A NOVEL FUZZY AND ARTIFICIAL NEURAL NETWORK REPRESENTATION OF OVERCURRENT RELAY CHARACTERISTICS

M. Jannatian
Tehran Regional Electricity Company
Tehran, Iran, trec@systemgroup.net

H. K. Karegar
Department of Electrical Engineering of Amirkabir University of Technology
Tehran, Iran, h_kazemi_ir@yahoo.com

H. Askarian Abyaneh
Department of Electrical Engineering, Amirkabir University of Technologh
Tehran, Iran, askarian@yahoo.com

G. Heidari
Transmission and Distribution Department of Electric Power Research Center
Tehran, Iran, ghheidari@matn.com

M. Al-Dabbagh
Department of Electrical Engineering, RMIT University
Melbourne, Australia, majid@rmit.edu.au

(Received: August 6, 2002 - Accepted in Revised Form: May 15, 2003)

Abstract Accurate models of Overcurrent (OC) with inverse time relay characteristics play an important role for coordination of power system protection schemes. This paper proposes a new method for modeling OC relays curves. The model is based on fuzzy logic and artificial neural networks. The feed forward multilayer perceptron neural network is used to calculate operating times of OC relays for various Time Dial Settings (TDS) or Time Multiplier Settings (TMS). The new model is more accurate than traditional models. The model is validated by comparing the results obtained from the new method with linear and nonlinear Sachdev models as applied for various types of overcurrent relays.

Key Words Power System, Protection Systems, Overcurrent Relay

چکیده مدل های دقیق رله های جریان زیاد با مشخصه های خیلی معکوس نقش مهمی برای هماهنگی سیستمهای حفاظتی دارند. این مقاله یک روش جدید برای مدل کردن رله های جریان زیاد پیشنهاد می کند. مدل مذکور بر اساس منطق فازی و شبکه های عصبی قرار دارد. از شبکه عصبی پرسپترون چند لایه برای محاسبه زمان عملکرد رله های جریان زیاد با ضریب تنظیمهای زمانی مختلف استفاده شده است. مدل جدید نسبت به مدلهای موجود از دقت بالاتری برخوردار است. مزایای این مدل در مقایسه با مدلهای خطی و غیر خطی ساچدو با اعمال این مدلها بر روی رله های مختلف جریان زیاد و یافتن نتایج رایانه ای مشخص شده است.

1. INTRODUCTION

Many power systems are operated close to their design limits; therefore it is necessary to model relays to realistic conditions [1]. OC relay models are defined in various ways. The most familiar one is Time-Current (TC) curves of an OC relay [2]. There are two main methods for representing an OC relay on digital computers: software models and direct data storage. Software models of OC relay characteristics play a major role in coordinating protection schemes of power systems [3].

A complete review of computer representation of OC relays has been made in [4] and it states that Sachdev models are simple and useful polynomials

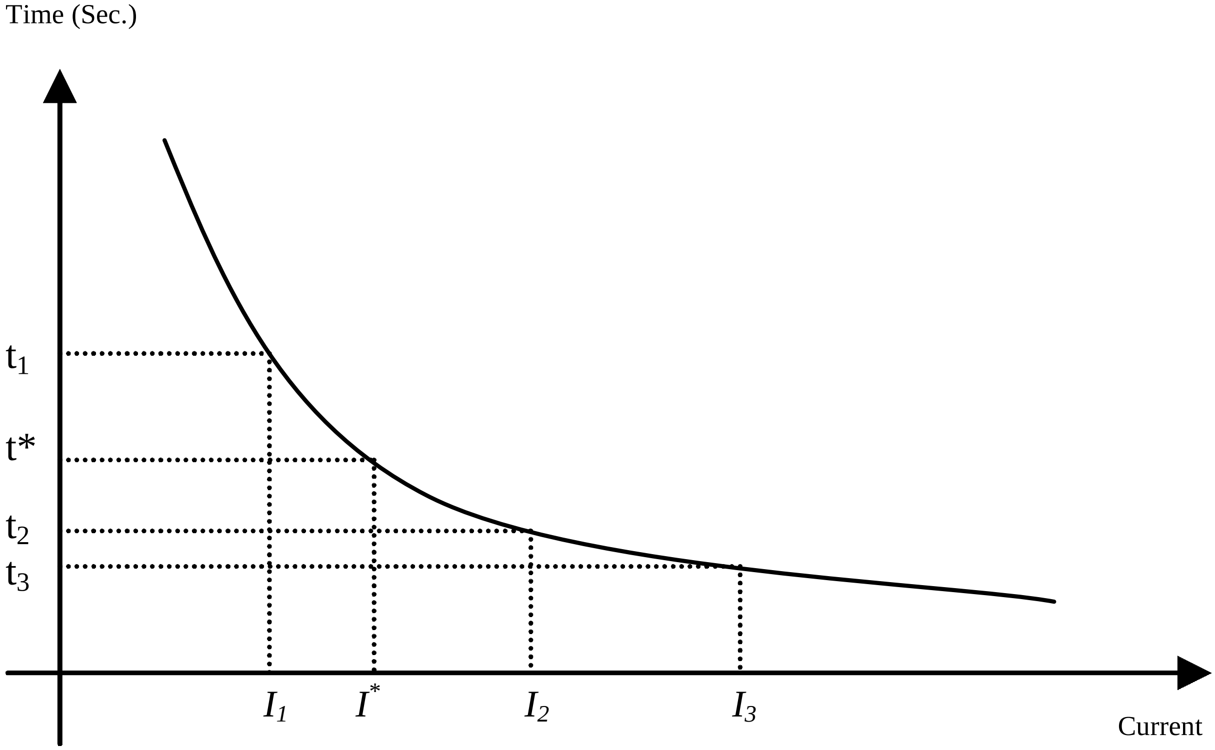


Figure 1. TC curve of an OC relay.

for modeling OC relays for coordination purposes. It should be noted that any microprocessor relay abiding to the IEEE Std. C37.112 [5], does not need any mathematical representation than the equations provided in to the standard. Furthermore, the time dial setting provided by the standard is linear.

