Optimal Directional Overcurrent Relay Coordination Using Artificial Immune Algorithm

التنسيق الأمثل لأجهزة الحماية الاتجاهية ضد زيادة التيار بإستخدام نظام المناعة الاصطناعى

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ملخص البحث

أدت زيادة المولدات الموزعة من الطاقة المتجددة فى شبكات التوزيع الى عدد من المزايا والتحديات لعملية تشغيل هذه النظم الكهربية. وقد كان تصميم نظم الحماية لشبكات التوزيع يعتمد على ان نظام التغذية لها يكون من اتجاه واحد فقط. لكن بعد توصيل المولدات الموزعة على اجزاء من شبكة التوزيع اصبحت التغذية فى هذه الاجزاء من اكثر من اتجاه وهذا ادى الى حدوث عدم تنسيق لاجهزة الحماية ضد زيادة التيار. وهدف التنسيق لاجهزة الحماية ضد زيادة التيار هو تحديد منطقة الخطأ الصحيحة (الانتقائية) وعدم فقدان الحساسية وكذلك تقليل زمن الفصل. وهذا البحث يقدم طريقة جديدة تعتمد على نظام المناعة الاصطناعى (AIS) لتحقيق التنسيق الامثل بين اجهزة الحماية ضد زيادة التيار فى شبكات التوزيع فى حالة وجود مصادر طاقة موزعة بنسب تخلل عالية. هذه الطريقة استخدمت لتحديد قيمة تيار ال Ip وقيمة ال TMS لكل جهاز حماية. كما انه يجعل جهاز الحمايه لديه القدرة على التكيف مع تغير قيمة ومكان المولدات الموزعة بشبكة التوزيع. وتم تطبيق هذه الطريقة على نظام توزيع مكون من خمسة قضبان توزيع للتحقق من فعالية ودقة الطريقة.

Abstract

High-penetration renewable energy-based generators in distribution systems cause a number of benefits and challenges for power system operators. The distribution system protection has traditionally been designed assuming the system to be radial. After connecting distributed generators (DG), part of the system may no longer be radial, which means that the coordination might not hold. The objective of protective relay coordination in an interconnected power system is to achieve selectivity without sacrificing sensitivity and fast fault clearance time. In this paper a novel method based on clonal selection algorithm of artificial immune system (AIS) is proposed for optimal coordination of overcurrent relays in distribution system connected to DGs. This method is used to find the optimal Time Setting Multiplier (TMS) and the pickup current (Ip). The proposed algorithm is utilized to obtain the optimal setting of overcurrent relays and make it adaptive with any DG penetration level and location. The coordination of directional overcurrent relays (DOCR) by this algorithm is implemented on a 5- buses distribution system.

Keywords

Distributed generation, Artificial immune system, Directional overcurrent relay Coordination, Adaptive overcurrent relay

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1. Introduction

The use of renewable sources of energy has reached greater importance to overcome the increase in the energy consumption and at the same time reduce environmental impact of power generation. It can be used in either small-scale applications away from the large sized generation plants or in large-scale applications in locations where the resource is abundant and large conversion systems are used.

Protection against faults is an essential requirement when designing distribution systems. A good protection coordination scheme is one that is able to isolate as little of the system as possible when a fault occurs, so as to avoid unnecessary disconnection of power to areas that are unaffected by the fault. Protection

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coordination in this sense is designing protection schemes such that each protective device performs its primary function as quickly as possible, but in the event that it fails, it should be backed up by another protective device [1].

As the traditional distribution systems have been designed to operate radially. The most common protection devices used to protect the distribution systems were the overcurrent relays. Overcurrent relays are applied as primary protection of the distribution lines. It is essential backup protection in distribution system and they should have a specified operating sequence, so they must be coordinated or selective, because any failure of protective device can cause equipment damage.

When the distributed generations (DGs) are integrated with the distribution systems, the distribution networks are becoming similar to transmission networks where generation and load nodes are mixed (“mesh” system) and more complex protection design is needed. The coordination becomes very difficult to set with multi-sources in distribution systems. In this new configuration, design considerations regarding the number, size, location and technology of the DG connected must be taken into account as the short circuit levels are affected and miss coordination problems with protection devices may arise. It creates an increase in the fault current when compared to normal conditions at which no DG is installed in the network. In the case of many small units, or few large units, the short circuits levels can be altered enough to cause miss coordination between protective devices [2-3].

