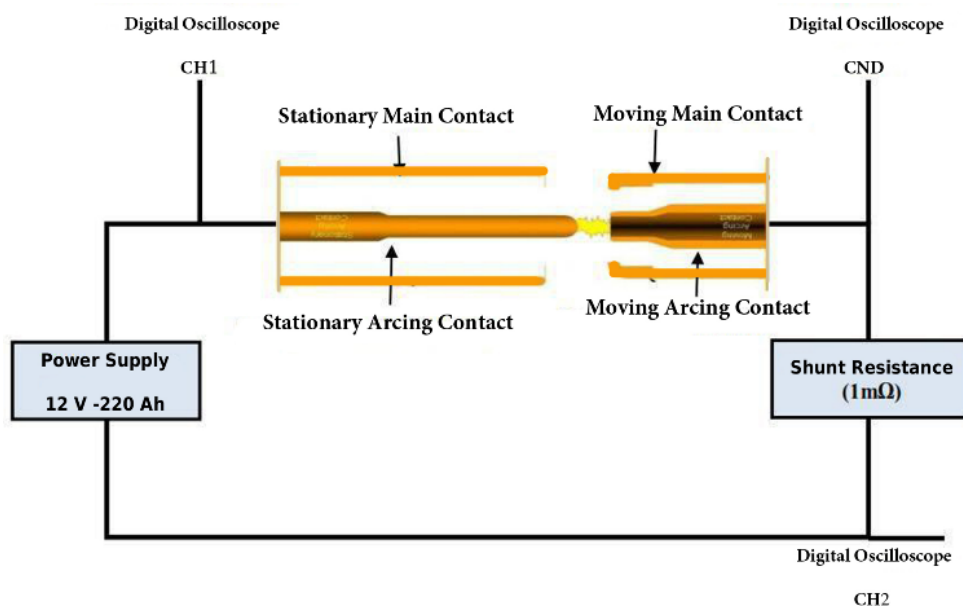


Fig.1. Experimental setup

Operating mechanism of the tested CBs is spring type. The contacts opening velocity is set to 0.2 m/s, controlled by the opening control mechanism. This is used to provide same test condition for all contact sets. In this contact speed, according to Ref. [4], resistance curves are smoother, reproducible in consecutive tests and main contact part can be easily identified. DRM curve will be obtained in this way:

During opening operation, a high DC current which is suggested to be more than 100 A [18] is injected through the contact sets and in the same time voltage drop across breaking elements is measured. By dividing instantaneous voltage to current, DRM curve will be achieved [3]. The DRM results are usually presented in contact resistance (ohm) versus displacement of moving contact (mm) or time of operation (s) [15]. During CB opening operation, the main contacts separate first, and instantly after that a partial arc for a short time (less than one millisecond) forms between the main contacts. The partial arc causes a sharp rise with high peak value in the voltage drop at the CB terminals and as a consequence contact's resistance will increase slightly. This point is considered as the instant of main contacts separation. After main contacts separation, the current commutates to arcing contacts. As soon as the arcing contacts separate an arc is drawn between them for a short time. This time depends on length of the arcing contacts and velocity of contact opening. As the arcing contact separate further, the contacts area becomes smaller. In the last instant of contact, the area of

contact is decreased to a spot which causes a spike in voltage. At this moment the resistance will take the maximum value. This moment is considered as the instant of arcing contacts separation. A typical healthy contact DRM waveform is illustrated in Fig. 2. Main and arcing contact parts are also marked in Fig. 2.

It is believed that any degradation on contact structure will cause variations and some abnormalities on dynamic resistance waveform and its parameters. So, study of these variations might be helpful in recognizing type of contact failure.

