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Fuzzy Logic Application in Fault Diagnosis of Transformers Using Dissolved Gases

Rahmat-Allah Hooshmand* and Mahdi Banejad†

Abstract – One of the problems with the fault diagnosis of transformers based on dissolved gas is the inability to match the result of the different standards of fault diagnosis with real world standards. In this paper, the results of the different standards are analyzed using fuzzy logic and then compared with the empirical test. The proposed method is based on the standards and guidelines of the International Electrotechnical Commission (IEC), the Central Electric Generating Board (CEGB), and the American Society for Testing and Material (ASTM) and its main task is to assist the conventional gas ratio method. The comparison between the suggested method and existing methods indicates the capability of the suggested method in the on-line fault diagnosis of transformers. In addition, in some cases the existing standards are not able to diagnose the fault. For theses instances, the presented method has the potential of diagnosing the fault. In this paper, the information of three real transformers is used to show the capability of the suggested method in diagnosing the fault. The results validate the capability of the presented method in fault diagnosis of the transformer.

Keywords: Dissolved gas, Fault diagnosis of transformer, Fuzzy logic

1. Introduction

Voltage breakdown in the liquid insulators of transformers releases gas. The gas distribution helps to reveal the kind of fault and the gas ratio indicates the severity of the fault in the transformer. There are several methods used in fault diagnosis based on the dissolved gas of the transformer [1-16] such as the Test of Combustible Gas (TCG). In TCG the combustible gas is collected from the transformer. This method does not give the amount of each component in the released gas.

The conventional method in fault diagnosing is analysis of dissolved gas in the transformer oil. The main benefit of this method is that the fault can be diagnosed incipiently. Therefore, the fault can be detected rapidly. The main issue in this method is to acquire the data. Then, the fault can be diagnosed from this data accurately. In this regard, some researchers use the extended Rogers method based on the Central Electric Generating Board (CEGB). According to the standards of the International Electric Committee (IEC) based on the Rogers method, a three code for three gas ratios as well as a specific table are used to describe the fault [10].

The standards of the American Society for Testing and Material (ASTM) use a four digit code and a specific table to determine four gas ratios [15].

It should be noted that if the magnitude of the data is small, the error in the Rogers is high. Moreover, if different standards are used to detect one fault, the results for the different methods are not the same. As a result, in the studies carried out by the researchers, several methods such as evidential reasoning algorithm [1], expert systems [2], [3], neural network [4-9], fuzzy logic [6], [10-13] and genetic algorithm [14] are incorporated in the dissolved gas analysis to obtain more accurate results.

In the methods that use the artificial network, the fault diagnosis is based on the operator's information from the approximate amount of gases and the oil appearance of the transformers. Since these methods are based on the operator's experience, there is a possibility for error in the fault diagnosis.

The neural network based methods need precise learning in a broad range of the faults of the transformers in order to obtain a correct response. In the various standards, the fault diagnosis is performed based on the ratios of the produced gases in the transformer oil. Due to the uncertainty of the ratio of the produced gases, fuzzy logic is used.

In this paper, three and four digit codes containing the fault information are created based on the fuzzy logic to achieve better results. The method is applied to three real transformers to diagnose the fault by analyzing the dissolved oil based on fuzzy logic.

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† Corresponding Author: Dept. of Electrical Engineering, University of Isfahan, Isfahan, Iran. (Hooshamd_r@eng.ui.ac.ir)

* Faculty of Electrical and Robotic, Shahrood University of Technology, Shahrood, Iran. (m.banejad@shahroodut.ac.ir)

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2. Dissolved Gases in the Transformer Oil

2.1 Dissolved Gas Analysis (DGA)

In the normal operation of the transformer, gases such as Hydrogen (H_2), Methane (CH_4), Ethylene (C_2H_4), Acetylene (C_2H_2), Ethane (C_2H_6) and so on are released. In the existing methods, parts per million (PPM) values are determined for each gas in the oil along with a total value of combustible gasses. When there is an abnormal situation such as a fault occurrence, some specific gases are produced in greater quantity than in the normal operation. Thus, the amount of these gases in the transformer oil increases. The increase in the amount of gases results in saturation of the transformer oil and no further gas can be dissolved in oil. Therefore, when the oil is saturated, the gas is released from the oil. The amount of the dissolved gas is related to the temperature of the oil and the type of gas. The produced gas can be classified into three groups: polarization, corona, and arcing. These groups coming from the severity of the released energy during the fault are different. The largest and lowest amounts of the released energy are associated with the arcing and corona.

a) **Polarization:** In the transformer oil, the released gases at low temperature are CH_4 and C_2H_6, and at high temperature are C_2H_6, CH_4, C_2H_4, and H_2. In cellulose, the generated gases at low and high temperatures are CO and CO_2.

b) **Corona:** In corona, the produced gas in oil is H_2 and the released gases in cellulose are H_2, CO, and CO_2.

