Analysis of Harmonic Effects on Electromechanical Instantaneous Overcurrent Relays with Different Neural Networks Models

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Abstract

The Elecromechanical Instantaneous Overcurrent Relays (EIOCR) are designed to operate with sinusoidal current. This paper presents an experimental study and a Neural Networks (NNs) analysis for the effects of harmonics on the operation of EIOCR. In the experiment, the non-linear load currents containing different harmonic spectrums are applied to EIOCR and harmonic analysis of the non-sinusoidal currents are realised by using a harmonic analyzer. The results of harmonic analysis and measured non-sinusoidal current values are applied for feed forward NN algorithms which are designed for four different input sets. By using the developed NN, it is possible to estimate the dynamic behaviour of this relay for unmeasured non-sinusoidal currents. According to the results, the pick up current value of the EIOCR increases proportionally to the total harmonic distortion (THD) value of the non-sinusoidal current. The results of the experiments and NN analysis also prove that this relay may not protect the system reliably, if the current has harmonic components.
Keywords: Overcurrent relay, harmonics and neural networks,.

I. Introduction

The overcurrent protection relays are used to provide protection and reliability for power systems. There are electromechanical, static and digital types of these relays. Overcurrent relays are designed to operate for sinusoidal currents. The relay manufacturers give the characteristics and all technical documents of these relays for only sinusoidal currents. It is not defined the operation of these relays for non-sinusoidal currents including harmonics.

Instantaneous overcurrent relays and inverse time overcurrent relays are mainly types of overcurrent relays. Effects of harmonics on overcurrent relays depend on types and structures of the relays. In the electromechanical instantaneous relays, if the current has harmonic contents, each frequency component would produce an independent and cumulative effect, causing the pick up value to increase depending on the harmonic components. For very high frequencies, the pickup current of the instantaneous relay increases since frequency increases [1]. In the electromechanical inverse time overcurrent relays (induction disc relays), if the frequency of current increases, the pickup current increases and disc rotation slows [1], [2]. Therefore, these relays may not protect the power system elements due to the unexpected increase of the pickup current value.

Electromechanical instantaneous overcurrent relays are economical and robust relays therefore, these relays are still widely used in Turkey. These relays are designed to operate for sinusoidal currents. The numbers and total power values of nonlinear loads in the power system increase in Turkey. Because of this problem, the waveforms of currents are heavily distorted, thus, non-sinusoidal currents occur and they contain harmonics. Therefore, it is a necessary and important study to research the effects of harmonics on the electromechanical instantaneous overcurrent relays. In this paper, the effects of harmonics on the operation of Electromechanical Instantaneous Overcurrent Relay (EIOCR) are studied. The non-sinusoidal load currents containing different harmonic spectrums are applied to EIOCR. Harmonic analysis of nonlinear load current is realised by a harmonic analyzer. The results of harmonic analysis and measured non-sinusoidal current values are applied to a feed forward NN algorithm. Thus, the evaluation of the response of the relay operations for the simulated non-sinusoidal current conditions became possible and the pickup current values of the EIOCR are obtained for various nonlinear load currents. Then, the relay's dynamic characteristic for nonlinear load currents are simulated in computer environment with NNs. By using the developed NN intelligent controller simulation, it is possible to estimate the dynamic behaviour of this relay for unmeasured non-sinusoidal currents.

II. Instantaneous Overcurrent Relays

In power systems, lines and transformers are protected for overcurrents and short circuit currents by using overcurrent relays. These relays are defined according to their operating time-current curves. Two main types of these relays are instantaneous overcurrent relays and inverse time overcurrent relays [3], [4]. These curves are shown in Fig. 1.