3. A review of Common Contact Failures

To investigate the impact of different failures on DRM characteristics, measurements are gathered from four similar electrical contacts. One of them is healthy while three other contacts are exposed to intentional malfunctions. In general, a contact failure may be a result of inaccurate designing, manufacturing or simply end of component life time. In these cases there is a potential risk for improper CB operation. Three major electrical contact failure modes are considered in this study and their influences on DRM characteristics are investigated. Applied defected contacts are subjected to intentional malfunction as discussed below:

3.1. First Failure Mode: Weld Spotted Contact

This is one of the most common failure modes of electric contacts. Energy fluxes on the arcing contact which

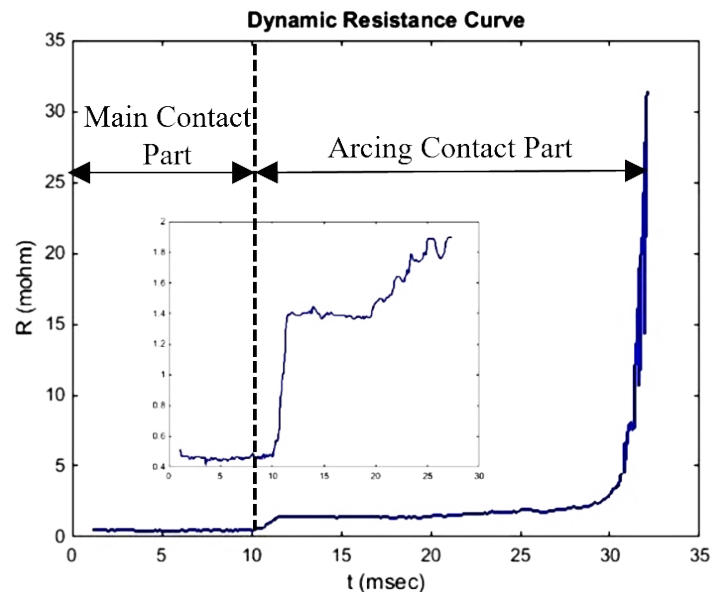


Fig. 2. Typical dynamic resistance waveform in normal condition

is an effect of high temperature arc plasma causes contact material melts and boils. Other possible contributing factors may be listed as follow:

- Contamination or corrosion of the contact surface
- A loose rivet joint, a poor weld or brazed joint
- Poor contact alignment or other mechanical problems
- And currents higher than normal ones [19].

According to various opening condition, such as load current level, power supply voltage level, velocity of heat flow and load circuit characteristics (i.e. resistive, capacitive or inductive), different types of arc discharges will occur [20-22]. Regardless of the type of arc discharge, weld spot formation will cause damage on contact surface. Material transfer, erosion, formation and deposition of arc products will change contact geometry and thus impress the reliability and contact lifetime [20, 23]. In the present study to discuss the weld spots effects on dynamic resistance waveform and its characteristics, opening con-

dition of a test contact is changed through increasing the contact interrupting current up to three times in ten levels. Weld spots are formed on contact area in proportion with the interrupting current magnitude and progressively spread over the contact surface. Fig. 3 presents the impact of welded spots formation on DRM curve in three current levels (1.1, 2 and 3 times of nominal current which are associated to levels one, five and ten of degradation process, respectively). These figures are plotted in comparison with the healthy situation as reference one to illustrate well the impact of specific failure. Fig. 4 shows how weld spots are spread on arcing contact area. This photo is taken in 10th stage of failure.

3. 2. Second Failure Mode: Arcing Contact Erosion

One of the main factors that determines the end of the lifetime of a circuit breaker, is amount of contact erosion [8]. In fact, eroded contacts will result in lower contact forces that can lead to undesired contact heating [24]. It is known that the erosion of contact material depends on