Another way for representation of OC relays is based on direct data storage. Direct data storage consists of storing data in the memory of the computer for different TDS/TMS and then selecting operating points of a relay based on the stored data for different TDS/TMS. If the operating point does not match with one set of the stored values, then an interpolation is necessary to determine the corresponding time or TDS/TMS. Therefore, the problems with this method are due to the need for storing and using large amount of data. For the midpoints, interpolation is necessary otherwise the accuracy is affected.

In this paper a new model, which is more accurate than Sachdev models and does not have difficulties of look up table method, based on fuzzy logic and artificial neural networks for OC relays is presented. The fuzzy part is modified and more accurate model compared with the model introduced in [6] is proposed. In addition, the neural network part is completely new and efficient, which is found flexible and suitable for over current relay characteristics modeling. The fuzzy logic based model calculates the operating times of OC relays for a given TDS/TMS.

The neural network part has accurate estimation for operation times of the OC relays when the operating times of an OC relay lay between two sampled data obtained from experimental results or different curves with different TDS/TMS. The validity of the proposed model is achieved by using experimental tests, applying the sampled data to the new model. In addition, the results were compared with linear and nonlinear Sachdev models for various types of OC relays.

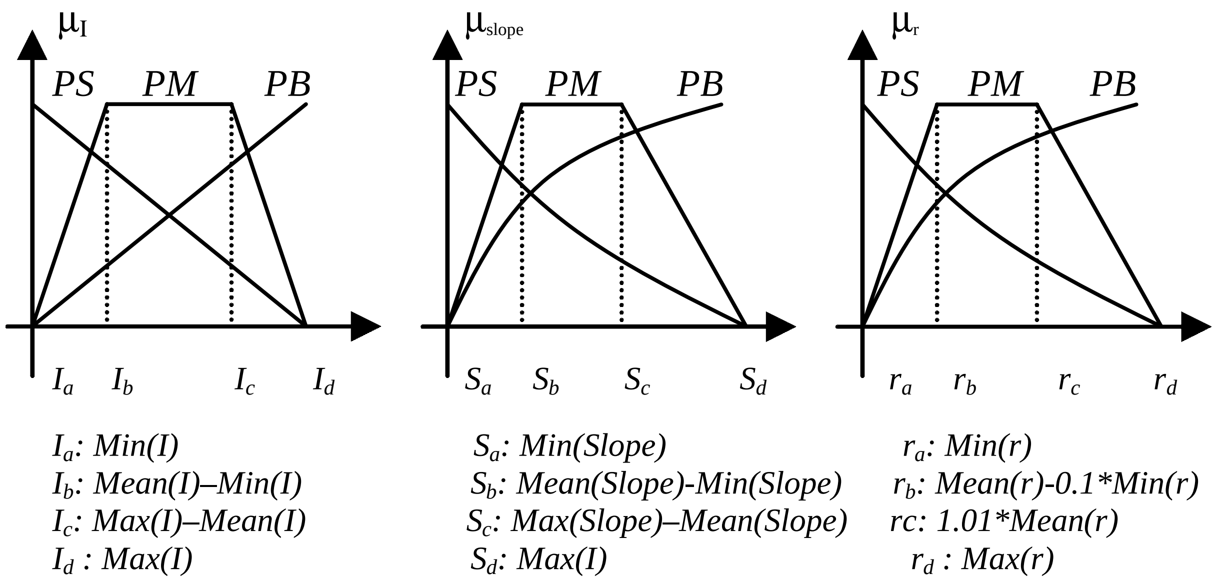


Figure 2. Membership functions of slope, r and I.

2. THE NEW METHOD

The proposed model includes two parts, the first one is based on fuzzy logic and the second is based on artificial neural networks. The fuzzy model has the same function as the linear Sachdev model and the neural network model includes nonlinearity feature similar to nonlinear Sachdev model but with higher accuracy. The neural network model is based on the feed forward multilayer perception neural network with one hidden layer.

2.1. Fuzzy Model The proposed fuzzy model is based on finding a simple mathematical equation with a fuzzy correction coefficient to calculate the operating time of OC relays.

In Figure 1, (t_1, I_1), (t_2, I_2) and (t_3, I_3) are sampled data and t^* is the operating time of OC relay for a given I^*. Obviously, the simplest equation for fitting two points on a curve is a direct line equation. This mathematical equation does not need any complicated curve fitting technique. But two adjacent points on OC relays curves are connected with a curve and not a direct line. So that, the proposed fuzzy logic model finds a fuzzy correction coefficient to simulate the curve of the OC relay under consideration.

According to Figure 1, any operation time like t^* for a given I^* can be calculated by Equation 1:

$$t^* = (t_2 - t_1).(I^* - I_1)/(I_2 - I_1) + t_1 \qquad (1)$$

As mentioned before, calculating t^* by Equation 1, produces some errors. To overcome this problem, a fuzzy correction coefficient must be included in Equation 1, Equation 2, shows the added fuzzy correction coefficient to Equation 1.

$$t^* = r.(t_2 - t_1).(I^* - I_1)/(I_2 - I_1) + t_1 \qquad (2)$$

The fuzzy correction coefficient r varies between 0 and 1 when the location of I^* changes on the current multiplier setting axis of TC curves. The value of I^* and the slope of line between adjacent data play an important role in calculating the variation of r. For example, when I^* gets large and goes near the tale of TC curve, the *slope* gets small. Subsequently the curve between two neighboring data is close to a direct line. Therefore the value of r increases and approaches a value closes to one.

