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A new method for adaptive protection and optimal co-ordination of overcurrent relays

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Abstract: In this paper kennedy-chua neural network method for optimal co-ordination of overcurrent relays is proposed. The existing optimal co-ordination of overcurrent relays methods, the simplex &dual simplex with both objective function and constraints are used. Recently a method has been developed to coordinate overcurrent relays without objective function. The method of this paper which is an optimal approach is based on kennedy-chua neural network with the advantages of higher speed, no need of auxiliary variables and capability of handling non linearity of relay characteristics. The method does not need any initial solution. In this paper, the optimal settings of overcurrent relays for the IEEE 8-BUS network are obtained and comparison between the new method and existing methods is made. From the results, the advantages of the kennedy-chua neural network method can be concluded.

Key words: *Optimal Co-ordination; Simplex; Dual simplex; Kennedy-Chua neural networks; Overcurrent relay*

1. Introduction

Directional overcurrent relays are commonly used as economical means for protecting interconnected power systems. The selection of appropriate settings of these relays under various systems conditions play an important role in timely removal of the faulty section of power systems.

Several methods have been proposed for the co-ordination of these relays. Ordinary co-ordination algorithms consider different techniques, both for interconnected and industrial networks (Urdaneta et al., 1988 and 1996). In the optimal methods the operating times of the relays are minimised, subject to the so-called co-ordination constraints, the relays characteristic curves and the limits of the relays settings. Due to the complexity of non-linear optimal programming techniques, the co-ordination of overcurrent relays are commonly performed by linear programming techniques, including the Simplex, Two-phase Simplex and Dual Simplex methods (Chattopadhyay et al., 1996). In all of the above-mentioned techniques, auxiliary variables must be defined, so that the total number of variables becomes equal to the number of constraints (Abyaneh, 1997). The introduction of auxiliary variables requires a complicated solution. As a result, the use of the conventional optimal techniques always imposes limitations in terms of the low numbers of constraints to be used in the problem.

In the conventional optimal co-ordination techniques, relay characteristic curves are assumed to be linear, so that the operation time of a relay is defined as a linear function of its time dial setting (TDS). Therefore, these techniques are unable to efficiently use nonlinear (N.L.P) relays models.

In this paper, kennedy-chua neural network for optimal co-ordination of overcurrent relays is proposed which can include relays with N.L.P characteristic model. The speed of calculation and execution is much higher than the previous methods. There is no need for introducing additional auxiliary variables in this method. The outline of the paper is given in the following sections. The existing co-ordination problems in interconnected power systems are first described. Subsequently, the new optimal co-ordination method including its advantage is outlined. Finally, the performance of the new method is evaluated by comparing its results with those of optimal conventional methods.

2. Existing optimal methods

Fig. 1 shows a section of a power system with several protection zones. Each protection zone consists of a primary and a backup overcurrent relays. It is desirable that all overcurrent relays operate as fast as possible in order to reduce the shock to the power system. This can be achieved by using optimal co-ordination of the overcurrent relays in the system.

The optimal co-ordination of relays is described as an optimization problem where the sum of the weighted relay operation times is minimized as follows:

$$Min\ (obj = \sum_i \sum_j \sum_k W_{ijk} * T_{ijk}) \quad (1)$$

subject to:

$$TDS_{\min} \le TDS_i \le TDS_{\max} \quad (2)$$

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$$I_{pi_{\min}} \leq I_{pi} \leq I_{pi_{\max}} \quad (3)$$

$$T_{i_{\min}} \leq T_i \leq T_{i_{\max}} \quad (4)$$

$$T_i(br) - T_j(pr) \geq CTI \quad (5)$$

Where:

