A Fuzzy Approach for Overcurrent Relays Simulation

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Abstract. Accurate models for Overcurrent relays (OC) with inverse time characteristics have an important role for efficient coordination of power system protection devices. This paper proposes a new method for modelling of OC relays based on fuzzy logic. The new model is more accurate than traditional models and has been validated by comparing it with the linear and nonlinear analytical models.

1 Introduction

Due to unforseen load expansion, many power systems are operated close to their design limits, therefore it is necessary to revise modelling of relays under these conditions [1]. OC relay models are defined in various ways. Time-Current (TC) curves of an OC relay is the most commonly used method [2]. There are two main methods for representing an OC relay i.e., by using digital computers: software models and direct data storage. Software models of OC relay characteristics play a major role in coordinating protection schemes in power systems [3].

A comprehensive review of computer representation of OC relays has been made in reference [4]. In this review, it is stated that Sachdev models are simple and useful polynomials for modelling OC relays for coordination purposes. It should be noted that any microprocessor relay abiding to the IEEE Std. C37.112 [5], should follow in this representation the equations provided by their standard. Furthermore in this context, the time dial setting provided by this standard is linear.

An alternative method for the representation of OC relays is based on direct data storage techniques. These techniques store data in memory of the computers for different TDS/TMS and then select operating points of a relay based on the stored data for different TDS/TMS. If the selected operating point does not match with one of the stored values an interpolation is necessary to determine the corresponding time. Therefore, this method requires storing large amount of data.

In this paper a new model based on fuzzy logic and is more accurate than analytical models and does not need look up tables is presented. The new methodology employed gives a more accurate model, compared with the model introduced in [6].

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2 The New Method

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 Fig. 1, (t_1, I_1), (t_2, I_2) and (t_3, I_3), sampled data are given is the operating time of OC relay for a given I^*. The simplest equation for fitting two points on a curve is the straight line equation. This mathematical equation does not need any complicated curve fitting technique. In reality, two adjacent points on OC relay characteristics are connected as a line. Therefore, the proposed fuzzy logic model finds a fuzzy correction coefficient to simulate the curve of the OC relay under consideration.

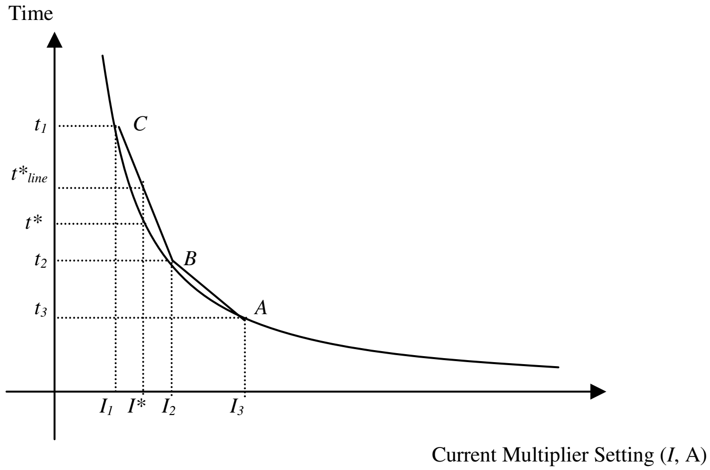

Fig. 1. A TC curve of an overcurrent relay

If the two points (t_1, I_1) and (t_2, I_2) of Fig. 1 are the considered sampled data, then the operation time associated with I* can be calculated by As follows:

$$t^*_{line} = (t_2 - t_1).(I^* - I_1)/(I_2 - I_1) + t_1 \tag{1}$$

The calculated operation time according to equation (1) is t^*_{Line} which differes from actual one, i.e. t*. Therefore, a correction factor must be added to equation (1). The variation of correction factor, r, is determined using fuzzy logic technique. The equation with correction factor is given as:

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

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 values of I^* and the slope (s) of the 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 the TC curve, and the slope gets smaller. Subsequently, the curve between two neighbouring data is close to a direct line. Therefore, the value of r increases and approaches a value close to one.

Equations (3) and (4) describe the calculation of r and s for the sampled data.

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

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

For example, in considering Fig. 1, r_1 can be obtained by Eq. (5).

$$r_1 = [(I_3 - I_1).(t_2 - t_1)]/[(I_3 - I_1).(t_2 - t_1)] \tag{5}$$

The membership functions of I, r and s 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 can be obtained from the catalogues of OC relays. For example, I varies from 2 to 30 for RSA20, an electromechanical OC relay. However, the values of s and r must be calculated based on the stored data and then used for the calculation of the membership functions of r (μ_r) and s (μ_s). Because the values of I, r and s are positive, only Positive Small (PS), Positive Medium (PM) and Positive Big (PB) are effective.

The membership functions of I, r and s are shown in Fig. 2.