Equations 3 and 4 describe how to calculate r and the *slope* for a sampled data:

$$r_i = (I_{i+2} - I_i).(t_{i+1} - t_i)/(t_{i+2} - t_i).(I_{i+2} - I_i) \quad (3)$$

$$slope_i = (t_{i+1} - t_i)/(I_{i+1} - I_i) \quad (4)$$

For example, in considering Figure 1, r_1 can be obtained by Equation 5:

$$r_1 = (I_3 - I_1).(t_2 - t_1)/(t_3 - t_1).(I_2 - I_1) \quad (5)$$

The membership function of *I*, *r* and *slope* of sampled data are necessary for calculating the value of r for other set of data. It is worth mentioning that the value of I could be obtained from the catalogue of OC relays. For example, I varies from 2 to 30 for RSA20 electromechanical OC relay. However, the value of *slope* and r must be calculated based on the stored data and then used for the calculation of membership function of r (μ_r) and the membership function of the slope (μ_{slope}).

The membership functions of the *slope, I,* and *r* are shown in Figure 2.

Because the values of the *slope, I,* and *r* are positive, only Positive Small (PS), Positive Medium (PM) and Positive Big (PB) are effective.

It is found by trial and error that the trapezoid shape for PM produces better results than triangle shape, which is used in [6]. This feature is regarded as an advantage in the new fuzzy model, compared with the previous method, which proposed by the authors in [6].

As can be seen from Figure 1, when I is small, near pick-up current, and the *slope* is large, because TC curve closes to its asymptotic, then the value of r must be selected large, i.e., 1. In other words, TC curves of OC relays near the pick-up currents are very straight like a direct line.

Based on above assumptions, the fuzzy rules for the proposed method are as below:

- If *I* is small and *slope* is large then *r* is large.
- If *I* is small and *slope* is medium then *r* is medium.
- If *I* is medium and *slope* is small then *r* is medium.
- If *I* is medium and *slope* is medium then *r* is small.
- If *I* is medium and *slope* is large then *r* is medium.
- If *I* is large and *slope* is medium then *r* is medium.
- If *I* is large and *slope* is small then *r* is large.

The last step in fuzzy modeling is determining the value of r. In this paper, the centroid method is used to calculate r. Equations 6-8 show how to obtain r.

$$a_i = \mu_i \wedge \mu_{slope} \quad (6)$$

$$\mu_r^{'} = a_i \wedge \mu_r \quad (7)$$

$$r_i = centroid(\mu_r^{'}) \quad (8)$$

$$r = \sum_1^n a_i.r_i / \sum_1^n a_i \quad (9)$$

2.2. Artificial Neural Network Model The proposed model is based on a feed forward multilayer neural network for calculating operating times of an OC relay when different TDS/TMS besides the sampled data is selected.

The data of TC curves are sampled for specific TDS/TMS first, and then stored in the memory of the computer. When TDS/TMS has a continuous variation feature, it is not practicable to store all TC curves in the memory of the computer. In this case an interpolation process is necessary. The relation between operating times of an OC relay for different TDS/TMS is ideally linearly proportional, i.e. when TDS/TMS increases two times then the corresponding operating time will increase two times. However, in real situation the relationship is nonlinear, especially for electromechanical OC relays, which will be shown in the next section.

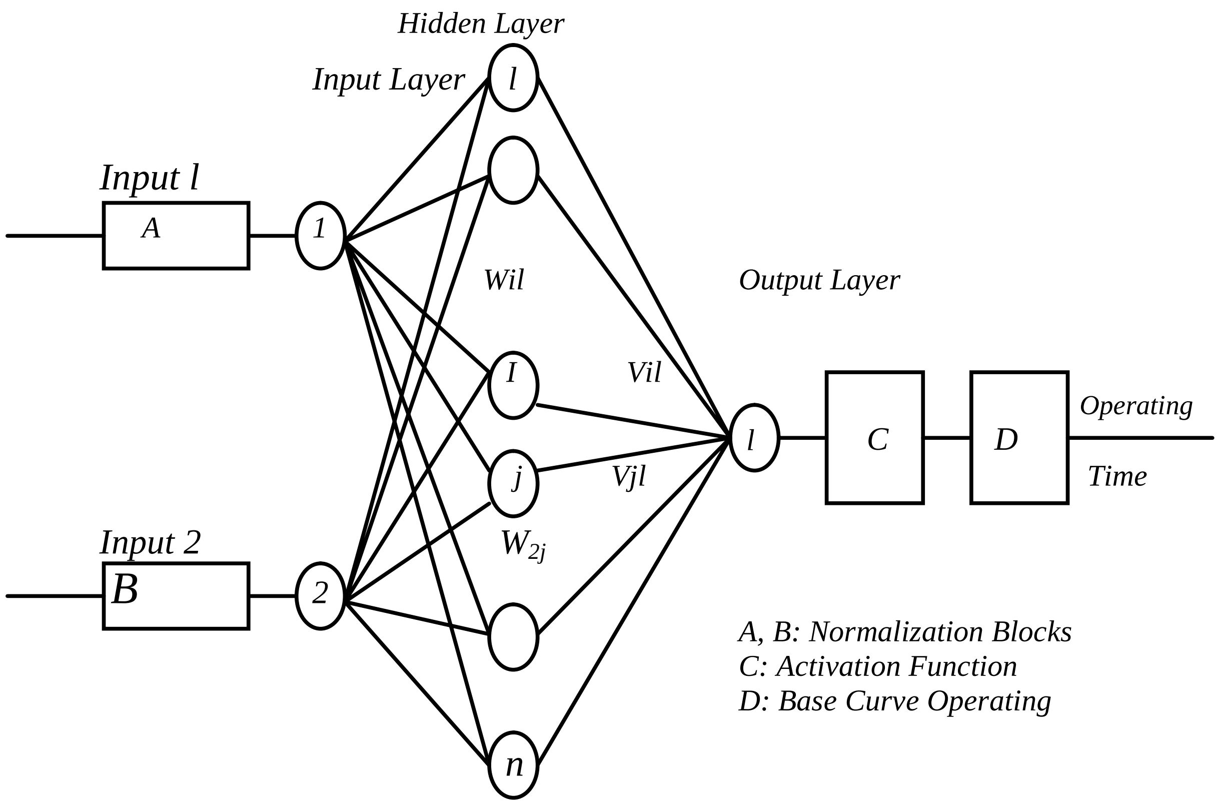


Figure 3. Feed forward multilayer perceptron neural network for relay operating time calculation.