C) **Arcing:** In this case, the released gases are C_2, H_2, C_2H_6, CH_4, C_2H, and H_2.

2.2. Explanation for Generated Gases

The produced gas can also be categorized into three groups:

1) Hydrogen and hydrocarbons: H_2, CH_4, C_2H_4, and C_2H_2
2) Carbon oxides: CO, CO_2
3) Non-faulty gases: O_2 and N_2

Finally, there are five main characteristics in fault diagnosis in the transformers:

a) H_2 (Hydrogen) and C_2H_2 (Acetylene): Large amounts of C_2H_2 and H_2 are almost always a sign of arcing faults. To generate C_2H_2, temperatures of greater than 500 degrees are needed. The presence of C_2H_2 supersedes the criteria for combustible gas levels and needs instant attention.

b) C_2H_6 (Ethane), C_2H_4 (Ethylene), CH_4 (Methane), C_3H_8/C_3H_6 (Propane/Propylene), and H_2 (Hydrogen): A large amount of C_2H_4 with CH_4 or with the other four above mentioned gases show thermal decomposition of oil. At temperatures less than 250 degrees, these gases are produced.

c) H_2 (Hydrogen) and CH_4 (Methane): These two gases are produced if a partial discharge (corona) occurs in the transformer oil.

d) CO_2 (Carbon Dioxide) and CO (Carbon Monoxide): These two gases show thermal aging of cellulosic insulation or partial discharge (corona) in the cellulosic insulation. Partial discharge in the cellulosic insulation should be suspected if the two gases are mixed by considerable amounts of H_2.

e) H_2 (Hydrogen) and O_2 (Oxygen): The presence of these gases in the lack of hydrocarbons is a sign of hydrolysis and it means the oil is contaminated with water.

3. Methods of Analyzing Dissolved Gases in Oil

In this method, at first, a sample of the transformer oil is taken. Then, the dissolved gases are extracted, separated, and measured by means of chromatography.

In order to interpret the results of the experiment, we produce data in a suitable form to diagnose the fault. The formation of this data is based on the different standards, which are explained in the following subsections.

3.1. IEC Standard

According to the IEC standards, the extended Rogers method is used to produce a three digit code. The code is determined based on the three gas ratios of C_2H_2/C_2H_4, CH_4/H_2, and C_2H_4/C_2H_6 as given in Table (1). Regarding the obtained codes and data of Table (2), the faults are diagnosed.

Table 1. IEC Code determination criteria

Gas Ratio	Value	Code
$X = C_2H_2/C_2H_4$	$X<0.1$	0
	$0.1 \leq X \leq 3$	1
	$X>3$	2
$Y = CH_4/H_2$	$Y<0.1$	1
	$0.1 \leq Y \leq 1$	0
	$Y>1$	2
$Z = C_2H_4/C_2H_6$	$Z<1$	0
	$1 \leq Z \leq 3$	1
	>3	2

3.2. CEGB Standard

In this standard, a four digit code based on Table (3) is created using the Rogers method and four gas ratios of CH_4/H_2, C_2H_6/CH_4, C_2H_4/C_2H_6, and C_2H_2/C_2H_4. Regarding the obtained codes and data in Table (4), the faults are diagnosed.

Table 2. Fault diagnosis using IEC codes

No.	**Kind of Fault**	**Code**		
		X	Y	Z
0	No fault	0	0	0
1	Partial discharge with low energy density	0	1	0
2	Partial discharge with high energy density	1	1	0
3	Discharge (arc) with low energy density	1 or 2	0	1 or 2
4	Discharge (arc) with high energy density	1	0	2
5	Thermal fault with temperature less than 150^0C	0	0	1
6	Thermal fault with temperature between 150^0C to 300^0C	0	2	0
7	Thermal fault with temperature between 300^0C to 700^0C	0	2	1
8	Thermal fault with temperature greater than 700^0C	0	2	2