The methods which are used for determining the setting of the overcurrent relay can be classified into three classes: trial and error [4], topological analysis [5-6], and optimization methods [7-10]. Researchers have described various optimization methods to solve relay coordination problem. Ref. [11]-[12] use a PSO technique to determine the optimal directional relay coordination in an interconnected power system. Ref. [13] presented a pre-processing method to reduce the number of constraints and detect those make the optimization of overcurrent relay settings to be infeasible. Ref. [14] used the genetic methodology to solve the optimal relay coordination problem and ref [15] used the evolutionary programming. Ref. [16] uses the ant-colony optimization technique to determine the optimal relay coordination in an interconnected power system. The optimization method gives a solution better than the topological method but this method is a time consuming as it is not adaptive so if any change occurs in the system, a new solution must be found to keep up with the system changes. Adaptive relaying [17] considers the fact that the status of a power system can change, thus, the settings of relays need to be changed on-line to accommodate these changes. In recent years a number of optimal adaptive relaying concepts have been proposed [18-19]. They used the linear programming method to design the optimal relay settings but their methodology may be good for simple systems but in complex systems, the solution takes a large time.

This paper proposes a new algorithm to determine the optimal setting of the overcurrent relay. The algorithm is based on the Artificial Immune Systems (AIS). AIS are a biomimetic intelligent calculation from imitating intelligent behavior of biological immune system. The objective function and constraints corresponds to antigen, and the feasible solution corresponds to the antibody. (AIS) are inspired by theoretical immunology and observed immune functions, principles and models, which are applied to solving engineering problems. It has been successfully used in power system optimization problems [20-23]. In this paper, it used the clonal selection optimization method to compute the optimal coordination among the protective device and make it adaptive with any penetration of DG size and location.

2. Overcurrent Relay Coordination

Power system protection performs the function of fault detection and clearing as soon as possible, isolating whenever possible only the faulted component or a minimal set of components in any other case. Since the main protection system may fail (relay fault or breaker fault), protections should act as backup either in the same station or in the neighboring lines with time delay according to the selectivity requirement. The determination of the time delays of all backup relays is known as coordination of the protection system. Coordination of protective relays is necessary to obtain selective tripping. The coordination problem could be formulated as a linear or nonlinear programming problem. In the linear model, only the time dial settings are optimized and the pickup current settings are fixed at values between the maximum load current and minimum fault current. However, in the nonlinear programming approach, based on the relay characteristic, time dial and pickup current settings are optimized simultaneously [24]. The first rule of protective relaying is that the relay should trip for a fault in its zone. The second rule is that the relay should not trip for a fault outside its zone, except to back up a failed relay or circuit breaker. To coordinate this backup protection with the primary relay characteristic and ensure that the backup relay has sufficient time delay to allow the primary relay (and its breaker) to clear the fault [25]. Theoretical studies of the impact of DG on the network faults current indicate that DG may invalidate overcurrent protection. DG may affect the operation of existing distribution networks by providing flows of fault currents which were not expected when the protection was originally designed. In practice, the presence of DG may result in increased fault currents which depend on capacity, penetration, technology, interface of the DG, and system voltage prior to the fault.

2.1 Modeling of Overcurrent Relay Characteristic

Overcurrent relay generally include an instantaneous unit and inverse time equipment. The inverse time operation characteristic can be provided in terms of a family of curves depending on a parameter usually referred as the time multiplier setting (TMS). The mathematical modelization of this family of curves can be performed using multiple regression techniques in order to obtain an expression giving the operating time in function of time multiplier and the current flowing through the relay. In general, overcurrent relays respond to a characteristic function of their type [12],

$$T = f\left(TMS, I_p, I\right) \qquad (1)$$

Where T is the operation time, TMS is time multiplier setting, Ip is the pickup current and I is the current flowing through the relay. Under simplistic assumption, the above equation can be approximated by the following equation

$$T = K_1 \frac{TMS}{(I/I_P)^{K_2} + K_3} \qquad (2)$$

Where K_1, K_2 and K_3, are constants that depend upon the specific device being considered.