T_{ijk} : The operation time of relay i in zone j for a fault in zone k

W_{ijk} : The weighted coefficient associated with T_{ijk}

TDS_i : The time dial setting of relay i

I_{pi} : The current value of relay i

$I_{pi_{\min}}$:The minimum of pick up current value of relay i

$I_{pi_{\max}}$: The maximum of pick up current value of relay i

T_i : The operation time of relay i, $T_i = f_i(TDS_i, I_{pi}, I_i)$

$T_{i_{\min}}$: The minimum of operation time of relay i

$T_{i_{\max}}$: The maximum of operation time of relay i

$T_i(br)$: The operation time of back up relay i

$T_j(pr)$: The operation time of primary relay j

The weighted coefficients, W_{ijk} in equation (1) are positive real numbers whose values depend on the probability of the short circuit fault occurrence in each zone, the value of which is commonly determined experimentally. Several models have been proposed for expressing the time-current characteristics curves of overcurrent relays, for example:

$$T_i = K * TDS_i \quad (6)$$

Where:

$$K = \frac{0.14}{(\frac{I_i}{I_{pi}})^{0.02} - 1} \quad (7)$$

and I_{pi} and I_i are known from the system requirements [4].

Using equation (6), the operating time of an overcurrent relay can be described as a linear function of TDS. So that the objective function is defined as a linear function whose solution can be obtained by using a linear optimal programming algorithm.

3. Kennedy-Chua neural network

Neural networks have been widely studied in the last decades, and their fast processing characteristics have been largely highlighted (Urdaneta et al., 1998). They can be modelled as a close network of weighted connections and nodes, called artificial neurons, which are connected in a regular topology. Hopfield networks, which are single layer feedback neural networks, have been selected in this work for their interesting capabilities in minimization problems. One of the main applications of a Hopfield neural network is the minimization of a linear function in n variables, which is obtained through n properly connected neurons with fixed weights and threshold value. During the transient process, the values of the output voltages tend to the minimum value of the function to be minimized.

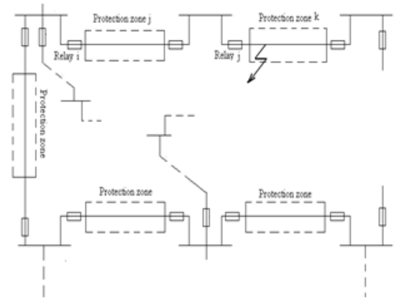

Fig. 1: Sample Power System

In (Mozaffari and Gadari, 2013) Kennedy and Chua proposed an extension of a Hopfield neural network for nonlinear programming with nonlinear constraints; this network was a neural implementation of the canonical nonlinear circuit proposed by Chua and Lin. A generic nonlinear problem is based on the minimization of a general cost function:

$$\phi(x_1, \ldots, x_n) \quad (8)$$

Subject to nonlinear constraints:

$$\begin{aligned} & h_1(x_1, \ldots, x_q) \leq 0 \\ & \vdots \\ & h_p(x_1, \ldots, x_q) \leq 0 \end{aligned} \quad (9)$$

where p is the number of constraints and q is the number of variables and they are two independent integer number. The circuit equation which solves (8) subject to (9) is:

$$C_i \frac{dv_i}{dt} = -\frac{\partial \phi}{\partial v_i} - \sum_{j=1}^{p} i_j \frac{\partial h_j}{\partial v_i} \quad (10)$$

where v_i is the output voltage of the generic i-th neuron, $i_j = g_j(h_j(V))$ is the output current of j-th constraint, and C_i is the output capacitor of i-th neuron. We have also indicated with $g_j(\cdot)$ the nonlinear continues function used to impose the j-th constraint. We can rewrite (10) as a vector notation of the form $\dot{V} = H(V(t))$, where $H(\cdot)$ is a continuous function from R^q to R^p. The system in

(8) and (9) tends to the equilibrium point of its Lyapunov function, also called co-content function [13], defined as:

$$E(V) = \phi(V) + \sum_{j=1}^{p} \int_{0}^{h_j(V)} g_j(x) d \quad (11)$$

To model non-ideal current sources factors, a correction term is added to (10), thus obtaining:

$$C_i \frac{dv_i}{dt} = -\frac{\partial \phi}{\partial v_i} - \sum_{j=1}^{p} i_j \frac{\partial h_j}{\partial v_i} - G_i \quad (12)$$

where G takes into account the above mentioned factors.