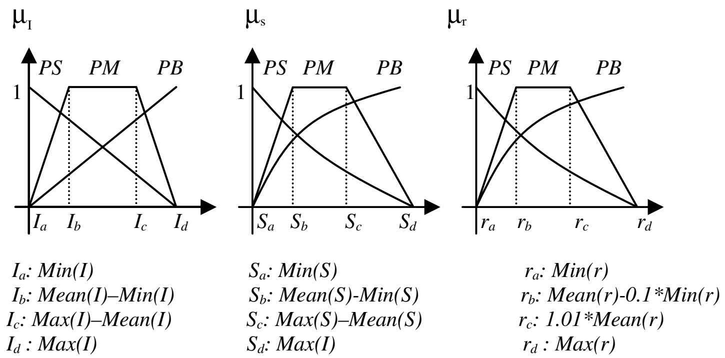

Fig. 2. Membership functions of I, r and s

It is found by trial and error that the trapezoid shape for PM produces better results than triangular shape, which is used in reference [6]. This feature is regarded as an advantage in the new fuzzy model, compared with the previous method, Determining fuzzy rules are the next step in fuzzy modeling. As can be seen from Fig. 1, when *I* is small, near pick-up current, and s 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 *s* is large then *r* is large.
- If *I* is small and *s* is medium then *r* is medium.
- If *I* is medium and *s* is small then *r* is medium.
- If *I* is medium and *s* is medium then *r* is small.
- If *I* is medium and *s* is large then *r* is medium.
- If *I* is large and *s* is medium then *r* is medium.
- If *I* is large and *s* is small then *r* is large.

The last step in fuzzy modelling 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*.

$$a_i = \mu_i \wedge \mu_s \tag{6}$$

$$\mu_r^{'} = a_i \wedge \mu_r \tag{7}$$

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

$$r = \sum_{1}^{n} a_i . r_i \,/ \sum_{1}^{n} a_i \tag{9}$$

Equation (9) describes the normalized weight method to produce a single output corresponding to r [7].

2 Case Study

Two types of OC relays were used for evaluating the proposed model. The first one was RSA20, an electromechanical OC relay, where its TDS varies from 4 to 20. The second one was CRP9, a very inverse electromechanical OC relay. For both relays, the used sampled data are shown in Table 1 and Table 2 respectively, Additional sampled data which is shown in Tables 3 and 4 is used for testing and comparing the analytical and the proposed models.

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 CRP9 OC relay in ms when TDS=4, 6, 7 and 10

I	TDS=4	TDS=6	TDS=7	TDS=10
3	2451	3521	4232	6495
4	1352	2107	2459	3935
5	953	1527	1853	2734
6	758	1243	1517	2175
7	653	1054	1302	1927
8	605	934	1153	1754
9	552	836	1051	1621
10	516	742	993	1523
12	459	658	894	1304
14	401	634	794	1221
16	375	618	744	1123
18	359	608	715	1059
20	358	585	669	1024

Table 3. Test operation time of RSA20 OC relay in ms when TDS=4, 8, 14 and 20

0I	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 4. Test operation time of CRP9 OC relay in ms when TDS=4, 6, 8 and 10

1I	TDS=4	TDS=6	TDS=8	TDS=10
3.5	1721	2832	3365	5241
4.5	1125	1746	2123	3289
5.5	849	1369	1648	2351
6.5	695	1124	1411	1986
7.5	634	1009	1213	1821
8.5	574	892	1098	1698
9.5	534	776	1035	1586
11	489	692	939	1401
13	425	642	835	1248
15	386	623	755	1167
17	367	612	732	1087
19	357	593	684	1048

The sampled data is obtained by performing experimental tests several times using an accurate computerised relay tester for RSA20 and CRP9 relays, to ensure the accuracy of the recorded expanded data.

3.1 Fuzzy Model Application

3.1.1 Fuzzy Model of RSA20 OC Relay

The recommended analytical model in reference [4] is selected for comparison between the new and the mathematical model. Due to the progresses in both calculating methods and software packages an equation with more polynomials coefficients is possible and provides more accurate results. MATLAB has provided a useful environment to calculate polynomials coefficients based on advanced non-linear curve fitting techniques [11,12]. Therefore, Eq. (10) with nine coefficients is chosen. It should be noted that when a polynomial equation with more than nine coefficients was used, ill-structure matrices and poor output results were reported by MATLAB. In addition, normalized operation time data were used to improve the accuracy of the obtained results by

$$t = a_0 + a_1/(I-1) + a_2/(I-1)^2 + \ldots + a_8/(I-1)^8 \tag{10}$$

The coefficients of Eq. (10), i.e. a_0 to a_8, are shown in Table 5 where data in columns TDS=4, 8 and 20 of Table 1 are selected as input. The first column of Table 5 shows the coefficients of Eq. (10) for the sampled data of TC curve when TDS=6.