2.2 Problem Formulation

The general relay coordination problem can be stated as a parametric optimization problem. The objective function is to minimize the operating time of the primary relays subject to keeping the operation of the backup relays coordinated. The objective function J to be minimized can be expressed as follow:

$$J = \sum_{i=1}^{n} T_{ii} \qquad (3)$$

Where T_{ii} is the operating time of the primary relay R_i for a close fault to relay i. It is assumed that the network consisting of n relays. The operating time of the backup relay must be greater than the sum of the operating time of its primary relay and the coordination margin. This can be expressed as:

$$T_{ji} \geq T_{ii} + CTI \tag{4}$$

Where T_{ji} is the operating time of the backup relay R_j for the same near-end fault at *i*, and *CTI* is the coordination time interval. There are many equations such Eq. (4) for any pair of primary/backup relays for a given fault. Generally as shown in Eq. (1), the relation between the operation time *T* of the time overcurrent unit, and the pickup current *Ip*, and time multiplier setting is a nonlinear function. As a consequence, in general this problem is a nonlinear optimization problem, but if the pickup current are determined prior and considering the Eq. (2) as a relay characteristic. This paper solves this problem in general form, that means it considers the pickup current (Ip) and the time multiplier setting (TMS) as the optimization parameters and find the optimal value of them by solving the nonlinear optimization problem.

The other constraints in this optimization problem are the limitation of the variables that are listed as follows:

$$TMS_{i\,min} \leq TMS_i \leq TMS_{i\,max}$$

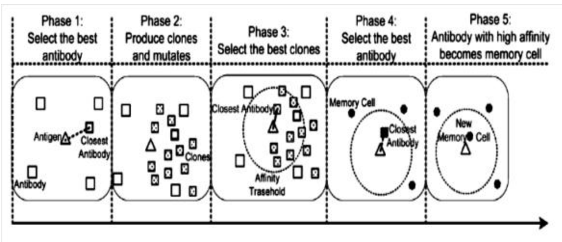
$$I_{p_{i\,min}} \leq I_{p_i} \leq I_{p_{i\,max}} \tag{5}$$

3. Artificial Immune System

Human natural immune system protects the body from foreign cells called antigens by recognizing and eliminating them. This process is called an immune response [26]. Our immune system constitutes a self-defense mechanism of the body by means of innate and adaptive immune responses. An adaptive immune response contains metaphors like pattern recognition, memory, and novelty detection. The fundamental components of the immune systems are lymphocytes or white blood cells, which are divided into two classes: B-and T-cells. B-cells have a more important function than T-cells because each B-cell has its distinct chemical structure and secretes many antibodies from its surface to eliminate the antigens. A huge variety of antibodies are generated to neutralize and eliminate antigens. Each antibody is constituted by a specific B-cell whose aim is to recognize and bind to antigens [27]. In the immune system, an important function is clonal selection. The clonal selection algorithm is a part of AIS based on clonal expansion and affinity maturation [28]. Clonal selection determines how an immune response is given when an antigen is detected by a B-cell.

In Fig. 1, once a B-cell is stimulated through a certain affinity to any antigen, it immediately produces its clones and it exposes to a hyper mutation process. This process produces new cells to match the antigen more closely. The B-cells that do not match any antigen will eventually die. Activated B-cells produced by the clonal selection process are selected to become memory cells. The main characteristics of the immune system are learning and memory [29]. The adaptive immune system can learn the structure of an antigen and remember this antigen for future response. This factor ensures the reinforcement learning in the natural immune system.

Fig. 1. The process of clonal selection.



The fundamental of AIS is inspired by the theoretical immune system and the observed immune functions, principles, and models [30]. The modeling of the natural immune system usually aims to provide a better understanding of immune functions. On the other hand, AIS can be used to solve problems in engineering, science, computing, and other research areas. With these features, AIS is akin to soft computing.

4. AIS – Clonal Selection for Optimal Coordination

This paper proposes an AIS algorithm to optimize the coordination of overcurrent relays in distribution systems connected to DGs. This method is based on the clonal selection algorithm. The aim of the optimization is to minimize the total operation times of relays. The process of optimizing the overcurrent relay coordination is illustrated in Fig. 2.

Step 1. A definite number of antibodies are produced for the values of the TMS and Ip between [0.05, 1] and [I_{pmin} , I_{pmax}]. Each antibody consists of TMS and Ip.