4. Application of neural network to optimal coordination

Although several methods have been proposed for optimal co-ordination of overcurrent relays with linear objective functions, the Simplex and Dual-Simplex techniques are commonly used due to their many features, including the unnecessary initial solution requirement. It should be however mentioned that in all linear optimal programming methods, auxiliary variables are to be defined so that the total number of variables becomes equal auxiliary variables therefore, increases the size of matrices, which in turn, requires a large computer memory. The linear representation of the relays characteristic curves may lead to inaccurate results too. To overcome these limitations, a different methodology has been chosen for solving the problem, which is described as follows.

Solving the optimal problem implies finding the co-ordinated settings TDS for all directional overcurrent relays in the system with a predetermined value for I_p. The constraints in equations (2-5) must be defined based on one type variable which is TDS. The relation between the operating time and TDS is shown in Fig.2.

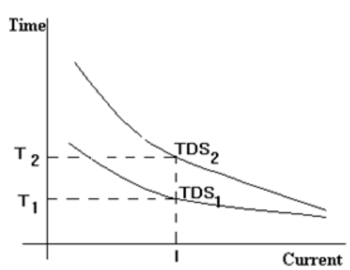

Fig. 2: TDS and operation time relation

Fig.2 shows that when the current setting I is well known, then the lower curve has faster operating time and less TDS. Therefore, the minimization of TDS leads to the minimization of operating time. This in turn leads to the minimization of objective function. Therefore a proper model for overcurrent relay characteristic is needed.

As mentioned earlier, the ordinary optimal co-ordination method can only use the L.P. Therefore, the co-ordination problem in the existing method is based on equation (6) and therefore the linear definition of operating time can be shown as in equation (13).

$$Min(obj) = \sum_i \sum_j \sum_k W_{ijk} * f(I_{pi}, I_{jk} \quad (13)$$

Coefficient W_{ijk} was defined in section 2.
Subject to:

$$T_i = f(I_{pi}, I_i) * TDS_i \quad (14)$$

$$TDS_{\min} \le TDS_i \le TDS_{\max} \quad (15)$$

$$f(I_{pi}, I_i) * TDS_i(br) - f(I_{pj}, I_j) * TDS_j(pr) \ge CTI \quad (16)$$

f is an equation describing the time-current characteristics curve of overcurrent relay i. The left hand side of equation (16) describes the operating times between backup and primary relays under six pairs fault currents. Among them two important faults locations are taken into account. One of the fault points is considered to be on the line on which the primary relay under consideration exists and immediately close to the relay, the other at the remote end of the line. However the right hand side of the equation, CTI being time interval is normally fixed with 0.3 or 0.4 sec.

The objective function of optimal co-ordination of overcurrent relays which is shown in equation (13), is stated as the sum of the positive values multiplied by TDS. Also the positive coefficients, W_{ijk}, are usually set to one (=1). According to the theory of optimization technique, the solution of constraint equations only, is optimal when all of the coefficients of variables of objective function are positive. This usually exists in the optimal coordination problems.

Based on Kenndy-Chua neural network, the optimal solution can be found to minimize the objective function in (13) subject to follow nonlinear costraints:

$$TDS_i - TDS_{\max} \le 0 \quad (17)$$

$$TDS_{\min} - TDS_i \le 0 \quad (18)$$

$$CTI - f(I_{pi}, I_i) * TDS_i(br) + f(I_{pj}, I_j) * TDS_j(pr) \le 0 \quad (19)$$

But the constraint equations have infinite solutions. Therefore the optimal solution is which one has the smallest TDS values. It should be noted that TDS of the relays are found according to the linear equation first, then the results are expanded to nonlinear models using Fuzzy Logic relays characteristics models.