To model the nonlinearity, a supervised multilayer perceptron neural network, which is shown in Figure 3, is proposed as the neural network model.

The neural network has two nodes in the input layer, 108 nodes in hidden layer and one node in the output layer. The current multiplier setting and TDS/TMS are selected as input nodes in the proposed method. The input data, i.e. input 1 and input 2, are normalized before applying to the neural network, because normalizing improves the learning process of neural network [7]. For the neural network-training pattern, delta rule, based on squared error minimization is used [8].

The output of the neural network including activation function is time ratio, which is defined as the ratio of operating time of OC relay to the sampled operating time of the lowest TDS/TMS. By multiplication the output to the corresponding operating time of the base curve, the operating times of the relevant points are calculated. Since an asymmetric activation function typically makes the learning process faster, a hyperbolic activation function as shown in Equation 10 is used [9].

$$f(y) = a.(1 - e^{-by})/(1 + e^{-by}) \tag{10}$$

where y is the internal activity of neurons.

The coefficients of a and b are constants. In this paper, the values of a and b are obtained by trial and error and set to 9 and 0.25 respectively.

TABLE 1. Operation Time of RSA20 OC Relay in Ms when TDS = 4, 8, 14 and 20.

I	TDS = 4	TDS = 8	TDS = 14	TDS = 20
4	4238	5690	8840	11975
5.5	2235	3255	5439	7516
7	1648	2412	4012	5797
8.5	1373	2070	3522	5070
10	1240	1960	3283	4702
11.5	1155	1890	3146	4525
13	1112	1825	3076	4411
14.5	1075	1778	3025	4333
16	1061	1754	2993	4264
17.5	1045	1735	2954	4194
19	1028	1714	2911	4126
20.5	1017	1691	2874	4083
22	1010	1659	2846	4043
23.5	1008	1636	2799	4003
25	1006	1626	2771	3965
26.5	1004	1611	2747	3935
28	1002	1603	2734	3915
29.5	1000	1594	2697	3893

TABLE 2. Operation Time of Siemens 7SK88 OC Relay in Ms when TMS = 0.05, 0.2, 0.4 and 0.5.

I	TMS = 0.05	TMS = 0.2	TMS = 0.4	TMS = 0.5
4	941	3579	7117	8885
5.5	617	2407	4787	5978
7	461	1811	3609	4513
8.5	368	1452	2896	3624
10	309	1220	2433	3046
11.5	275	1085	2162	2707
13	248	977	1948	2439
14.5	227	891	1776	2224
16	214	841	1677	2099
17.5	207	812	1616	2023
19	199	782	1561	1952
20.5	193	755	1508	1887
22	187	731	1459	1826
23.5	181	710	1414	1769
25	176	689	1372	1716
26.5	171	668	1331	1666
28	166	649	1296	1618
29.5	162	633	1262	1577

3. CASE STUDY

Two types of OC relays were used for evaluating the proposed model. The first one was RSA20, an electromechanical OC relay, which its TDS varies from 4 to 20. The second one was SIEMENS

TABLE 3. Sachdev Polynomial Coefficients of RSA20 OC Relay when TDS=4, 8 and 20.

Coefficient	TDS=6	TDS=8	TDS=20
a_0	0.2343	0.2386	0.2924
a_1	-0.1957	1.4592	1.0945
a_2	6.222	-9.0501	-4.7457
a_3	-0.0351	36.2787	26.2756
a_4	-2.9201	25.0367	14.3067
a_5	2.259	-39.6346	-33.2044
a_6	11.4195	-117.835	-87.3217
a_7	20.7218	-186.711	-133.39
a_8	28.6445	-239.456	-167.828

TABLE 4. Comparing Error Percentage between Fuzzy and Sachdev with Actual Operation Time of Rsa20 OC Relay.

TDS	Error Percentage of Fuzzy Model	Error Percentage of Sachdev Model
4	0.78	1.18
6	0.49	1.03
8	0.40	0.58
10	0.43	0.65
12	0.46	0.74
14	0.47	0.78
16	0.43	0.63
18	0.38	0.59
20	0.35	0.63

7SK88, a solid-state OC relay. For both relays, some parts of sampled data are shown in Table 1 and Table 2 and another sample data for testing the models are shown in appendix.

The sampled data are obtained by performing experimental tests five times using an accurate computerized relay tester for RSA20 and SIEMENS 7SK88 relays, to make sure the measurements results are correct. For RSA20 and SIEMENS 7SK88 the operating time for TDS = 14 and TMS = 0.4 are sampled but they will be used as test data to compare the models.

3.1. Fuzzy Model Application

3.1.1. Fuzzy Model of RSA20 OC Relay The recommended Sachdev model in [4] is selected for comparison between the new and the mathematical model. Regarding with vast progresses in calculating methods and software packages, like MATLAB, using more polynomials coefficients are possible. Especially, when MATLAB has provided a powerful environment to calculate polynomials coefficients based on advanced non-linear curve fitting techniques [10,11]. Therefore, for obtaining accurate results and better evaluations, Equation 11, with nine coefficients are chosen. Using higher order of the polynomials produces ill-structure matrices and poor output results reported by MATLAB. In addition, normalized operation time data were used to improve the accuracy of the obtained results by both methods.

$$t = a_0 + a_1/(I-1) + a_2/(I-1)^2 + \ldots + a_8/(I-1)^8 \qquad (11)$$

TABLE 5. Sachdev Polynomial Coefficients for Siemens 7sk88 OC Relay when TMS = 0.05, 0.2 and 0.5.