Step 2. Initial population of each antibody is produced randomly. The size of the population is selected as (400).

Step 3. After initial antibody population is produced, the operating time of the overcurrent relays are determined and tested.

Step 4. The value of the objective function (antigen Ag) (F(Ab)) can be calculated and affinity between the antibody Ab and Ag is obtained. The affinity is a nonlinear transformation of the value of the objective function for a given antibodies and is defined by Eq. 6.

$$F(Ab) = \frac{1}{\varepsilon(Ab)+J(Ab)} \quad (6)$$

Where J is the objective function and ε is the extent of constraint violation of the Ab.

Step 5. The performance of the relays is evaluated for each individual in population.

Step 6. The algorithm is iterated until a certain number of generations. If the terminating condition is satisfied, the algorithm is stopped and the optimum solution is found.

Step 7. If the optimum solution is not reached, the highest affinity elements are selected of population and clones of these individuals proportionally to their affinities with the antigen are generated. The higher affinity is resulted with higher clones.

Step 8. Mutation rate of an individual is inversely proportional to its affinity. An exponential function is used to mutate the clone population, which defined by Eq. 7

$$m(a) = \exp(-sa) \quad (7)$$

Where a is the affinity of population and s is smoothing parameter having a values from 1 to 10 depending on the affinity values.

Step 9. Replace the new best antibodies with the old antibodies, if the best antibodies are not changed for many iteration, apply the mutation to it and it selects new antibodies every ten iteration to avoid the best local solution.

5. Simulation and Results

5.1 Distribution system modeling and simulation

The single line diagram of 5- buses test system is shown in Fig. 3. The system is used to verify the effectiveness of the proposed approach. Two DGs are installed at buses B4 and B5 then after inserting DGs, the system inverted to mesh system. It consists of 5 buses (10.5kV), 4 transmission lines and 11 directional over current relays. The distribution system fed from primary distribution substation (10.5kV) at bus B1.

The generators and transmission lines data are given in Appendix. The distribution system consists of two laterals with the following protective devices:

- Directional overcurrent relays at both ends of each line, they are inverse type overcurrent relay.
- Fuse at each load.

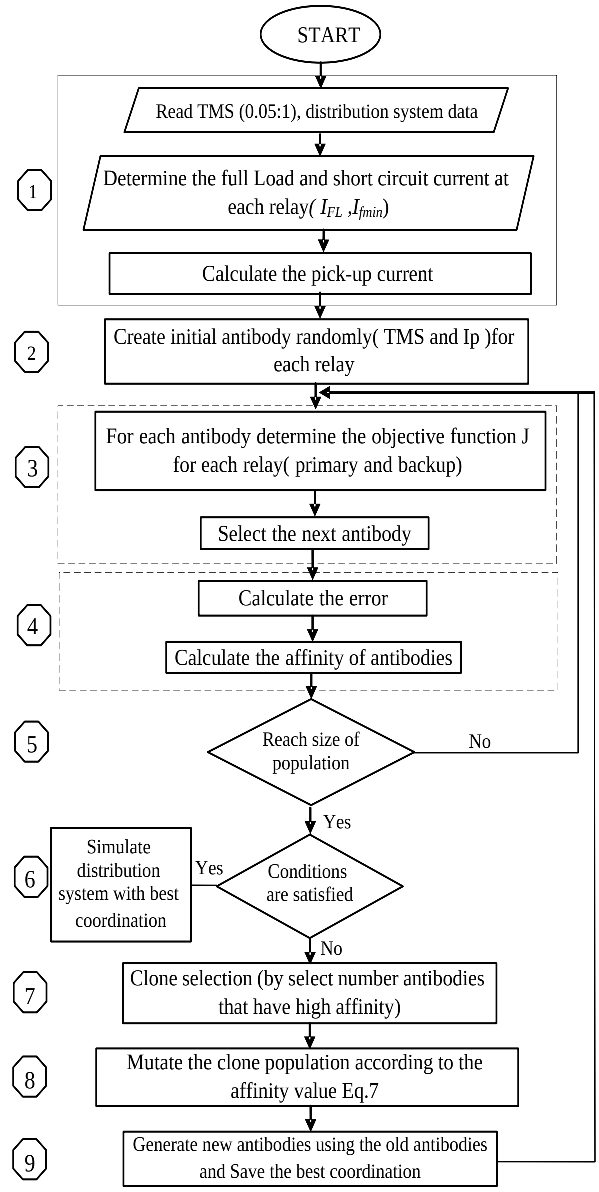


Fig. 2 Flowchart of the proposed algorithm

The modeling and the simulation of the tested distribution system is done by using MATLAB/SIMULINK to obtain the full load and short circuit current at each relay (Primary and Backup relays). The information about short circuit current and the number of the primary and secondary relays are given in Table 1. Obviously, when the system topology is changed the presented data in table 1 should be updated.