Table 3. CEGB code determination criteria

Gas Ratio	**Value**	**Code**
$W = CH_4/H_2$	$W \leq 0.1$ $0.1 < W < 1$ $1 \leq W < 3$ $W \geq 3$	5 0 1 2
$X = C_2H_6/CH_4$	$X < 1$ $X \geq 1$	0 1
$Y = C_2H_4/C_2H_6$	$Y < 1$ $1 \leq Y < 3$ $Y \geq 3$	0 1 2
$Z = C_2H_2/C_2H_4$	$Z < 0.5$ $0.5 \leq Z < 3$ $Z \geq 3$	0 1 2

3.3 ASTM Standard

In this standard a four digit code is generated based on the codes given in Table (5) using the Rogers method and the four gas ratios of C_2H_4/C_2H_6, C_2H_6/CH_4, C_2H_2/C_2H_4, and CH_4/H_2. Regarding the obtained codes and data from Table (6), the faults are diagnosed.

In this paper, the ratio of CO_2/CO (Carbon Dioxide/Carbon Monoxide) in each standard is also measured. This value is used in diagnosing fault location (in oil and cellulose). In general, if the ratio of CO_2/CO is greater than 11 (or in many cases less than 3) it indicates that in the vicinity of the cellulosic insulation, higher than normal temperatures are taking place.

Table 4. Fault diagnosis using CEGB codes

No.	**Kind of Fault**	**Code**			
		W	X	Y	Z
0	No Fault	0	0	0	0
1	Partial discharge	5	0	0	0
2	Increase in temperature < 150^0C	1 or 2	0	0	0
3	Increase in temperature 150^0C to 200^0C	1 or 2	1	0	0
4	Increase in temperature 200^0C to 300^0C	0	1	0	0
5	Increase in overall temperature in the conductive parts	0	0	1	0
6	Circulating currents in windings	1	0	1	0
7	Circulating currents between core and tank	1	0	2	0
8	Arc with low energy density	0	0	0	1
9	Arc with high energy density	0	0	1 or 2	1 or 2
10	Continuous spark	0	0	2	2
11	Partial discharge with tracking	5	0	0	1 or 2
12	Abnormal increase in insulator temperature	$CO_2/CO > 11$			

Table 5. The ASTM code determination criteria

Gas Ratio	**Value**	**Code**
$W = CH_4/H_2$	$0 < W \leq 0.1$ $0.1 < W < 1$ or $W=0$ $1 \leq W < 3$ $W \geq 3$	1 2 3 4
$X = C_2H_6/CH_4$	$X < 1$ $X \geq 1$	0 1
$Y = C_2H_4/C_2H_6$	$Y < 1$ $1 \leq Y < 3$ $Y \geq 3$	0 1 2
$Z = C_2H_2/C_2H_4$	$Z < 0.5$ $3 \leq Z < 0.5$ $Z \geq 3$	0 1 2

Table 6. Fault diagnosis using ASTM codes

No.	Kind of Fault	Code			
		W	X	Y	Z
0	Normal	2	0	0	0
1	Partial discharge	1	0	0	0
2	Increase in temperature ≤ 150^0C	3	0	0	0
3	Increase in temperature ≤ 150^0C	4	0	0	0
4	Increase in temperature 150^0C to 200^0C	3	1	0	0
5	Increase in temperature 150^0C to 200^0C	4	1	0	0
6	Increase in temperature 200^0C to 300^0C	4	1	0	0
7	Increase in all conductors	2	0	1	0
8	Circulating currents in windings	3	0	1	0
9	Circulating currents between core and tank	3	0	2	0
10	Flashover with very low energy density	2	0	0	1
11	Arc with high energy density	2	0	1	1
12	Arc with high energy density	2	0	1	2
13	Arc with high energy density	2	0	2	1
14	Continuous spark	2	0	2	2
15	Partial discharge with tracking	1	0	0	1
16	Partial discharge with tracking	1	0	0	2

As explained before, despite the fact that the Rogers method is useful for assessing the quality of the transformer insulation, no quantitative criterion is provided for the possibility of occurrence of each fault in the insulation. In the case of the occurrence of multiple faults, the gases from different faults are mixed together. As a result, the matching between the gas ratios and code are difficult. This can be overcome by the aid of fuzzy diagnosis as presented in this paper.