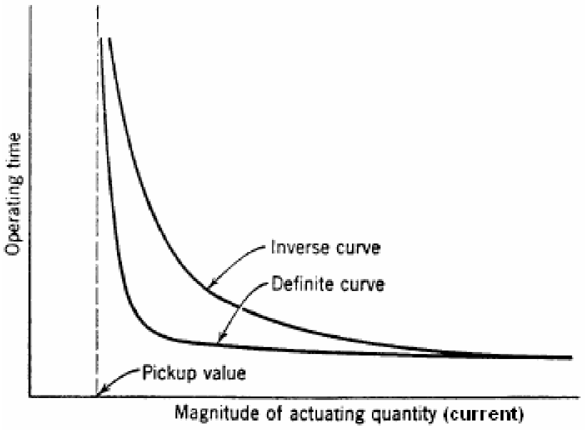

Fig. 1. Operating time-current curves of overcurrent relays.

An inverse-time curve is one in which the operating time becomes less since the magnitude of the actuating quantity (current) is increased, as shown in Fig.1[4]. Operating time of an instantaneous overcurrent relay is approximately constant, if the current is higher than several times of pickup current. Therefore, operating time-current curve of an instantaneous overcurrent relay is called as definite curve. These curves are given for sinusoidal current and they change, if the current contain harmonic components.

III. Experimental Study

The circuit which is used for measurements is shown in Fig.2. A triac controlled and resistive loaded circuit is used as a nonlinear load. Root mean square (rms) value of current (I_{rms}) and total harmonic distortion value of current (THD_i) for such a nonlinear load current are defined in Eq.1 and Eq.2 respectively [5],

$$I_{rms} = \sqrt{I_1^2 + \sum_{n=2} I_n^2} \quad (1)$$

$$THD_i = \frac{\sqrt{\sum_{n=2} I_n^2}}{I_1} \quad (2)$$

The variation of nonlinear load current versus time is shown in Fig.3.

In the experimental circuit, the rms value and the total harmonic distortion (THD_i) of the nonlinear load current are changed by adjusting the firing angle of triac (α) and the voltage which is applied to the nonlinear load.

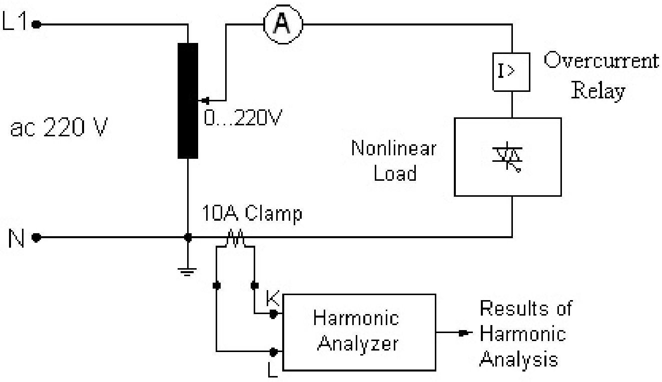

Fig. 2. Test circuit

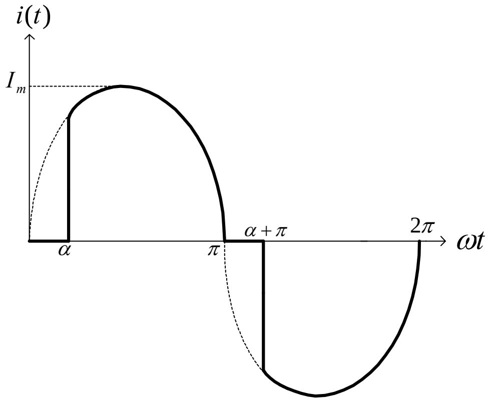

Fig. 3. Nonlinear load current

In order to obtain the different non-sinusoidal currents, firing angle (α) of triac is set to different values. The pickup current value of EIOCR (I_{pickup}), total harmonic distortion value (THD_i), rms value of fundamental current (I_1) and rms value of harmonic currents (I_n) for 3rd, 5th, 7th, 9th, 11th, 13th harmonic components are measured for each firing angle (α) value. These measurement results are used to constitute data tables for NNs study as given in Table 1. For all modes the pick up current of relay is adjusted to 1.095 A for pure sinusoidal current and this setting is not changed during the experiments.

