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A New Method for Optimal Coordination of Overcurrent Relays Considering the Communication Channels Constraints

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Abstract

The most of the new protective schemes are based on a communication channel, which cannot be guaranteed in practice. However, during blackouts or cascading failures in the power grid, as system conditions change significantly and rapidly, more information exchanges may be required by the control centers and substations. In other words, the communication channels are operating with high load and therefore become more vulnerable when the power grid is in contingent conditions. Thus, relying on the communication channel for decision making may not be the optimal solution for protective relays, although it might be beneficial to have information exchange. In this article, a novel protective logic is proposed based on phasor measurement units (PMUs) data for optimal coordination of overcurrent relays. PMUs measure the positive sequence voltage at two substations separated by hundreds of miles which are synchronized precisely with the aid of a GPS satellite system. The precise time-tags are attached with samples, and this information is exchanged over communication channels and collected by control centers and/or substations. By extracting the relevant information from these measurements, phasor information can be obtained at any node where PMUs are installed in the power grid. This can be used to do more accurate state estimation, control, and protection. In these relays, besides current and voltage, phasor information has become an important measurement in decision making. The proposed method is tested on IEEE 8-bus standard network.

***Keywords**: Overcurrent relay, phasor measurement unit, optimization methods, optimal coordination of relays, optimal PMU placement*

1. Introduction

Because of the increasing dependence on electricity, ensuring its delivery in a secure and reliable manner is very importance to both customers and suppliers. On the other hand, short circuit conditions can occur unexpectedly in any part of a power system [1]. The incidence of the fault is harmful and must be isolated by a set of protective devices. The protection systems must be reconnect the affected equipment as soon as the conditions return to normal. To solve these problems, the systems have to be monitored, controlled, and protected [2-5]. Indeed, relays are the core and the brain of power system protection. Protective relays are installed as a "fault sensor" in power system and to isolate a faulty part from the other parts of the network if there exists a fault event. Therefore, modern relays are operating as sensors and protectors [6]. The traditional relays which respond to preset tripping thresholds values, continuously obtain voltage and current values from these local measurements and decisions to SCADA. These thresholds might not be valid when the state of the power system changes, due to equipment failure or other disturbances. Also, the traditional relays properly are not able to distinguish between fault and normal conditions [7]. Malfunctioning of relays is among the most common modes of failure that makes the cascade of faults. Every four months, the United States experiences a blackout large enough to leave half a million homes in dark [8]. According to the historical data, relay malfunctioning is one of the major contributing factors to 70% of the major disturbances in the United States [9-10].

Usually is not simultaneous measurements of the SCADA system and the sampling rate is very slow. Also, the program of its state estimation is non-linear and time-consuming. Therefore, the access to the various parameters of the power system at any time, is one of

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the effective steps in order to provide the appropriate quality and sustainable electrical energy. One of the appropriate tools and useful in this field, is the use of phasor measurement units (PMUs) that have been used in many different countries. The use of synchronous measurements, will increase significantly accuracy of diagnosis and fault location in transmission lines. For this purpose, algorithms and methods based on phasor measurements are provided in order to detect and locate the fault [11]. Overcurrent relays are used as both primary and backup protection for heavily meshed and multi-source power network. Low cost and simplicity to implement are the advantages of overcurrent relays for Power system protection. The issue of coordination of overcurrent relays includes time setting multipliers (TSM) and plug setting multipliers (PSM). The protective system must have ability to the sensitivity, selectivity and reliability [12]. Over the past five decades, several studies have been carried out on optimal coordination of overcurrent relays. These studies can be divided into three categories: 1) Trial and error method 2) Structural analysis method based on graph theory 3) Optimization method [13]. In recent years, artificial intelligence methods and nature-inspired algorithms such as Evolution Programming [14], Genetic Algorithm (GA) [15-17], Particle Swarm Algorithm (PSO) [18-19] among others are used to solve the issue of optimal coordination of overcurrent relays.

In this article, a novel protective logic based on phasor measurement units (PMUs) data is proposed for optimal coordination of overcurrent relays. Compared to conventional relays, in coordination of overcurrent relays based on PMU are used from the real time wide area measurement system (WAMS). Therefore, they can accurately detect and locate the initial disturbance in the system, as well as the system situation or state after the isolation of this disturbance. Namely, PMUs makes observability the amount of current and fault location. In this method, by using the PMU measurements, phasor information can be obtained continuously at any node where PMUs are installed in the power grid. For this purpose, initially the Optimal PMU placement is determined for full network observability. Then, the dynamic changes of network will be observable by using wide area measurements based on PMUs data. Finally this information is sent via communication links PMUs for the optimal coordination of overcurrent relays and the relays can decide whether and when to trip a transmission line. This can stop the propagation (or cascading) of failures and/or confine it to a limited small area. PMU will have this advantage to systems that relays setting close to PMU, is done online for every fault. The use of PMU for the Coordination of overcurrent relays can improve the decision making capability and performance of protective relays and help them to form a reliable and robust protection system.

2. Optimal Placement of Phasor Measurement Units

Phasor measurement units are a new technology for power system state estimation. Using the technology of PMU, the power system is converted from a static infrastructure to a flexible and live infrastructure [20]. Phasor measurement unit (PMU) as one of the main exception field of transmission smart grid, is the fundamental solutions for the real time monitoring power grids. That able to conversion of nonlinear state estimation equations to linear equations, which improves the speed control systems, safety and management systems that use the results of state estimation [21].