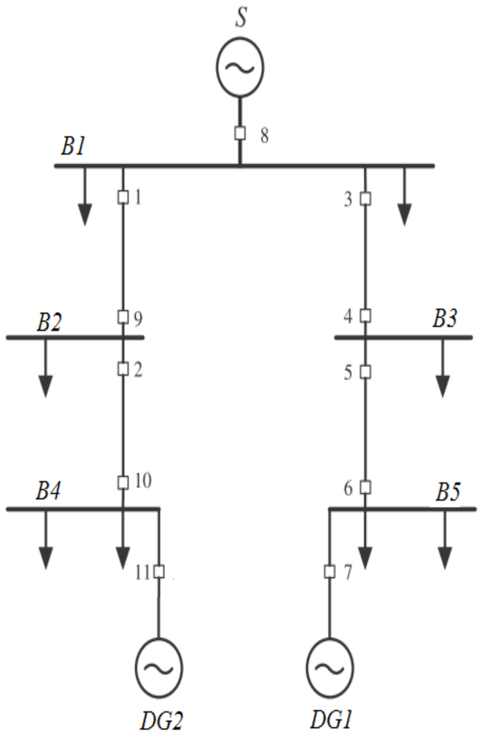


Fig.3 Single line diagram of the tested distribution system

Table 1 Primary and Backup relays information

Primary Relay	Backup Relay	Primary Relay Fault Current (A)
2	1	1385
1	4	2492
1	8	2492
3	8	2494
3	9	2494
4	6	397.4
9	10	398.4
5	3	1396
6	7	467.2
10	11	464.3

In this case study the TMSs for relays have been used in range of (0.05-1). The coordination times have been considered from 0.2 to 0.3 seconds. The algorithm presented in Fig. 2 is coded in MATLAB. Objective function is assumed operating time summation of main relays for fault front of them.

5.2 Results and discussion

In order to validate the applicability of the proposed method (AIS), the method is used to coordinate the directional overcurrent relays of three different system conditions. First with DG1 is installed at bus B5 of the tested distribution system shown in Fig. 3, second DG2 is installed at bus B4 and finally DG1 and DG2 are installed at B5 and B4.

First with DG1 is installed at bus B5, it generates a 10-30% of the total feeder rated power. The proposed AIS algorithm is used to obtain the optimal time setting multiplier (TMS) and the pickup current I_P of the DOCR. The proposed method can be applied to larger and more complicated distribution system with multiple DGs. The TMS and Ip obtained from the proposed method are compared with simplex method and differential evaluation coordination method. The differential evaluation method is given in [31].

After implementing the proposed algorithm, the minimum value of the objective function was obtained. Finally the objective function value is 4.7688sec. Table 2 shows a comparison results between the proposed method (AIS) and the other two methods. The first column in table 2 represents the relay number and the others are the TMS results from proposed and other methods.

As table 2 shows, the proposed method has a smallest total operating time (best objective functions), so it is faster and more reliable than other optimal methods.

The proposed method is tested for the three cases of DG1, DG2 and both of them installed in the test system. The results with these specified parameters are listed in table 3.