Coefficient	TMS = 0.05	TMS = 0.2	TMS = 0.5
a_0	0.131	0.134	0.1358
a_1	0.9997	1.0154	0.9793
a_2	7.4338	8.436	8.9012
a_3	-6.2499	-9.5023	-10.8173
a_4	-12.7329	-15.7364	-16.9237
a_5	-3.7674	-0.808	0.7567
a_6	13.0162	24.1055	29.4931
a_7	30.3587	49.1104	58.1511
a_8	45.1082	70.0239	82.033

TABLE 6. Comparing Error Percentage between Fuzzy and Sachdev with Actual Operation Time of SIEMENS 7SK88 OC Relay.

TMS	Error Percentage of Fuzzy Model	Error Percentage of Sachdev Model
0.05	0.34	0.69
0.1	0.32	0.79
0.15	0.31	0.76
0.2	0.30	0.73
0.25	0.31	0.72
0.3	0.32	0.70
0.35	0.31	0.68
0.4	0.30	0.65
0.45	0.32	0.63
0.5	0.33	0.62

For instance, the coefficients of Equation 11, i.e. a_0 to a_8, are shown in Table 3 where data in columns TDS = 4, 8 and 20 of Table 1 are selected as input. The first row of Table 3 shows the coefficients of Equation 11, for the sampled data of TC curve when TDS = 6.

Calculating the average error percentage for each curve of RSA20 made evaluating of the fuzzy model versus the mathematical model. The obtained results are shown in Figure 4, Figure 5 and Table 4.

As can be seen from Figure 4, the average of error percentages of fuzzy model results are smaller than polynomial form and in most cases is near 0.4 percent. In addition, Figure 5 and Table 4 show that the error percentage of the fuzzy model decreases when the fault current through the relay increases. This is an important feature, because high fault currents can cause sever damages to power systems components.

3.1.2. Fuzzy Model of Siemens 7sk88 OC Relay In this section, the fuzzy model is applied to SIEMENS 75K88 OC relay to find its characteristic. The relay is a solid-state type and its data are given in Table 2. The data are obtained by experimental tests. The coefficients of Sachdev model, i.e. a_0 to a_8 for the relay, are calculated and shown in Table 5.

Comparison between Figures 6-7 with Figures 4-5 and Table 4 with Table 6 show the error percentage of SIEMENS 7SK88 is generally smaller than for RSA20 even are smaller, particularly for low current values. However, the

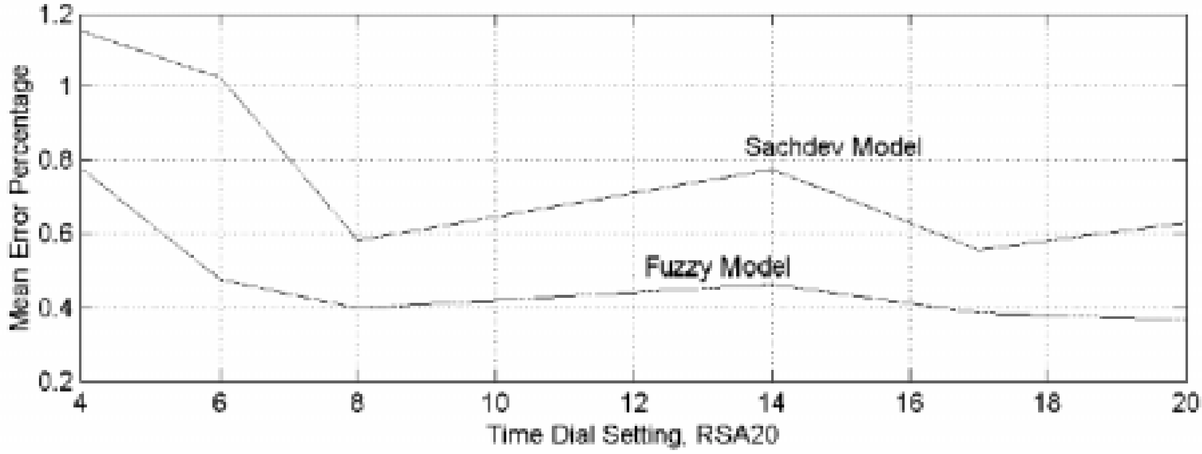


Figure 4. Average error percentage of fuzzy and Sachdev model for RSA20.

fuzzy model of SIEMENS 7SK88 is more precise than Sachdev model in both cases. Similar to RSA20, the average error percentage of proposed model is below one percent and usually decreases when current multiplier setting is increased. On the other hand, the fuzzy method uses very simple mathematical equation and does not involve to complicated curve fitting techniques. Consequently, ill-structure matrices and poor results are not reported. Moreover, the accuracy of the polynomial model is under some circumstances associated with mathematical techniques where it happened for the test cases and limited the order of polynomials to 8, i.e. from a_0 to a_8.

3.2. Artificial Neural Network The relationship between the operating times of an OC relay specially for electromechanical relay at different TDS/TMS is not usually linear.