Table 1. Training sets

THD_i	I_1	I_3	I_5	I_7	I_9	I_{11}	I_{13}	I_{pickup}(A)
0.0	1.095	0.0	0.0	0.0	0.0	0.0	0.0	1.095
11.9	1.091	3.2	9.4	3.4	3.1	2.7	2.1	1.099

12.6	1.102	3.1	10.1	3.6	3.2	2.6	1.8	1.106
28.4	1.081	20.5	13.4	8.5	5.7	4.4	4.1	1.124
37.3	1.078	30.0	12.8	10.8	6.6	6.4	4.8	1.152
52.0	1.042	46.1	12.2	10.9	10.2	6.6	6.2	1.174
58.3	1.030	51.6	15.0	11.5	10.4	7.7	6.9	1.190
71.5	0.997	61.4	23.7	15.2	10.3	10.5	7.5	1.226
76.4	0.994	64.6	27.4	17.2	11.3	10.8	8.8	1.253
79.6	0.984	66.2	30.6	18.6	12.5	10.9	9.4	1.262
86.7	0.965	70.1	35.7	22.1	16.3	11.8	11.5	1.285
92.8	0.963	72.6	39.4	24.6	18.9	12.9	11.7	1.311
99.8	0.959	75.1	43.7	27.6	22.6	15.8	13.2	1.380

According to the experimental results, the variation of relay's pickup current versus to third harmonic current distortion and the total harmonic distortion value of relay current (THD_i) is shown in Fig.4 and Fig.5 respectively.

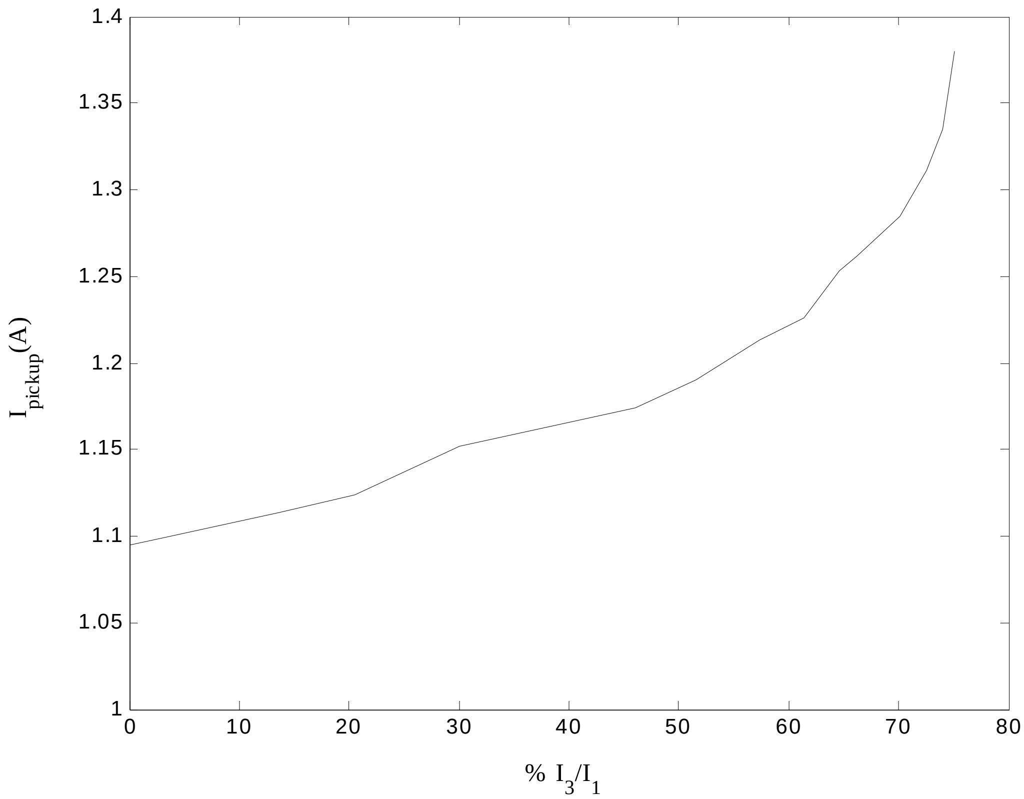

Fig. 4. The pickup current values of EIOCR versus third harmonic current distortion ($\%I_3/I_1$)