Relay No.	**TMS (Simplex method)**	**TMS (differential evaluation method)**	**TMS (proposed method)**
1	**0.0196**	**0.0196**	**0.0183**
2	**0.0195**	**0.0195**	**0.0182**
3	**0.0192**	**0.0192**	**0.0189**
4	**0.0565**	**0.0565**	**0.0565**
5	**0.0120**	**0.0120**	**0.0120**
6	**0.0136**	**0.0136**	**0.0134**
7	**0.0689**	**0.0689**	**0.0689**
8	**0.0782**	**0.0782**	**0.0782**
Total operating time	**4.8576**	**4.8576**	**4.7688**

Table 2 Comparison results of the three methods

	Case 1 With DG1		Case 2 With DG2		Case 3 With DG1 and DG2	
Relay No.	TMS	I_P	TMS	I_P	TMS	I_P
1	0.0183	800	0.0183	800	0.0183	800
2	0.0182	400	0.0182	400	0.0182	400
3	0.0189	800	0.0190	800	0.0190	800
4	0.0565	100	-	-	0.0565	100
5	0.0120	450	0.0120	450	0.0120	450
6	0.0134	150	-	-	0.0136	160
7	0.0689	100	-	-	0.0689	100
8	0.0782	600	0.0782	600	0.0782	600
9	-	-	0.0525	500	0.0531	550
10	-	-	0.0206	110	0.0203	100
11	-	-	0.0699	70	0.0709	76
Total operating time (s)	4.7688		4.6688		5.4634	

Table 3 TMS and pickup current of relays for the three cases

As shown from table 3. By changing the location of DG, the TMS and Ip of the directional overcurrent relays and the total operating time are changed.

6. Conclusion

In this paper, an optimization methodology is proposed based on AIS to solve the problem of coordinating the overcurrent relay in distribution system. AIS algorithm utilizes adaptive clone selection. In this method both the I_p and the TMS are considered as optimization parameters. It is used to obtain the optimal setting of overcurrent relays in 5 buses distribution system. By comparing the results with the other methods, a reduction in operation time of the relays is achieved by AIS algorithm. The results show that AIS can be faster and more reliable than other optimization methods for solving the coordination problem. The proposed algorithm is general and can be applied for any distribution system.

7. References

[1] W.K.A. Najy, H.H. Zeineldin, and W. Woon, “Optimal Protection Coordination for Microgrids With Grid-Connected and Islanded Capability”, IEEE Transactions on Industrial Electronics, Vol. 60, No. 4, April 2013

[2] E.J. Holmes, J.M. Gers: "Protection of Electricity Distribution Networks", United Kingdom: Power and Energy Series 47, 2004.

[3] C. Fortoul, and F. Gonzalez-Longatt, " Review of Distributed Generation Concept: Attemp of Unification", Porceding of International Conference on Renewable Energies and Power Quality, España, (2005).

[4] R.E. Albrecht, M.J. Nisja, W.E. Feero, G.D. Rockefeller, and C.L. Wagner, "Digital computer protective device coordination program – I – general program description", IEEE Trans. PAS 83 (4) (1964) 402–410.

[5] M.J. Damborg, R. Ramswami, S. Venkata, and J. Posforoosh, “Computer aided transmission protective system design, Part I: algorithms”, IEEE Trans. PAS 103 (4) (1984).

[6] L. Jenkines, H. Khincha, S. Shivakumar, and P. Dash, “An application of functional dependencies to the topological analysis of protection schemes”, IEEE Trans. Power Delivery 7 (1) (1992) 77–83.

[7] A. Urdenta, R. Nadria, and L. Jimenez, “Optimal coordination of directional over current relays in interconnected power systems”, IEEE Trans. Power Delivery 3 (1988) 903–911.

[8] N.A. Laway, and H.O. Gupta, “A method for coordination of over current relays in interconnected power systems”, IE J. 74 (1993) 59–65.

[9] B. Chattopadhyay, M.S. Sachdev, and T.S. Sidhu, “An on-line relay coordination algorithm for adaptive protection using linear programming technique”, IEEE Trans. Power Delivery 11 (1) (1996) 165–173.

[10] A.J. Urdenta, L.G. Perez, and H. Resterbo, “Optimal coordination of directional over current relays considering dynamic changes in the network topology”, IEEE Trans. Power Delivery 12 (4) (1997) 1458–1464.

[11] H.H. Zeineldin, E.F. EI-Saadanv, and M.M.A Salama, “Protective Relay Coordination for Micro-grid Operation Using Particle Swarm Optimization.” IEEE Power Engineering Conference, 26 - 28 July 2006.

[12] M.R. Asadi, and S.M. Kouhsari, “Optimal Overcurrent Relays Coordination using Particle-Swarm-Optimization Methodology.” IEEE Power System Conference, 15 - 18 March 2009.