In Figure 8-a, the relay operating times for

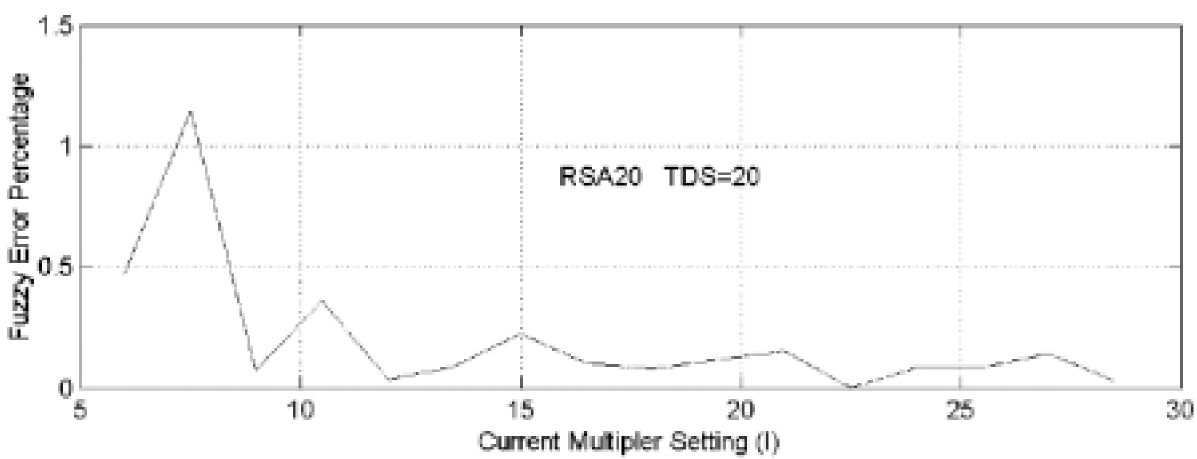


Figure 5. Error percentage of fuzzy model for RSA20 when TDS = 20.

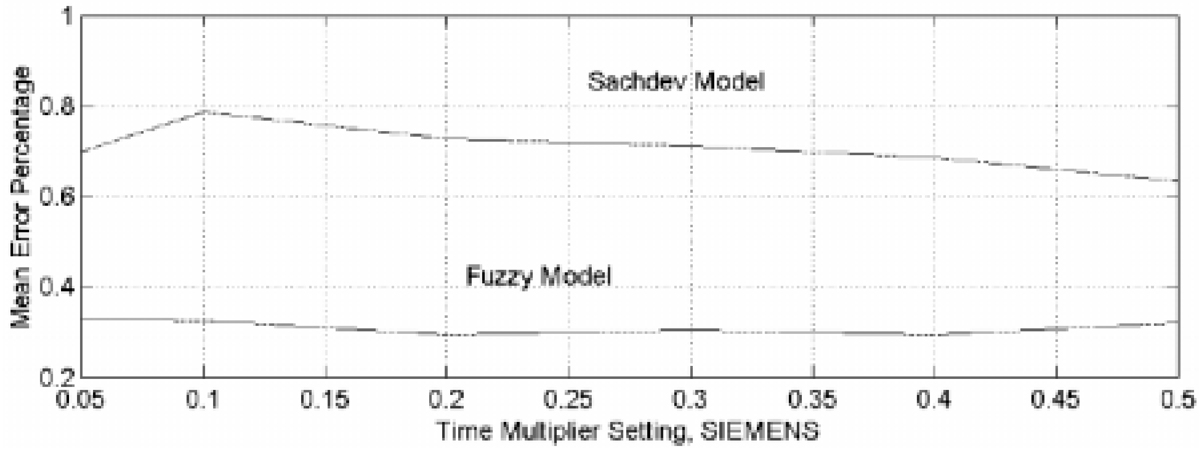


Figure 6. Average error percentage of fuzzy and Sachdev Model for SIEMENS.

TDS = 4 are selected as a base to find the relationship between operating time of RSA20 for TDS variation. In Figure 8-b, the operating times of SIEMENS 7SK88 for TMS = 0.05 are chosen as a base for comparison.

Figure 8, shows that the relation between operating times of RSA20 relay is completely nonlinear, whereas for solid-state SIEMENS 7SK88 relay has less nonlinearity.

To compare the new model results with nonlinear Sachdev model, the Sachdev equation model is illustrated as Equation 12 [4]:

$$g(x) = b_0 + b_1.x + b_2.x^2 + ... + b_6.x^6 \qquad (12)$$

where x is TDS/TMS.

The coefficient of Equation 12, is obtained by curve fitting techniques and the number of the coefficients is limited to six because of conditions that stated before. The input data for curve fitting are the sampled operating times of different TDS/TMS of an OC relay for a given current multiplier setting.

If the operating times of OC relay for various

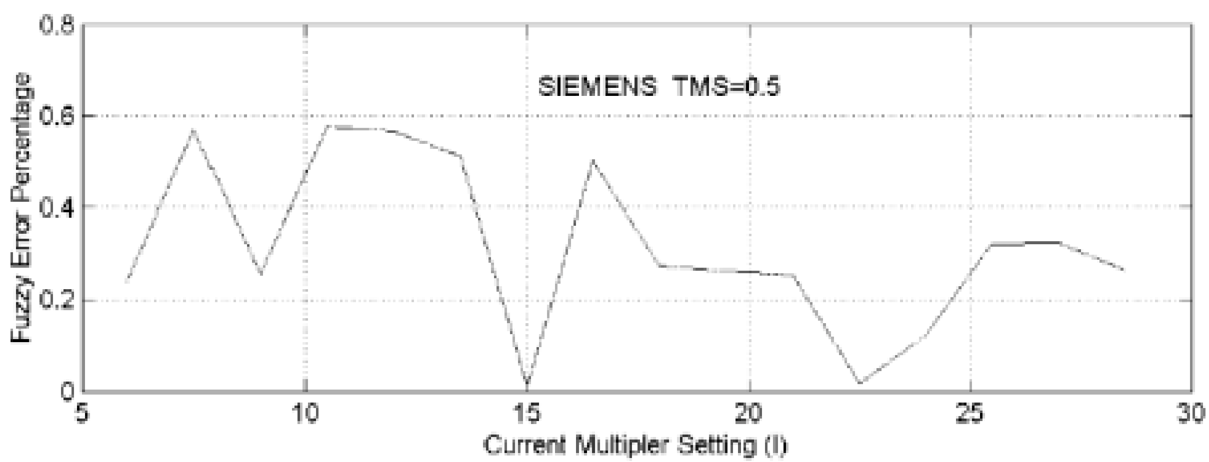
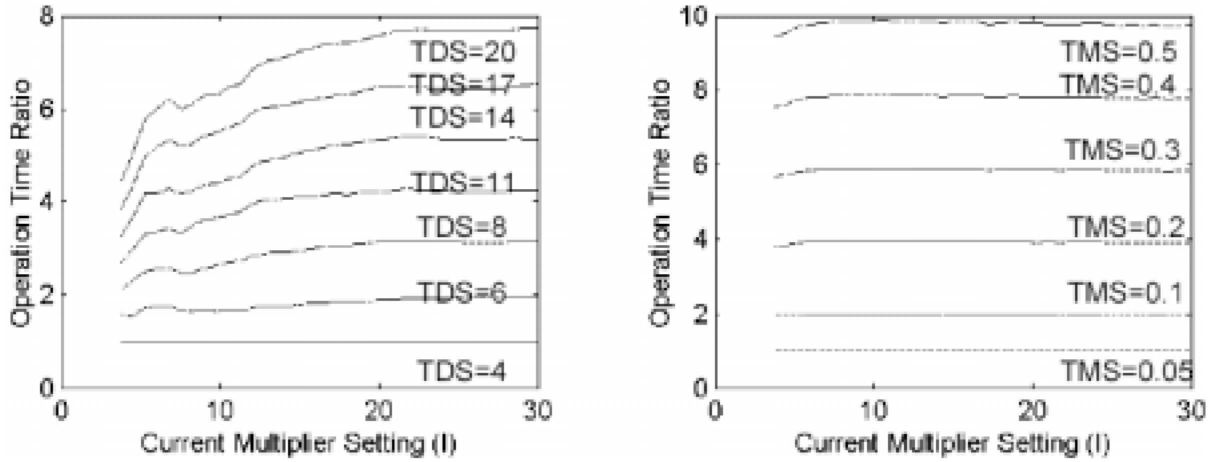