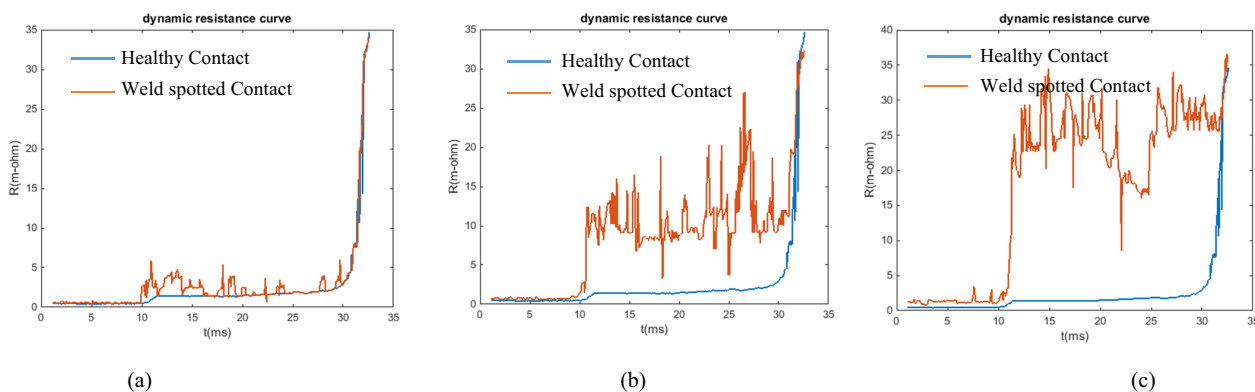


Fig. 3. Impact of weld spot formation on DRM curve, level of degradation (a) 1 (b) 5 (c) 10

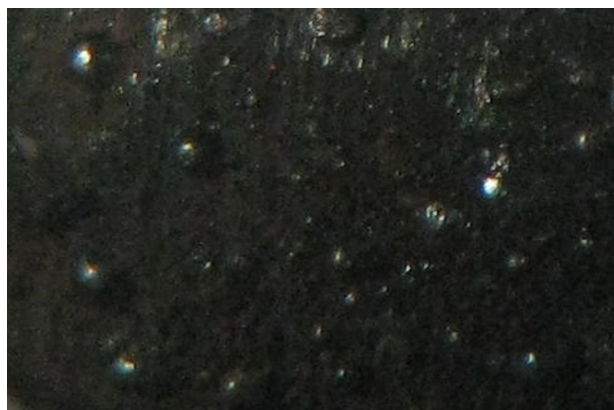


Fig. 4. Weld spots on arcing contact surface



Fig. 5. A view of eroded contact

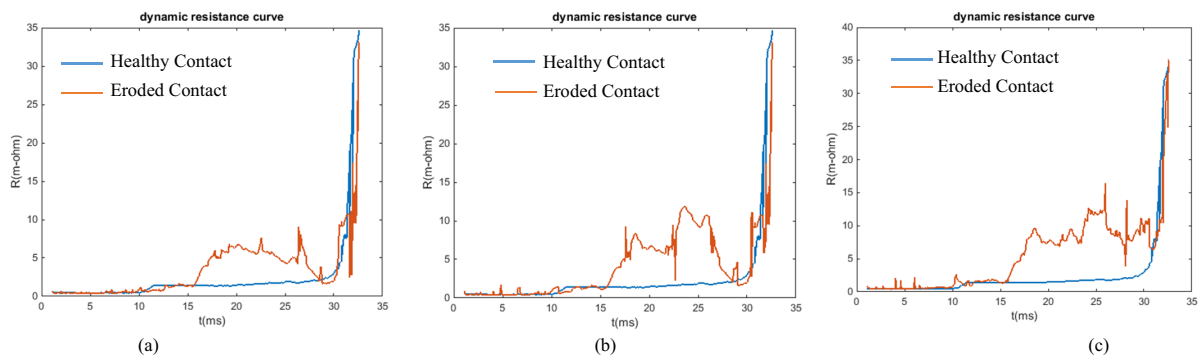


Fig. 6. Impact of erosion on DRM curve, level of degradation (a) 1 (b) 5 (c) 10

some parameters like the arcing current magnitude, arcing time, total charge, and contact material properties [8, 24-25].

To scrutinize the impact of erosion on DRM characteristics, the level of contact erosion is increased upon the consecutive tests in this case either by increasing the arc-

ing time or by creating more friction force between fix and moving contacts. A view of eroded contact is illustrated in Fig. 5. This picture is related to the 5th level of degradation. Fig. 6 presents impacts of three levels of contact erosion on DRM curve.