[13] H.K. Karegar, H.A. Abyaneh , V. Ohis and M. Meshkin: “Pre-Processing of the Optimal Coordination of Overcurrent Relays.” Electric Power Systems Research, Vol. 75, pp. 134 - 141, 2005.

[14] F. Razavi, et al., “A New Comprehensive Genetic Methodology Method for Optimal Overcurrent Relays Coordination.” Electric Power Systems Research Vol. 78, pp. 713 - 720, 2008.

[15] C.W. So, and K.K. Li, “Overcurrent Relay Coordination by Evolutionary Programming.” Electric Power Systems Research, Vol. 53, pp. 83 - 90, 2000.

[16] N. Nimpitiwan, et al., “Consequences of Fault Currents Contributed by Distributed Generation.” Report, Power Systems Engineering Research Center, June 2006.

[17] A. Phadke, and S. Horwitz, “Adaptive Relaying.” IEEE Computer Application in Power, Volume 3, Issue 3, pp. 47 - 51, July, 1990.

[18] B. Chattopadhyay, M.S. Sachdev, and T.S. Sidhu, “An On-Line Relay Coordination Methodology for Adaptive Protection using Linear Programming Technique.” IEEE Transactions on Power Delivery, Vol. 11, Issue 1, pp. 165 - 173, 1996.

[19] A.Y. Abdelaziz, et al., “An Adaptive Protection Scheme for Optimal Coordination of Overcurrent Relays.” Electric Power Systems Research, Volume 61, Number 1, pp. 1 - 9, Feb. 2002.

[20] T.K.A. Rahman, S.I. Suliman, and I. Musirin, “Artificial immune – based optimization technique for solving economic dispatch in power system”. Berlin Heidelberg: Springer-Verlag; 2006 pp. 338–345.

[21] L. Gwo-Ching, “Short-term thermal generation scheduling using improved immune algorithm”. Electr Power Syst Res 2006; 76:360–73.

[22] B.K. Panigrahi, S.R. Yadav, S. Agrawal, and M.K. Tiwari, “A clonal algorithm to solve economic load dispatch”. Electr Power Syst Res 2007; 77:1381–9.

[23] T.L. Huang, Y.T. Hsiao, C.H. Chang, and J.A. Jiang, "Optimal placement of capacitors in distribution systems using an immune multi-objective algorithm", Int J Electr. Power Energy Syst. 2008; 30(3):184–92.

[24] T. Amraee, "Coordination of Directional Overcurrent Relays Using Seeker Algorithm". IEEE Transactions on Power Delivery, Vol. 27, No. 3, July 2012

[25] J. Sadeh, "Optimal Coordination of Overcurrent Relays In An Interconnected Power System". 15th PSCC, liege, 22-26 August 2005.

[26] L.N. De Castro, and J. Timmis, "Artificial Immune Systems: A New Computational Intelligence Approach". Springer-Verlag, 2002.

[27] A.S. Perelson, "Immune network theory. Immunol", Rev. 110, 5–36, 1989.

[28] N.K. Jerne, "Towards a network theory of the immune system", Annu. Immunol. 125 (C), 373–389, 1974.

[29] L.N. De Castro, and F.J. Von Zuben, "Learning and optimization using the clonal selection principles", IEEE Trans. Evolut. Comput. 6 (3), 239–251, 2002.

[30] J. Timmis, A. Hone, T. Stibor, and E. Clark, "Theoretical advances in artificial immune systems", Theor. Comput. Sci. 403, 11–32, 2008.

[31] H. Yang, F. Wen, and G. Ledwich, “Optimal coordination of overcurrent relays in distribution systems with distributed generators based on differential evalution algorithm", Euro. Trans. Electr. Power (2011).

8. Appendix

Power supply parameters [31].

S_s	100 MVA	V_s	10.5 kV
S_{DG1}	10 MVA	V_{DG1}	10.5 kV
S_{DG2}	10 MVA	V_{DG2}	10.5 kV
X_s	1.46 Ω	F	50 Hz
X_{DG1}	0.42 Ω	X_{DG2}	0.42 Ω

Feeder parameters [31].

Lines	R(Ω)	L(H)
1-2	1.155	0.005
2-4	1.155	0.005
1-3	1.155	0.005
3-5	1.155	0.005