4. Fuzzy Logic Application

One of the difficulties in the use of the IEC, CEGB, and ASTM ratio codes is that it is shown in the form of significant numbers of the DGA. The accuracy of the diagnosis may be under question, if the obtained results fall outside the proposed codes. In this section, in order to solve the difficulties of the DGA, the application of the fuzzy logic in fault diagnosis is presented. Regarding the similarities of the three standards, only the procedure of the IEC standard is explained as follows:

Fuzzy IEC Codes

As shown in Table (1), in the IEC codes the three gases C_2H_2/C_2H_4, CH_4/H_2, and C_2H_4/C_2H_6 are labelled by the codes of 0, 1, and 2, respectively. To make clear the relationship between the ranges of each gas ratio, its corresponding codes are rearranged. Table (7) shows the new arrangement of the codes.

Table 7. The rearrangement of IEC Codes

Gas Ratio	Code 0	Code 1	Code 2
$X = C_2H_2/C_2H_4$	$X < 0.1$	$0.1 < X < 3$	$X > 3$
$Y = CH_4/H_2$	$0.1 < Y < 1$	$Y < 0.1$	$Y > 1$
$Z = C_2H_4/C_2H_6$	$Z < 1$	$1 < Z < 3$	$Z > 3$

As Table (2) indicates, the transformer faults are identified based on the three gas ratios of $X=C_2H_2/C_2H_4$, $Y=CH_4/H_2$, and $Z=C_2H_4/C_2H_6$. For example if X, Y, and Z are values of 0, 2, and 1, respectively, it means fault No. 7, i.e., thermal fault of medium temperature $300\text{-}7000^{0C}$, has taken place.

In fact, conventional logic "AND" and "OR" are employed, for example, in the IEC code diagnosis. The 7th fault in Table (7) is described by:

$$F(7): code_{\mathrm{ZERO}}(X)\ \mathrm{AND}\ code_{\mathrm{TWO}}(Y)\ \mathrm{AND}\ code_{\mathrm{ONE}}(Z)$$

In this relation, $code_{\mathrm{ZERO}}(X)$, $code_{\mathrm{TWO}}(Y)$, and $code_{\mathrm{ONE}}(Z)$ represent the coded values of gas ratio X, Y, and Z, respectively. As a result, fault (F7) will take the value of one (true) or zero (fault).

In the fuzzy logic method, the IEC codes are used to rebuild sets ZERO, ONE, and TWO. Each gas ratio is shown by a fuzzy vector as

$$[\mu_{\mathrm{ZERO}}(\bullet), \mu_{\mathrm{ONE}}(\bullet), \mu_{\mathrm{TWO}}(\bullet)]$$

where $\mu_{\mathrm{ZERO}}(\bullet)$, $\mu_{\mathrm{ONE}}(\bullet)$, and $\mu_{\mathrm{TWO}}(\bullet)$ represent the membership functions for fuzzy codes ZERO, ONE, and TWO, respectively.

The membership function is described by a descending or/and an ascending demi-Cauchy distribution function [3]:

$$\mu_d(r) = \begin{cases} 1 & for\ r \le A \\ \dfrac{1}{1+\left(\dfrac{A-r}{a}\right)^2} & otherwise \end{cases} \tag{1}$$

$$\mu_a(r)=\begin{cases}1 & \text{for } r\geq A\\ \dfrac{1}{1+\left(\dfrac{A-r}{a}\right)^2} & \text{otherwise}\end{cases} \qquad (2)$$

where A and a are a pair of parameters which can be chosen to produce appropriate membership function [3]. The parameters a and A are treated as parameter distribution and boundary parameter, respectively.

The fuzzy IEC codes ZERO, ONE, and TWO are produced using Equations (1) and (2). Therefore, fuzzy IEC codes for each set of ratios are determined.

The eight fuzzy diagnosis vectors are formed by substituting the fuzzy logic operator "AND" with minimization operation and the logic operator "OR" with maximization operation. In fact, the conventional true-false logic is replaced by a fuzzy multi-value logic [17]. Therefore, the following equations are produced based on the IEC rules to diagnose the different faults of Table (1), labelled by No. 0 to 8.

$$F(0)=\min[\mu_{\text{ZERO}}(\text{X}),\mu_{\text{ZERO}}(\text{Y}),\mu_{\text{ZERO}}(\text{Z})]$$

$$F(1)=\min[\mu_{\text{ZERO}}(\text{X}),\mu_{\text{ONE}}(\text{Y}),\mu_{\text{ZERO}}(\text{Z})]$$

$$F(2)=\min[\mu_{\text{ONE}}(\text{X}),\mu_{\text{ONE}}(\text{Y}),\mu_{\text{ZERO}}(\text{Z})]$$

$$F(4)=\min[\mu_{\text{ONE}}(\text{X}),\mu_{\text{ZERO}}(\text{Y}),\mu_{\text{TWO}}(\text{Z})]$$