Table 5. 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

By calculating the average error percentage for each curve of RSA20, the two curves illustrating the mean error percentage of the fuzzy and the mathematical nine-coefficient model are shown in Fig. 4 and Fig. 5.

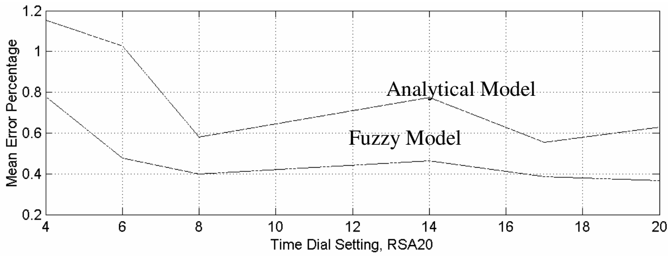

Fig. 4. Average error percentage of fuzzy and Analytical model for RSA20

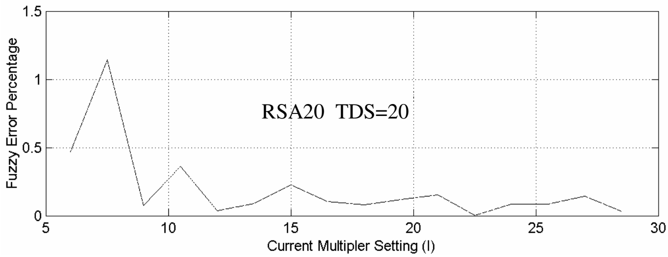

Fig. 5. Error percentage of fuzzy model for RSA20 when TDS=20

As can be seen from Fig. 4, the average of error percentages of the fuzzy model results are smaller than the polynomial form and in most cases is near 0.4 percent. In addition, Fig. 5 shows 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 more damages to the power systems components.

3.1.2 Fuzzy Model of CRP9 OC Relay

In this section, the fuzzy model is applied to CRP9 OC relay to find its characteristic. The relay is an electromechanical type and its data are given in Table 2. The data are obtained by experimental tests. The coefficients of the analytical model, i.e. a_0 to a_8 for the relay, are calculated and shown in Table 6.

Figures 6–7 show the obtained results after applying two different methods.

Table 6. Analytical polynomial coefficients for CRP9

Coefficient	TDS=4	TDS=6	TDS=10
a_0	0.0769	0.1401	0.0757
a_1	1.3063	0.1726	1.7057
a_2	-1.8269	5.262	-3.8979
a_3	4.7069	-3.3488	7.9226
a_4	6.6728	-5.9993	11.2491
a_5	1.3859	-0.9672	1.0027
a_6	-7.1234	6.6096	-15.5886
a_7	-15.6564	13.4513	-32.4335
a_8	-22.6173	18.796	-46.5238

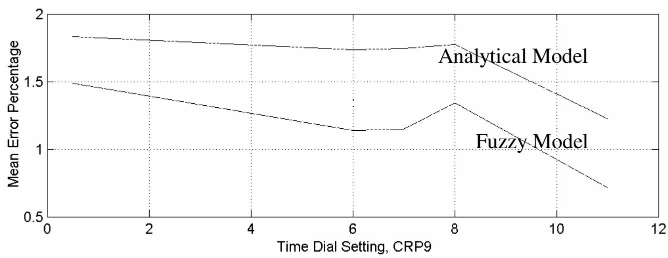

Fig. 6. Average error percentage of fuzzy and Analytical model for CRP9

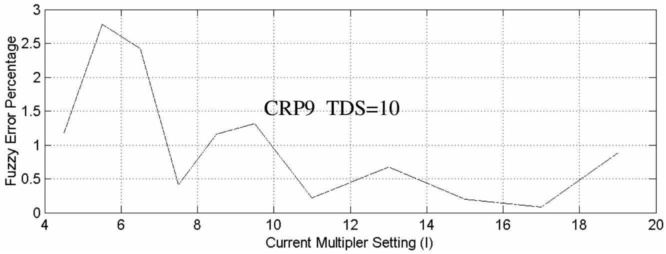

Fig. 7. Error percentage of fuzzy model for CRP9 when TDS=10

Figure 6 shows the fuzzy model of CRP9 is more precise than the analytical nine-coefficient model. Similar to RSA20, the average error percentage of proposed model is below 1.5 percent and usually decreases when current multiplier setting increases. 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.

4 Conclusion

In this paper a new model for OC relays, based on fuzzy logic is presented. The new model was evaluated by experimental tests on two types of OC relays. The results revealed that the error percentages of fuzzy model for both relays were low. In comparing, the results of the new method with the analytical model, it was evident that the new model did not need any curve fitting technique. 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
s: Slope between two neighboured points on TC curve
r: Fuzzy correction factor
μ_r: Membership function of r
μ_s: Membership function of s
μ_I Membership function of I
f: Asymetric activation function
y: Internal activity of neuron
a,b: Constants
x: *TDS* or *TMS*

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