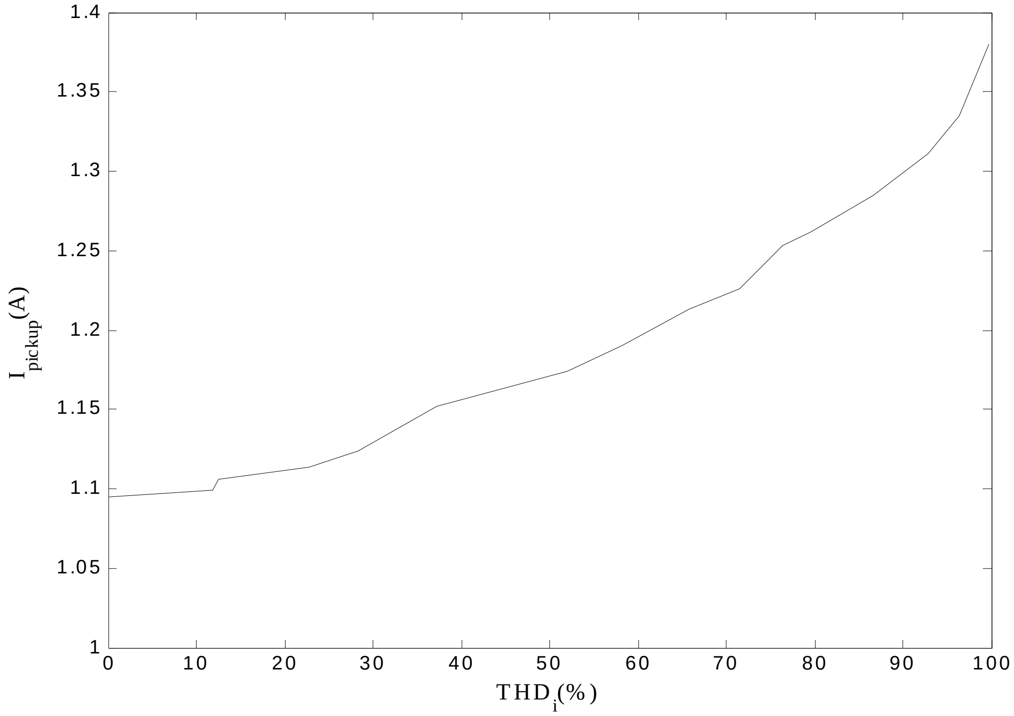

Fig. 5. The pickup current values of EIOCR versus %THD_i

The relay's pickup current value will increase as long as third harmonic current value and THD value of current increases as given in Fig.4 and Fig.5. Because of this problem, the relay can not perform protection function and this circumstance causes damage or heating according to the rms value of the current in power system components like transmission lines, motors and transformers. Therefore, it is necessary to obtain the pickup current values of EIOCR for nonlinear load currents that consist of different harmonic spectrums. To determine the relay's dynamic characteristics and the pickup current values for unmeasured non-sinusoidal current values, the harmonic analysis results and the measured nonsinusoidal current values for relay are applied to a feed forward NN algorithm. Thus, by using the developed NN, it is possible to estimate the dynamic behaviour and pickup current of this relay for unmeasured non-sinusoidal currents.