$$F(5)=\min[\mu_{\text{ZERO}}(\text{X}),\mu_{\text{ZERO}}(\text{Y}),\mu_{\text{ONE}}(\text{Z})]$$

$$F(6)=\min[\mu_{\text{ZERO}}(\text{X}),\mu_{\text{TWO}}(\text{Y}),\mu_{\text{ZERO}}(\text{Z})]$$

$$F(7)=\min[\mu_{\text{ZERO}}(\text{X}),\mu_{\text{TWO}}(\text{Y}),\mu_{\text{ONE}}(\text{Z})]$$

$$F(8)=\min[\mu_{\text{ZERO}}(\text{X}),\mu_{\text{TWO}}(\text{Y}),\mu_{\text{TWO}}(\text{Z})]$$

$$\begin{aligned}F(3)=\max\{\ &\min[\mu_{\text{ONE}}(\text{X}),\mu_{\text{ZERO}}(\text{Y}),\mu_{\text{ONE}}(\text{Z})],\\ &\min[\mu_{\text{ONE}}(\text{X}),\mu_{\text{ZERO}}(\text{Y}),\mu_{\text{TWO}}(\text{Z})],\\ &\min[\mu_{\text{TWO}}(\text{X}),\mu_{\text{ZERO}}(\text{Y}),\mu_{\text{ONE}}(\text{Z})],\\ &\min[\mu_{\text{TWO}}(\text{X}),\mu_{\text{ZERO}}(\text{Y}),\mu_{\text{TWO}}(\text{Z})]\ \}.\end{aligned}$$

Normalizing the above equations results in

$$F_r(i)=\frac{F(i)}{\sum_{j=0}^{8}F(j)} \qquad i=0-8 \qquad (3)$$

Figure (1) compares the conventional IEC code 1 and the fuzzy membership function $\mu_{\text{ONE}}(\text{Z})$ for the gas ratio Z=C_2H_4/C_2H_6.

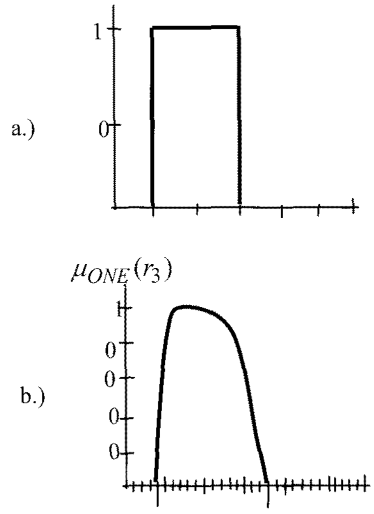

Fig. 1. a.) IEC Code 1, b.) Fuzzification of IEC code 1 for the gas ratio C_2H_4/C_2H_6

5. Results of Simulation

In order to evaluate the performance of the proposed algorithm, four transformers are tested. The amounts of the gases of the transformers are given in Table (8). Transformers 1 and 2 belong to the Isfahan Shahid Montazeri power plant. The data information of Transformers 3 and 4 are given in [10]. In Transformers 1 and 2, the amounts of gas CO are 236 and 389, respectively, and the values of gas CO_2 are 3305 and 1334, respectively.

Table 8. The amount of gases in the test transformers

Transformer Number	**Amount of Gases**				
	H_2	**CH_4**	**C_2H_2**	**C_2H_4**	**C_2H_6**
1	796	999	31	1599	234
2	3091	46	239	101	17
3	95	110	<0.1	50	160
4	120	17	4	23	32

The diagnosed faults for the transformers are obtained for two crisp and fuzzy cases using the mentioned standards, and the results are shown in Table (9). In this paper a reliability factor is considered for each transformer in the fuzzy case to obtain better results. As this table indicates, the fault with larger reliability factor is closer to the actual fault.

Based on the amount of gases for Transformer 2 (in Table (9)), the existing standard methods cannot diagnose fault. However, if the proposed method in this paper is used, all of the three standard methods can detect fault somewhat and with some degree of reliability. However, it should be noted that in the IEC standard, arcs with high energy density are diagnosed by reliability of 0.7 and are the arcs with power flow in the actual transformer.