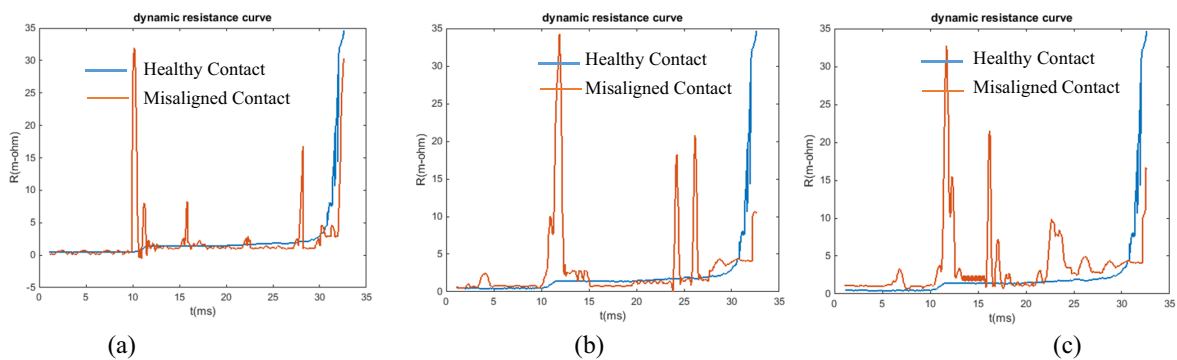


Fig. 7. Impact of misalignment on DRM curve, level of degradation (a) 1 (b) 5 (c) 10

3. 3. Third Failure Mode: Contact Misalignment

Due to misalignment between two connectors at the breaker assembly, damage to fixed and moving contacts may occur. The misalignment between two assembled connectors should not exceed a certain limit across the entire contact surface and in any direction. Direct consequence when this misalignment limit is exceeded is the reduction of the actual contact area where the current transfer occurs [26]. This defect makes change in the contact geometry as well and tend to have a detrimental impact on CB performance. To discuss this failure on DRM curve, a sample contact is exposed to intentional axis displacement which cause damage on both main and arcing contacts. Current interruption during this faulty situation causes the contact expose to ununiformed stress on the contact surface and then the failure level has increased upon consecutive CB operation. Fig. 7 shows impact of this failure on DRM curve in three levels of CB operation.

In the next session some DRM diagnosis parameters are introduced which can be used in identifying contact condition.

4. DRM diagnosis features

In order to assess the condition of electrical contact through its dynamic resistance waveform, it is essential that diagnosis parameters provide comprehensive and effective insight to the condition of it. Considering DRM changes in each specific contact failure, Table I presents description of seven diagnosis features which can be used in evaluating electrical contact condition. The average of these parameters during 100 measurements of healthy contact is also calculated and shown in Table I. The first

Table 2. Confidence interval of $[\mu h - 3\sigma h, \mu h + 3\sigma h]$ for each feature

Feature	Confidence interval
$R_{p,max}$ (m Ω)	[0.5828 1.0208]
$R_{p,avg}$ (m Ω)	[0.1866 1.2360]
$R_{a,max}$ (m Ω)	[4.3690 4.8550]
$R_{a,avg}$ (m Ω)	[2.8425 3.2115]
R_{a,t_a} (m Ω .ms)	[798.14 955.46]
$R_{a,max}/R_{a,avg}$	[1.3205 1.7267]
$R_{a,avg}/R_{p,avg}$	[3.9478 4.5634]

step of any diagnosis process is to find out whether the condition is healthy or not. In this research, based on normal distribution, for each defined feature the interval of $[\mu h - 3\sigma h, \mu h + 3\sigma h]$ is considered as normal performance's confidence interval, where μh and σh are the average and standard deviation of selected feature during healthy operation, respectively. In Table II, the calculated intervals of different features are shown.

5. Fuzzy based diagnosis algorithm

Making decision on contact condition is the most important task of a CB maintenance operator. The reason is because disassembly of breakers that have no defects means unnecessary expenses and may also lead to, or accelerate, the onset of new problems in the equipment [5].