IV. Neural Networks Analysis

The following equations show the basic computational steps of error back-propagation algorithm [6].

$$\text{if } o_j = f(net_j) = f(x) \text{ then } net_j = \sum_j^i w_{ji} o_i + \theta_j \quad \textbf{(3)}$$

$$E_p = \frac{1}{2} \sum_{j-output} (t_{pj} - o_{pj})^2 \quad \textbf{(4)}$$

$$\left.\begin{aligned} \delta_{pj} &= (t_{pj} - o_{pj}) \\ \Delta_p w_{ji} &= -\alpha\left(\frac{\partial E_p}{\partial w_{ji}}\right) \\ \Delta_p \theta_j &= -\alpha\left(\frac{\partial E_p}{\partial \theta_j}\right) \end{aligned}\right\} \quad \textbf{(5)}$$

If a sigmoid transfer function is used in the operation element

$$\text{If} \quad o_{pj} = \frac{1}{\sum_i 1 + e^{-w_{ji}o_{pi} + \theta_j}} \quad \text{then,} \quad (\text{net}\, p_j) = \sum_i w_{ji} o_{pi} + \theta_j \tag{6}$$

If (ε) momentum term is added to the general equation set to speed up the computation of the algorithm, in general condition, output and hidden layer equations will take the following form

$$\Delta_p w_{ji}(t+1) = \alpha \delta_{pj} o_{pi} + \varepsilon \Delta_p w_{ji}(t) \tag{7}$$
$$\Delta_p \theta_j(t+1) = \alpha \delta_{pj} + \varepsilon \Delta_p \theta_j(t)$$

Here;
t : the number of learning cycles.
α: learning rate, $0.01<\alpha<10$
ε: momentum rate, $0<\varepsilon<1$

Table 2. List of input sets for NN algorithm

	THD_i (%)	I_1 (A)	$\% \frac{I_3}{I_1}$	$\% \frac{I_5}{I_1}$	$\% \frac{I_7}{I_1}$	$\% \frac{I_9}{I_1}$	$\% \frac{I_{11}}{I_1}$	$\% \frac{I_{13}}{I_1}$
Input Set-I	+	+						
Input Set-II	+	+	+	+				
Input Set-III	+	+	+	+	+	+		
Input Set-IV	+	+	+	+	+	+	+	+

In the application of the feed-forward neural network structure of back propagation algorithm, the input values are taken into account for the NNs structure (controller) with respect to the variables of the total harmonic distortion of the current (THD_i), rms value of the fundamental current (I_1) and the ratios of harmonic current rms values to the fundamental current (I_1) for 3rd, 5th, 7th, 9th, 11th and 13th harmonics (I_3/I_1, I_5/I_1,…, I_{13}/I_1). Therefore, there are maximum 8 inputs in the model of NNs structures. The output value is the pickup current of the relay (I_{pickup}). In this study, four different input sets are used for NN algorithm. Only total harmonic distortion values for current (THD_i) and rms value of fundamental current (I_1) are considered in input set-1. In the other input sets, harmonic current distortion values are considered addition to THD_i and I_1 as shown in Table 2.