Table 9. Comparison of the results of dissolved gas analysis for the three transformers using different standards based on crisp and fuzzy logics

	Standard	Transformer 1	Transformer 2	Transformer 3	Transformer 4
Diagnosis using Crisp Logic	IEC	Thermal fault with the temperature above 700°C	Non diagnosable	Thermal increase with the temperature of 200°C to 300°C	Non diagnosable
	ASTM	Circulating currents between core and tank	Non diagnosable	Thermal increase with the temperature of 150°C to 200°C	Non diagnosable
	CEGB	Thermal fault with the temperature above 700°C	Non diagnosable	Thermal increase with the temperature of 150°C to 200°C	Non diagnosable
Diagnosis using Fuzzy Logic	IEC	Thermal fault with the temperature above 700°C having reliability of 1.0	Discharge (arc) with high energy density with reliability = 0.70	Thermal fault with the temperature less than 150°C with reliability = 0.75	Thermal Fault with the temperature less than 150°C with reliability = 0.85
	ASTM	Circulating current or electric arc with energy discharge having reliability of 0.50	Arc with high energy density with reliability = 0.30	Thermal fault with the temperature less than 150°C with reliability = 1.0	Thermal Fault with the temperature of 200°C to 300°C with reliability =1.0
	CEGB	Circulating current or electric arc with energy discharge having reliability of 0.80	Arc with high energy density with reliability = 0.50	Increase in temperature less than 150°C with reliability = 1.0	Thermal Fault with the temperature of 200°C to 300°C with reliability = 0.80
Actual Fault		Thermal fault with the temperature above 700°C and electric arc	Arc with power flow through	Increase in temperature less than 150°C	Increase in Temperature less than 150°C

Also, as shown for the crisp case of Transformer 4, when the ratio values of the gases are small, the existing standards are unable to diagnose the fault. However, the proposed method is capable of diagnosing the actual fault. As a result, the problem of inability to diagnose the fault when the values are small is now solved.

The second step in DGA is fault locating, meaning whether the fault has progressed to cellulosic insulation or not. In this regard and as previously explained, the gas ratio CO_2/CO should be computed. For example, for Transformers 1 and 2, this ratio is 14 and 3.43, respectively. Since for Transformer 2 this ratio is greater than 11, it can be concluded that the arc with high energy density has progressed to cellulose insulation for this transformer, but this is not the case for Transformer 1.

6. Conclusion

In this paper, the analysis of the transformer dissolved gas is used to diagnose the faults in the transformer using IEC, ASTM, and CEGB standards. The comparison between crisp and fuzzy logic methods used in the fault diagnosis of the transformer indicates that in the cases that the crisp logic is incapable of diagnosing the faults, the fuzzy logic is able to detect the faults with a high accuracy. The results of analysis of the data of three transformers using different standards, based on crisp and fuzzy logics, reveals the quality of the fuzzy logic in diagnosing the faults, especially for the cases that the crisp logic is unable to diagnose the fault.

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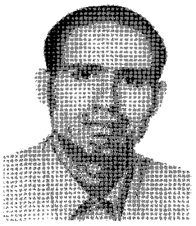

Rahmat-Allah Hooshmand

He received his B.Sc. degree from Ferdowsi Mashad University in 1989 (Mashad/Iran), his M.Sc. degree from the University of Tehran (Tehran/Iran), and his Ph.D. degree from Tarbiat Modarres University (Tehran/Iran) in 1990 and 1995, respectively, all in Electrical Engineering. Since 1995, he has been with the Department of Electrical Engineering as an Associate Professor at the University of Isfahan (Isfahan/Iran). His main areas of research interest are modelling of power systems and distribution electricity networks. (University of Isfahan, Department of Electrical Engineering, Isfahan, Iran, Tel.: +98 311 7934073, Fax: +98 311 7933071, E-mail: Hooshmand_r@eng.ui.ac.ir, Hooshmand_r@yahoo.com).

Mahdi Banejad

He received his B.Sc. degree from Ferdowsi Mashad University in 1989 (Mashad/Iran) and his M.Sc degree from Tarbiat Modarres University (Tehran/Iran), both in Electrical Engineering. From 1994 to 2000 he was a Lecturer in the Electrical Department of Shahrood University of Technology. He received his Ph.D. degree in Electrical Engineering from Queensland University of Technology (QUT) (Brisbane/Australia). After finishing his Ph.D., he worked as a Senior Research Assistant in the area of load modelling and distribution generation at QUT. From 2005 to date, he has been an Assistant Professor of Electrical Robotics at Shahrood University of Technology. His interested areas are load modelling, power system dynamics, and distributed generation. Tel.: +98 912 573 0943, Fax: +98 273 3334419, E-mail: m.banejad@shahroodut.ac.ir, m.banejad@gmail.com).