Table 1. Typical DRM parameters and their mean values during 100 normal tests

Feature	Description	Average value during 100 normal test
$R_{p,max}$ (m Ω)	Maximum value of main contact resistance	0.8018
$R_{p,avg}$ (m Ω)	Average main contact resistance	0.7113
$R_{a,max}$ (m Ω)	Maximum value of resistance just before the arcing contact part	3.612
$R_{a,avg}$ (m Ω)	Average arcing contact resistance before the beginning of vertical slope of DRM curve	2.027
R_{a,t_a} (m Ω .ms)	Cumulative area beneath the dynamic contact resistance curve just before the maximum value reached in the arcing contact part	876.7818
$R_{a,max}/R_{a,avg}$	The ratio of maximum arcing contact resistance to its average	1.5236
$R_{a,avg}/R_{p,avg}$	The ratio of average arcing contact resistance to main contact average resistance	4.2556

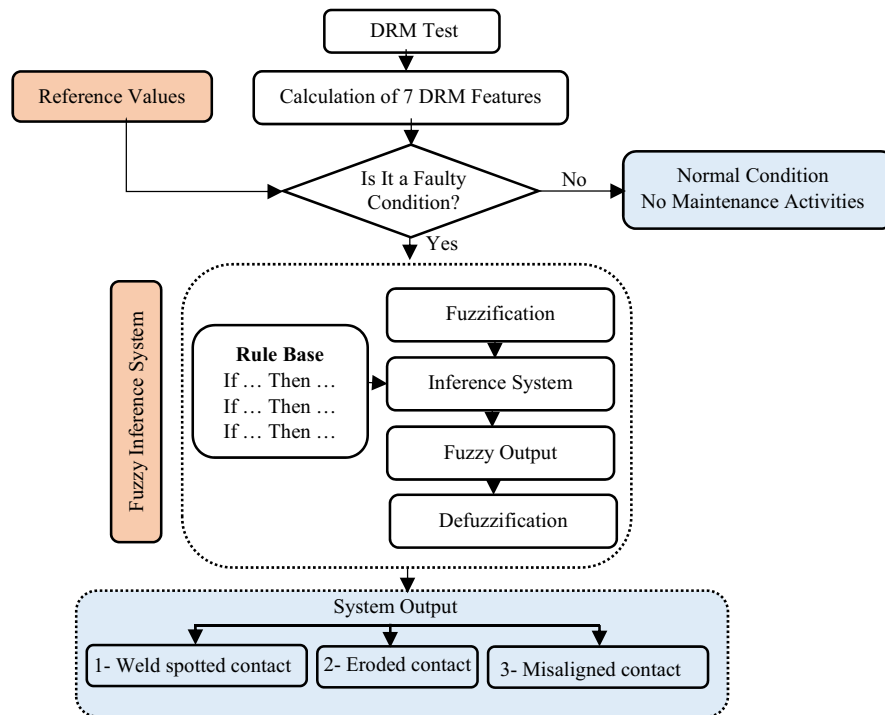


Fig. 8. Outline of the proposed fuzzy-based failure detection algorithm

The great number of decision making parameters and possible existence of overlapping between them, makes the decision more risky. In this paper, a fuzzy classifier is employed to assess the condition of contact sets. This method can reveal healthy versus faulty condition and in faulty modes, it is able to suggest types of contact failure with very high accuracy. The proposed diagnosis algorithm is shown in Fig. 8.

Fuzzy inference system includes four sub-processes, that is, fuzzification of inputs, fuzzy inference, fuzzy output and defuzzification of outputs. In fuzzification step, for each selected feature Gaussian membership functions (MFs) are defined to determine the degree of truth for each rule premise.

Once the input and output variables and MFs are defined, fuzzy inference system uses the rule-base composed of IF “antecedents” THEN “conclusions” rules to map the input variables to an output. In defuzzification sub-process, the fuzzy value of outputs is converted to a single number (crisp value) [27-30].