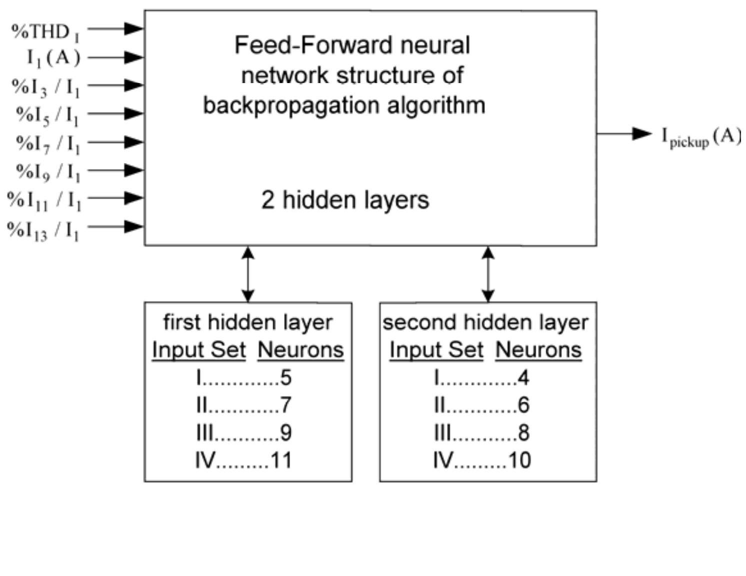

Fig. 6. General block diagram of NN structure

The general block diagram and the model of NNs structure used in this research are given in Fig.6 and Fig.7, respectively. Momentum and learning rates are set to $\varepsilon = 0.9$ and $\alpha = 0.7$, respectively. For all input sets, two hidden layers are used in the NN models.

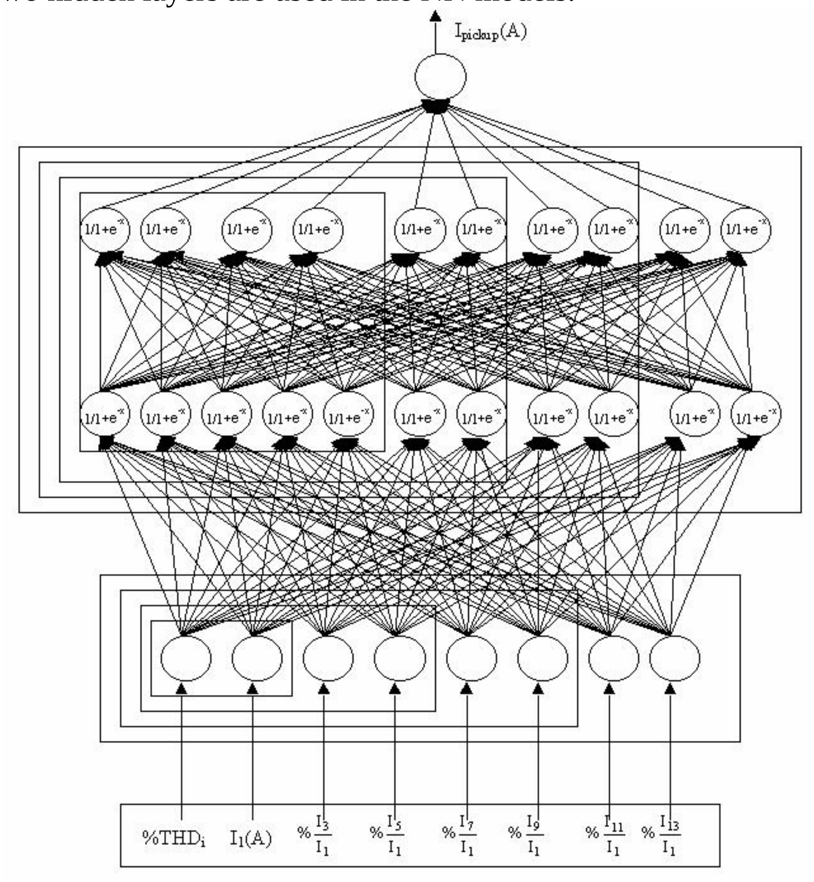

Fig. 7. Model of NNs structure

Measurement results which are obtained from the experimental study for EIOCR operation are successfully trained by using classic back-propagation algorithm. The architecture of NNs models are given in Table 3. Iteration numbers are 1050473, 1670964, 1866308, and 511171 for input set-I, input set-II, input set-III and input set-IV respectively. The pickup current of the relay (I_{pickup}) as the output value of NNs algorithm is successfully calculated.
The test phase results and relative errors of NNs analysis are given in Table 4 – Table 7.
According to the test phase results, relative error is between %0.019 and %0.75. For low THD_i values (%22.8, %65.8), the lowest errors are obtained in input set-I (two inputs). For high THD_i values (%96.4), the lowest errors are obtained in input set-III (six inputs).