Therefore in the equations of the Kennedy-Chua neural network method, to find the smallest TDS with positive coefficients is found as follows.

$$B * X - e \le 0 \quad (20)$$

B: The matrix of coefficient of TDS
X: The matrix of TDS
e: The matrix of restrictions

Matrix B is composed of three parts, upper, mid and lower part. The upper part is a union matrix because the constraints relating to the maximum of TDS are settled there and it can be found from equation (17). In other words the relative coefficients are equal to one. The mid part is a negative union matrix because the constraints relating to the minimum of TDS are settled there and it can be found from equation (18). In other words the relative coefficients are equal to negative one. The lower part of matrix B relates to the other constraints which depend on the back up and primary equations. Matrices B, X and e are shown in equation (21).

$$\begin{bmatrix} 1\ 0\ \ 0\cdots0 \\ 0\ 1\ \ 0\cdots0 \\ \vdots \\ 0\ 00\cdots1 \\ ------ \\ -1\ \ 0\ 0\cdots0 \\ 0\ -1\ \ 0\cdots0 \\ \vdots \\ 000\cdots-1 \\ ------ \\ B_{IJ} \end{bmatrix} \times \begin{bmatrix} TDS_1 \\ TDS_2 \\ TDS_{\min} \\ \vdots \\ TDS_q \end{bmatrix} - \begin{bmatrix} -TDS_{\max} \\ \vdots \\ -TDS_{\max} \\ ----- \\ TDS_{\min} \\ \vdots \\ TDS_{\min} \\ ---- \\ CTI \\ \vdots \\ CTI \end{bmatrix} \leq 0 \qquad (21)$$

For example in Fig.1, assumes that the first constraint of the optimal problem is related to the relay i and relay j, where relay i is the back up of relay j. Then the first constraint is as (19) and settles in the first row of the lower part of the matrix B.

In turn, other rows of the lower part of the matrix B are determined based on the primary and back up relays operating times relations. Equation (19) shows each row has only two numbers which are not equal to zero, one of them is positive and the other is negative and the number of the rows of the lower part is equal to the number of the constraints.

Finding the smallest TDS of the optimal problem can be easily find according to equation (10):

$$C_i \frac{dx_i}{dt} = -W_{ijk} - \sum_{j=1}^{p} B_{ji}\, i \qquad (22)$$

Where:

$$g_j(h_j(x)) = i_j = \begin{cases} 0 & h_j(x) \leq \\ \frac{1}{R} h_j(x) & h_j(x) \geq \end{cases} \qquad (23)$$

By making two blocks for equations (22) and (23), can solved the optimization problem. It can be done by using Matlab Simulink.

Nonlinear relay model was fully described in reference.

By this manner no initial solution is needed and the answers are optimal solutions. It can be seen that no auxiliary variables are necessary and the size of the matrices are much smaller than the Simplex and Dual Simplex method.

5. Test results

In this paper the IEEE 8-BUS network is considered. By using the graph theory, primary/back up relays pairs are determined. Fig. 3, shows the network under consideration.

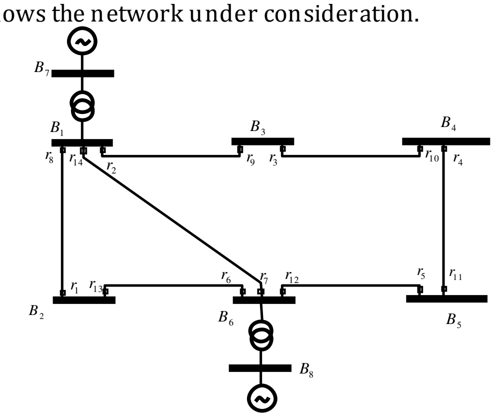

Fig. 3: IEEE 8 bus Network

Tables (1) to (4) reveal network information which is obtained from reference.