Fuzzy rule-based classifier is one of the most famous applications of fuzzy logic and fuzzy set theory. For an n-dimensional, c-class problem, we apply fuzzy if-then rule of the following form:

Rule R_j : IF x_1 is A_{j1} and x_2 is A_{j2} and x_n is A_{jn} ,

THEN Class is C_j with CF_j $j=1, \dots, n$

where R_j is the label of the i th fuzzy if-then rule, n is the total number of fuzzy if-then rules, $X=[x_1, \dots, x_n]$ is the n-dimensional pattern vector, A_{ji} presents antecedent fuzzy sets for the i th attribute, C_j represent a consequent class (i.e., one of the c classes), and CF_j is a certainty grade of the fuzzy if-then R_j [31]. The antecedent part of the fuzzy if-then rules is initialized manually. So, in this research the employed fuzzy rules are built as follows:

The condition of contact is categorized in one of four mentioned classes only if all seven diagnosis parameters belong to its boundaries. For example one rule is written in the form of:

If all values of $[R_{p,max}, R_{p,avg}, R_{a,max}, R_{a,avg}, R_{a,ta}, R_{a,max}/R_{a,avg}, R_{a,avg}/R_{p,avg}]$ belong to the boundaries of healthy condition, then the contact condition is considered as healthy one with certainly grade of CF_j . Similar rules are created for other three faulty conditions.

Because there are possible overlapping between different boundaries, there might be some conflicting rules. For example one rule suggests condition as healthy one and the other rule propose faulty condition. In such these situations fuzzy rule-based classifier’s output is determined considering two main below steps:

Step 1: calculate the firing strength of the rule R_j

Since there are lots of data pairs, and each data pair generates one rule, it is probable to have some conflicting rules, i.e. rules that have the same IF part but a different THEN part. One way to resolve this conflict is to assign a score to each rule generated from each data pair and accept the rule with maximum score. In fact, for any given pairs of $(x_1^i, x_2^i, \dots, x_n^i)$ the degree of the satisfaction of the antecedent part of the rules determines the firing strength of the rule. The firing strength of the rule $\tau_1(x)$ is calculated based on membership degree μ of $[x_1, x_2, \dots, x_n]$ as shown in Eq. (1).

$$\tau_1(x) = \mu_1(x_1) \times \mu_2(x_2) \times \dots \times \mu_7(x_7) \quad (1)$$

Step 2: find the class that has the largest firing strength

To find the output of the classifier, the votes of all rules are aggregated. Among the variety methods that can be used for this aggregation, in this paper, the maximum aggregation method is applied. Let $i \rightarrow j$ denote that rule i votes for class j . Then the soft label for x , $g_j(x)$ is obtained through Eq. (2) [32].

$$g_j(x) = \max_{(i \rightarrow j)} \tau_i(x) \quad (2)$$

x is assigned to the class with the largest $g_j(x)$.

The grade of certainty CF_j can be assigned as Eq.(3) [31].

$$CF_j(x) = \frac{g_j(x) - \min_j g_j(x)}{\sum_j g_j(x)} \quad j=1, \dots, c \quad (3)$$

With:

$$\overline{g_j(x)} = \frac{\sum_{i \neq j} g_i(x)}{c-1} \quad (4)$$

c is the total number of classes.

In this study, fuzzy classifier is used to accurately determine electrical contact condition. Suppose that we are given a set of input-output data with seven diagnosis parameters (x_i) and four classes for identifying contact condition (C_j) (i.e. C_1 for “healthy contact” and C_2, C_3 , and C_4 for “weld spotted contact”, “eroded contact”, and “misaligned contact”, respectively.)

First of all, based on Gaussian MFs, the degrees of given $(x_1^i, x_2^i, \dots, x_7^i)$ in different regions should be determined. For example one input data set $(x_1, x_2, x_3, x_4, x_5, x_6, x_7)$ has membership degrees of $[0.81, 0.63, 0.78, 0.44, 0.26, 0.31, 0.39]$, $[0.96, 0.93, 0.92, 0.91, 0.98, 0.86, 0.98]$, $[0.33, 0.17, 0.02, 0.14, 0.31, 0.09, 0.08]$ and $[0.05, 0.13, 0.02, 0.17, 0.08, 0.06, 0.08]$ in four regions respectively. The firing strength of each data set is calculated as below:

$$\tau_1(x) = 0.005, \tau_2(x) = 0.617, \tau_3(x) = 3.5e^{-7}, \tau_4(x) = 8.48e^{-9}$$

Then $g(x)$ would take number of 0.617 which suggests class of contact condition as C_2 (weld spotted one). In this case CF is 0.9893.