Table 3. Architectures of NN models

	Architecture of NN model
Input Set-I	2 – 5 – 4 – 1
Input Set-II	4 – 7 – 6 – 1
Input Set-III	6 – 9 – 8 – 1
Input Set-IV	8 – 11 – 10 – 1

Table 4. Test phase results for input set-I

I_1 (A)	THD_i (%)	Measured I_{pickup} (A)	NNs Results I_{pickup} (A)	Error (%)
1.085	22.8	1,114	1.11294103	0.095
1.017	65.8	1.213	1.21277361	0.019
0.960	96.4	1.335	1.34302773	0.601

Table 5. Test phase results for input set-II

I_1 (A)	THD_i (%)	$\%\frac{I_3}{I_1}$	$\%\frac{I_5}{I_1}$	Measured I_{pickup} (A)	NNs Results I_{pickup} (A)	Error (%)
1.085	22.8	13.6	13.2	1,114	1.11245036	0.139
1.017	65.8	57.3	19.8	1.213	1.21335741	0.029
0.960	96.4	74.0	41.1	1.335	1.33807610	0.230

Table 6. Test phase results for input set-III

I_1 A)	THD_i (%)	$\%\frac{I_3}{I_1}$	$\%\frac{I_5}{I_1}$	$\%\frac{I_7}{I_1}$	$\%\frac{I_9}{I_1}$	Measured I_{pickup} (A)	NNs Results I_{pickup} (A)	Error (%)
1.085	22.8	13.6	13.2	6.6	5.8	1,114	1.10572832	0.742
1.017	65.8	57.3	19.8	13.3	10.2	1.213	1.21108476	0.158
0.960	96.4	74.0	41.1	25.7	19.8	1.335	1.33410810	0.067

Table 7. Test phase results for input set-IV

I_1 (A)	THD_i (%)	$\%\frac{I_3}{I_1}$	$\%\frac{I_5}{I_1}$	$\%\frac{I_7}{I_1}$	$\%\frac{I_9}{I_1}$	$\%\frac{I_{11}}{I_1}$	$\%\frac{I_{13}}{I_1}$	Measured I_{pickup} (A)	NNs Results I_{pickup} (A)	Error (%)
1.085	22.8	13.6	13.2	6.6	5.8	4.0	3.3	1.114	1.1059729	0.72
1.017	65.8	57.3	19.8	13.3	10.2	9.3	7.0	1.213	1.2062142	0.56
0.960	96.4	74.0	41.1	25.7	19.8	13.8	13.0	1.335	1.3449765	0.75

V. Conclusions

In this study, electromechanical instantaneous overcurrent relay that is designed for sinusoidal current, operates faulty in non-sinusoidal current which contains of harmonic components and this circumstances is proved by experimental results. The relay's pickup current will increase as long as THD value of current increases. The increase in the distortion of the current causes the increasing pickup current of the relay. Because of this problem, the relay can not perform protection function and this result causes damage or heating according to the rms value of current in power system components such as transmission lines, motors and transformers.

This study shows that NN algorithm is used successfully for analyzing and simulation studies in protection relays. Relative errors between the measured values and results of NN controller in test phase change dependent to input sets. By using NN based intelligent controller, it is possible to determine pickup current value of this relay for a non-sinusoidal current.

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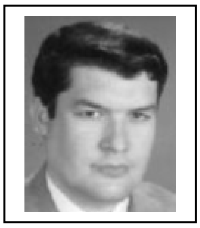

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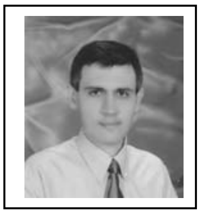

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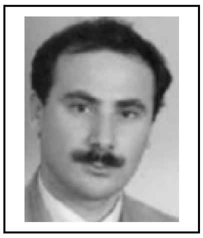

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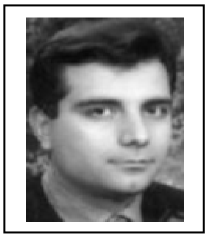

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