Figure 7. Error percentage of fuzzy model for SIEMENS 7SK88 when TMS = 0.5.



a) The operation time ratio of RSA20 relay when the operating times for for TDS=4 are selected as reference.

b) The operation time of SIEMENS 7SK88 when the operating times TMS=0.05 are reference.

Figure 8. The operating time relation relay when the operating times for n of different time multiplier setting.

TDS/TMS have a linear relation, then the curves in Figure 10-a, convert to horizontal direct lines. Hence, for each current multiplier setting there is a different set of data and different coefficients. For example if for I = 6, the coefficients of Sachdev model for a TDS/TMS relay curve is computed, for other currents, let say I = 4, different coefficients will be obtained. Therefore different error percentages will be for the same TDS/TMS curve. It means that for each value of current multiplier setting, there is a specific equation. But for the mathematical nonlinear model of OC relay, only one equation must be selected. It is not straightforward because in the protection of power systems, OC relays are set and operates under a wide range of current multiplier setting. Therefore, each equation produces some errors when a relay operates in a section, which is different from the section for which data is sampled. This is the problem of nonlinear Sachdev model, which neural network model does not have.

The coefficients of Equation 12 are shown in Table 7 and Table 8 for RSA20 and SIEMENS 7SK88 respectively. For each relay, the current multiplier setting (I) has different values, which vary from 6 to 24.

When the relation between different operating times of an OC relay is linear then the coefficients of Equation 12, are equal to each other. It can be seen from Table 8 that the coefficients of SIEMENS 7SK88 are close to each other. The table is consistent with Figure 8-b.

For both relays, RSA20 and SIEMENS 7SK88 OC relays, comparisons are made between the new neural network model and the Sachdev model. Both models calculate the operating time of OC relay for different current multiplier settings, i.e., when TDS=14 for RSA20 and TMS=0.4 for SIEMENS 7SK88. The results are shown in Table 9 and Table 10.

The first column of Table 9 and Table 10 gives different values of current multiplier settings (I). The second column shows the obtained results using the neural network model. Other columns, i.e. poly 1 to poly 3 refer to the obtained results by Equation 12, for the four rows of Table 7 or Table 8, as coefficients for RSA20 or SIEMENS 7SK88 relay. As a consequence, poly 2 is related to the second row of Table 7 and Table 8.

The results of RSA20 OC relay in Table 9 show

TABLE 7. Sachdev Polynomial Coefficients for Rsa20 OC Relay when I = 6, 12 and 18.

Coefficient	Poly1, I=6	Poly1, I=12	Poly1, I=18
b_0	1.1908	1.0249	1.0611
b_1	-15.1414	-11.8461	-11.8543
b_2	79.6322	55.4136	50.6364
b_3	-188.3968	-110.2849	-79.6902
b_4	230.5395	108.2454	36.1614
b_5	-140.4977	-48.5280	24.4574
b_6	33.6731	6.9750	-19.8040

TABLE 8. Sachdev Polynomial Coefficients for Siemens 7sk88 OC Relay when I = 6, 12 and 18.

Coefficient	Poly1, I = 6	Poly1, I = 12	Poly1, I = 18
b_0	0.0157	0.0090	0.0098
b_1	0.6886	0.8279	0.8218
b_2	2.7281	1.5131	1.5583
b_3	-11.0111	-6.2202	-6.3452
b_4	22.3364	12.8431	12.9203
b_5	-22.0115	-12.8670	-12.7632
b_6	8.2538	4.8940	4.7983

TABLE 9. Error Percentages of Calculated Operating Time Of RSA20 OC Relay for TDS = 14 when I = 6,12 and 18.

I	Neural	Poly 1	Poly 2	Poly 3
6	2.1941	0.3335	16.4352	19.1328
12	4.0419	12.4598	2.2686	4.6380
18	0.0511	20.6734	7.3268	5.1798

TABLE 10. Error Percentages of Calculated Operating Time of SIEMENS 7SK88 OC Relay for TMS = 0.4 when I = 6, 12 and 18.