Fig. 9 shows Gaussian membership functions for two features: $R_{a,avg}/R_{p,avg}$ and $R_{a,ta}$ for four aforesaid contact conditions. Parameters of Gaussian membership function i.e. mean (μ) and standard deviation (σ) for all indicator features during healthy and three mentioned

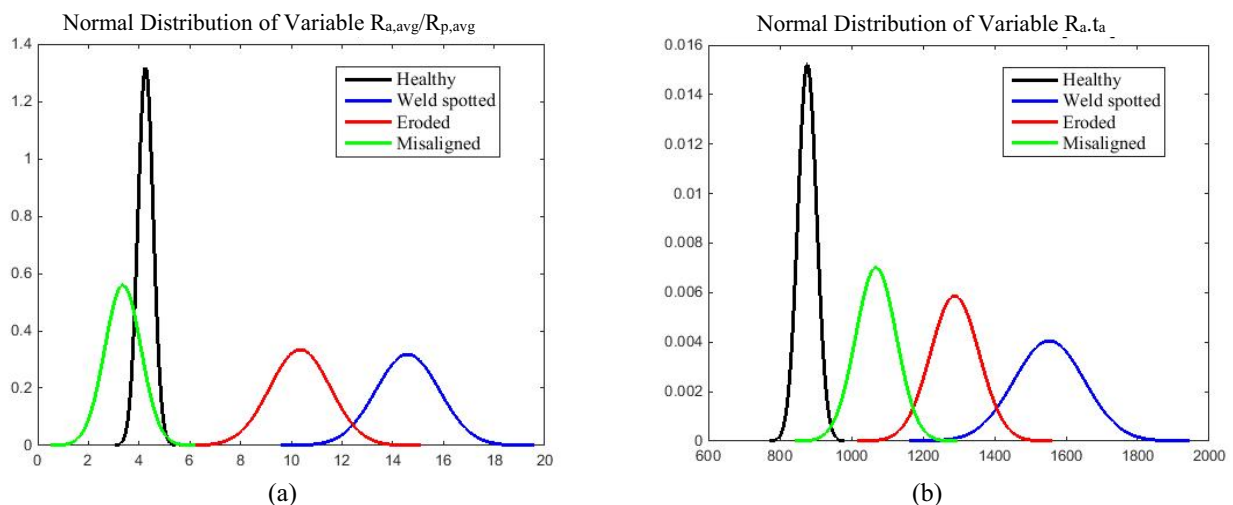


Fig. 9. Gaussian membership functions of (a) $R_{a,avg}/R_{p,avg}$ and (b) $R_{a,ta}$ for four mentioned contact conditions

Table 3. Mean (μ) and standard deviation (σ) for each defined parameters during 75 DRM test on each contact situation

Contact condition	μ [$R_{p,max}$, $R_{p,avg}$, $R_{a,max}$, $R_{a,avg}$, $R_{a,t}$, $R_{a,max}/R_{a,avg}$, $R_{a,avg}/R_{p,avg}$]	σ [$R_{p,max}$, $R_{p,avg}$, $R_{a,max}$, $R_{a,avg}$, $R_{a,t}$, $R_{a,max}/R_{a,avg}$, $R_{a,avg}/R_{p,avg}$]
Healthy	[0.8018,0.7113,4.612,3.027,876.8,1.524,4.256]	[0.073,0.1749,0.081,0.0615,26.2,0.067,0.3026]
Weld spotted	[1.2090,1.6371,22.58,18.08,1553,1.514,14.59]	[0.1256,0.2883,2.660,1.566,98.3,0.3344,1.250]
Eroded	[0.7607,2.035,12.772,9.374,1289,1.907,10.35]	[0.0617,0.1597,2.805,1.323,67.90,0.161,1.192]
Misaligned	[1.7341,2.7673,18.07,5.916,1069,2.463,4.256]	[0.2861,0.372,2.013,1.393,56.90,0.481,0.3026]

faulty conditions are listed in Table III. 300 measurements of different contact conditions (75 measurements from each category) are used to generate fuzzy classifier's rules. It should be noted that the recorded data during all faulty situations includes minor (the first level of degradation process) and catastrophic (the last level of degradation process) failures. So, the features' change during one specific failure are wide and may contain the overlaps with each other in another contact failure type.