Table 1: Line Information

Line	R/kmΩ	X/kmΩ	Length (km)
1-2	0.0040	0.0500	100
1-3	0.0057	0.0714	70
3-4	0.0050	0.0563	80
4-5	0.0050	0.0450	100
5-6	0.0045	0.0409	110
6-2	0.0044	0.0500	90
6-1	0.0050	0.0500	100

Table 2: Generator

Node	Sn (MVA)	Vn (kV)	Xbus(%)
7	150.0	10.0	15.0
8	150.0	10.0	15.0

Table 3: Transformer Information

Line	Sn(MVA)	Vp (kV)	Vs (kV)	X(%)
7-1	150.0	10.0	150.0	4.0
8-6	150.0	10.0	150.0	4.0

Table 4: Load Information

Node	2	3	4	5
P(MW)	40.0	60.0	70.0	70.0
Q(MVAR)	20.0	40.0	40.0	50.0

In this paper load flow and fault current programs are written using Matlab software and based on the information in Tables (2) to (4). Table (5) shows primary /back up relays pairs

Table 5: Primary / Back up Relay Pairs

Item	Primary	Back up	Item	Primary	Back up
1	1	6	11	14	9
2	7	13	12	8	9
3	12	13	13	5	4
4	2	7	14	2	10
5	8	7	15	4	3
6	6	14	16	3	3
7	12	14	17	10	11
8	13	8	18	2	1
9	6	5	19	14	1
10	7	5	20	11	12

Relay current setting depends on the pickup current value. It is minimum current which is used for the operation of overcurrent relay. The pickup current has value which falls between upper and lower limits. The lower limit is equal to the maximum load current multiplied to 1.3 of coefficient. The upper limit is equal to a minimum fault current at the far end bus, multiplied by less than one. So far, in the calculation of load and fault currents, it is required to evaluate load flow, fault current programs based on the information of lines, generators and transformers.

Westinghouse Co-9 relays are used for the given network.

Table 6: Comparison between Simplex, Dual Simplex and the Neural Network Method

Relay Number	TDS Dual Simplex	TDS Simplex	TDS New Method
1	1.9528	5.5303	1.6492
2	1.7165	3.6875	1.2456
3	2.1384	3.6034	1.4255
4	1.3311	2.1313	0.9232
5	1.4235	1.7701	0.9579
6	1.4662	2.1447	1.3127
7	2.8499	3.0741	1.3134
8	2.3744	2.9114	0.8982
9	0.8926	1.7143	0.5543
10	0.8759	2.1795	0.5788
11	1.2145	3.9344	0.7287
12	1.0170	4.0490	1.2271
13	2.2711	6.1096	1.1654
14	1.4982	3.3468	0.6566

The simplex results are taken from www.drmozaffarilegha.ir, whilst the two others i.e. the Kennedy-Chua neural network method and Dual Simplex are developed in this paper. For Simplex and Dual Simplex linear sachdev model is used. The Kennedy-Chua neural network method employs a fuzzy Model. As can be seen, the new results are more accurate and less operating times for protective gears. In addition the Kennedy-Chua neural network method possesses simplicity.

The dimension of matrix B in Dual Simplex Method is 101*100, but in the proposed method it is 77*14.

6. Conclusion

In this paper Kennedy-Chua neural network method has been presented for optimal co-ordination of overcurrent relays. Comparison between the Kennedy-Chua neural network and linear optimization methods is made. Two different computer programs being Dual Simplex and Kennedy-Chua neural network optimal method were written in Matlab and the programs have been tested on some power system networks. The results of the Kennedy-Chua neural network method for IEEE 8-bus system are compared with obtained Dual Simplex and existing Simplex Methods results.

It has been shown that the results of the Kennedy-Chua neural network method are more accurate. Furthermore, by employing the proposed Kennedy-Chua neural network technique, higher speeds of relays operating related to protection gear relays can be achieved.

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