I	Neural	Poly 1	Poly 2	Poly 3
6	0.0972	3.2734	1.5088	1.7822
12	0.0244	3.8874	2.1340	2.4057
18	0.0945	3.3895	1.6270	1.9001

that the error percentage of the neural network model for I = 6 is 2.1941 percent, while for Sachdev nonlinear model showing in columns Ploy 2, 3 and 4 are very large. Even the error of the neural network method is less than for column Poly 1, which is the Sachedev model with smallest error. The comparison shows the error percentage of poly 1 changes from 0.3335 to 20.0734 percent, however for the neural network column is from 0.0511 to 2.1941. In other words, the average and variation error is much lower for the neural network model.

The results of Table 10 show that the proposed model has a good performance even when the relations between TC curves of an OC relay are close to linearity. Again, it can be seen from Table 10, that the error percentage of the neural network model changes from 0.0244 to 0.0972 percent, but for the best case of Sachev model, i.e. ploy 2, it varies from 1.5088 to 2.1340 percent.

4. CONCLUSION

In this paper a new model for OC relays, based on fuzzy logic and artificial neural networks is presented. The new model was evaluated by experimental tests on two types of OC relays. The results show that the error percentages of fuzzy model for both electromechanical and static OC relays are low. To calculate the operating time of the OC relay with continuous TDS/TMS, an artificial neural network based model was proposed. In comparing, the results of the new method with Sachdev model, it is evident that the new model does not need any curve fitting techniques and its accuracy is better. It has been shown that the method is flexible and can take into account different relay characteristics with linear and nonlinear features.

5. GLOSSARY

t: Operation time of OC relay
I: Current multiplier setting
Slope: Slope between two neighbored points on TC curve
r: Fuzzy correction factor
μ_r: Membership function of *r*
μ_{slope}: Membership function of slope
μ_I : Membership function of *I*

6. APPENDIX

TABLE A. Test Operation Time of RSA20 OC Relay in Ms when TDS=4, 8, 14 and 20.

I	TDS=4	TDS=8	TDS=14	TDS=20
4.5	2816	4220	6637	9097
6	1881	2751	4512	6496
7.5	1478	2196	3706	5319
9	1314	2005	3373	4863
10.5	1206	1930	3206	4617
12	1128	1860	3105	4461
13.5	1096	1802	3049	4370
15	1074	1765	3008	4303
16.5	1051	1743	2971	4228
18	1032	1720	2934	4158
19.5	1025	1702	2894	4106
21	1015	1685	2862	4066
22.5	1009	1652	2825	4023
24	1007	1634	2785	3982
25.5	1005	1616	2756	3951
27	1003	1607	2743	3929
28.5	1001	1597	2718	3901
30	998	1593	2689	3886

TABLE B. Test Operation Time of SIEMENS 7SK88 OC Relay in Ms when TMS=0.05, 0.2, 0.4 and 0.5.

I	TMS=0.05	TMS=0.2	TMS=0.4	TMS=0.5
4.5	749	2882	5718	7140
6	527	2066	4115	5137
7.5	409	1611	3213	4019
9	335	1321	2631	3297
10.5	290	1147	2289	2866
12	261	1028	2051	2563
13.5	236	931	1857	2324
15	219	862	1718	2151
16.5	210	826	1646	2065
18	203	796	1587	1987
19.5	196	770	1534	1919
21	190	745	1484	1856
22.5	184	721	1436	1797
24	178	699	1392	1742
25.5	174	678	1352	1692
27	169	658	1312	1643
28.5	165	641	1278	1598
30	160	625	1244	1560

f: Asymmetric activation function
y: Internal activity of neuron
a,b: Constants
x: *TDS* or *TMS*

7. REFRENCES

1. Sidhu, T. S., Hfuda, M. and Sachdev, M. S, "A Technique for Generating Computer Models of Microprocessor-Based Relays", ***Proc. 1997 IEEE Communications, Power and Computing, WESCANEX'97***, (1997), 191-196.
2. McLaren, P. G., Mustaohi, K., Benmouyal, G., Chano, S., Giris, A., Henville, C., Kezunovic, M., Kojovic, L., Marttila, R., Meisinger, M., Michel, G., Sachdev, M. S., Skendzic, V., Sidue, T. S. and Tziouvaras, D., "Software Models for Relays", ***IEEE Trans. Power Delivery,*** Vol. 16, (April 2001), 238-245.
3. Sachdev, M. S. and Sidhu, T. S., "Modeling Relays for Use in Power System Protection Studies", ***Proc. 2001 IEE Development in Power System Protection,*** (2001), 523-526.
4. IEEE Committee Report, "Computer Representation of Overcurrent Relay Characteristics", ***IEEE Trans Power Deliver,*** Vol. 4, (July 1989), 1659-1667.
5. "IEEE Standard Inverse-Time Characteristic Equations For Overcurrent Relays", ***IEEE Std C37***, (1996), 112-.
6. Askarian, H., Faez, K. and Kazemi, H., "A New Method for Overcurrent Relay (Oc) Using Neural Network and Fuzzy Logic", ***Proc 1997 IEEE Speech and Image Technologies for Telecommunications***, ***TENCON '97***, (1997) 407-410.
7. Medsker, L. and Liebowitz, J., "Design and Development of Expert System and Neural Networks", New York: Macmillan, (1994), 196-203.
8. Fausett, L., "Fundamentals of Neural Networks, Architectures, Algorithms and Applications", NJ: Prentice-Hall, (1994), 86-87.
9. Haykin, S. S., "Neural Networks (A Comprehensive Foundation)", New York: Macmillan, (1994), 176-181.
10. Coleman, T. F. and Li, Y., "An Interior, Trust Region Approach for Non-Linear Minimization Subject to Bounds", ***SIAM journal on Optimization***, Vol. 6, (1996) 418-445.
11. Coleman, T. F. and Li, Y., "On the Convergence of Reflective Newton Methods for Large-Scale Nonlinear Minimization Subject to Bounds", ***Mathematical Programming***, Vol. 67, No. 2, (1994), 189-224.