6. Online condition assessment of 40 electrical contacts based on the proposed method

To inquire the capability of the proposed diagnosis method in assessing contact condition a database has been provided from 40 measurements on electrical contacts. 10 measurements were gathered from healthy contact, while 30 other measurements are conducted when contacts faced to three mentioned defects. Fig.10 presents the results of using fuzzy classifier. As it can be seen, 10 measurements related to healthy contacts are correctly

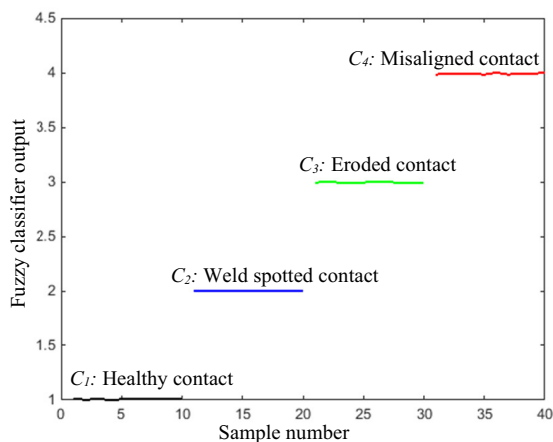


Fig. 10. Results of fuzzy classifier in assessing condition of 40 electrical contacts

classified in C1 and other three sets which are measurements obtained from DRM tests on weld spotted contact, eroded one, and misaligned contact are properly categorized in C2, C3, C4, respectively.

The total value of CF during 40 classification task is 0.9975. From the provided test results, it can be deduced that the proposed method can properly distinguish between the different contact conditions.

7. Conclusion

This paper is a research on the applicability of fuzzy based classifier model to assess the condition of electrical contacts. Seven criteria which are extracted from DRM, are used for this purpose. For each criterion confidence interval of healthy operation is defined. Using these values as reference ones, healthy versus faulty condition is recognized. To identify type of contact failure, a fuzzy classifier with Gaussian MFs is employed. Mean and standard deviation of Gaussian MFs are gathered from 300 measurements of different contact conditions. A database consist of 40 other measurements on electrical contacts are provided to examine the capability of the proposed method in detecting condition of contacts. The results clarify that the suggested scheme could properly find the contact condition.

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Maryam Khoddam was born in Arak, Iran, in 1985. She received the B.Sc. degree in electrical engineering from Buali-sina university of Hamedan, Hamedan, Iran, in 2007, the M.Sc. in electrical engineering from Shahid Beheshti university of Tehran, Tehran, Iran, in 2011. She is currently pursuing the Ph.D. degree at the Ferdowsi University of Mashhad, Mashhad, Iran. Her main interests include monitoring of power components and power system protection.



Javad Sadeh was born in Mashhad, Iran, in 1968. He received the B.Sc. and M.Sc. degrees in electrical engineering (Hons.) from Ferdowsi University of Mashhad, Mashhad, Iran, in 1990 and 1994, respectively, and the Ph.D. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, with the collaboration of the electrical engineering laboratory of the Institute National Polytechnique de

Grenoble (INPG), Grenoble, France, in 2001. Currently, he is a Professor in the Department of Electrical Engineering, Ferdowsi University of Mashhad and deputy dean of Faculty of Engineering for education and postgraduate studied. His research interests are power system monitoring, protection, dynamics, and operation.



Pedjman Pourmohamadiyan was born in Tehran, Iran, in 1976. He received the B.Sc. degree in electrical power engineering from Shiraz University, Shiraz, Iran, in 1998. The M.Sc. and Ph.D. degrees in electrical power engineering from University of Tehran, Tehran, Iran in 2001 and 2010 respectively. He was an assistant professor with the Ferdowsi University of Mashhad, Mashhad, Iran (2011-2014). He is currently a manager of HVDC valve electrical design in ABB, Ludvika, Sweden. His interests are HV apparatus failure diagnosis, Gas discharge and Circuit breakers.