2.1. Observability Analysis Based on PMU

The power network is could be observed, when are calculated the all state variables in order to system state estimation. That it means, can to calculated the voltage phasor for all bus and also current to all branches are connected to its [22]. PMU installed on a certain bus is able to measure the voltage phasor of that bus and also current phasor of the all branches connected to it. As a result, the bus voltage size and phase angle of a connected to bus has a PMU is calculated to using kirchhoff equations. Therefor, the buses that in their have been installed PMU, are directly observed, and buses that are connected to the bus with PMU, they are indirectly observed [23].

Bus observability index (BOI) is proposed as performance indicator on quality of the optimization. BOI for bus i (β_i) is defined as the number of phasor measuring units which are able to observe a given bus. System observability redundancy index (SORI) is defined as the total set of BOIs of system buses. In the other words, if bus i with the number of β_i PMU is observable, SORI is achieved as follows [24]:

$$SORI = \sum_{i=1}^{n} \beta_i \tag{1}$$

2.2. The Formulation of Optimal Placement PMU

The formulation of the optimal placement of PMU in a system with n buses is presented as equation (2) [25]:

$$min \sum_{i=0}^{n} w_i x_i \quad s.t \quad y = Ax \geq b \tag{2}$$

Which w is the cost function for the installed PMUs, and in normal stage, placement equaling to matrix of unit $n \times n$ is considered. A is connection matrix of $n \times n$ which reveals the way of connection of buses which is defined as follows (3):

$$A_{n\times n}(i,j) = \begin{cases} 1 & i = j \\ 1 & if\ buses\ i\ and\ j\ are\ connected \\ 0 & otherwise \end{cases} \tag{3}$$

The discrete nature of the optimal placement of PMU make it necessary that X vector to be defined as equation (4) such that the elements of that position show the installation of this equipment in each bus:

$$[x]_i = x_i = \begin{cases} 1 & if\ pmu\ is\ installe\ at\ bus\ i \\ 0 & otherwise \end{cases} \tag{4}$$

Also b matrix for at least one observability is as follows:

$$b_{n\times 1} = [111\ ...11]^T \tag{5}$$

3. Setting Overcurrent Relays

The objective function and constraints of the problem, to obtain the parameters of TMS and I_{set} is defined as follows [26]:

$$Minimize: \sum_{i=1}^{n} t_{opi}\ ,\ t_{opi} = f(TMS_i, I_{set_i}) = \frac{3TMS_i}{log \frac{I_{sci}}{I_{seti}}} \tag{6}$$

Where n is the number of overcurrent relays. Constraint optimization problem as follows:

$$TMS_{mini} \leq TMS_i \leq TMS_{maxi} \tag{7}$$

$$t_{op_b}(z_m) - t_{op_m}(z_m) \geq CTI \tag{8}$$

$$I_{ioad_i}^{Max} < I_{set_i} < I_{fault_i}^{Min} \tag{9}$$

Where t_{op_i} is operating time i^{th} relay, t_{op_m} and t_{op_b} are operating time of primary and backup relays respectively and CTI is the Coordination Time Interval.

Constraint (8) is used for each pair main and backup relay (m, b) and for errors relating to zone of protection z_m . With respect to the Figure 1, the failures are identified by the F1 and F2 points. Taking into account Constraint (9), the pickup value of an overcurrent relay must be set between the maximum load current and the minimum fault current experienced by the relay.

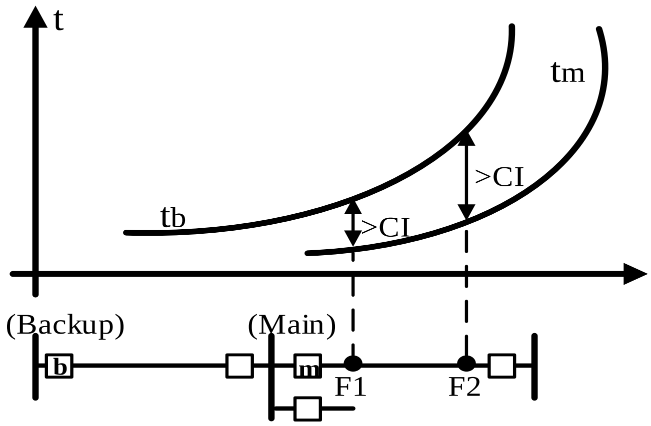

Figure 1. Coordination of overcurrent relays

4. The Proposed Method

The most of the new protective schemes are based on a reliable communication channel, which cannot always be guaranteed in practice. As well as, during blackouts or cascading failures in the power system, that system conditions change rapidly, more information exchanges be required by the control centers and substations. In other words, the communication channels are operating with high load and therefore become more vulnerable when the power system is in uninterruptible conditions. Moreover, the new protective schemes are based on the logic employed by traditional overcurrent and distance relays. This means that the modern relays are also based on the assumptions made for traditional relays, which are clearly invalid sometimes. Therefore, without changing the basic principles of protective relays, the malfunctioning of them cannot be avoided. Thus, a new and more comprehensive logic is needed in protective relays.

While most of relays still only use magnitudes of voltage and current measurements, a new technology is available for accurately measuring voltage and current phasors. These measurements offer new information in order to improve the functional logic of protective relays. The idea of phasor measurement was introduced after the blackout in North-East US. The first prototype phasor measurement unit (PMU) is developed by a Virginia Tech research team in 1988 [27]. PMU utilizes powerful signal processing technology, have capable of measuring voltage and current phasors with high accuracy (less than 0.1% error) and very high speed (60 samples per second). PMUs measure the voltage and current signals at two substations separated by hundreds of miles which are synchronized precisely with the aid of a GPS satellite system that is shown in Figure 2. The time-tags are attached with samples, and this information is exchanged over communication channels and collected by control centers and/or substations. By extracting the relevant information from these measurements, phasor information can be obtained at any node where PMUs are installed in the power grid. This information can be used to do more accurate state estimation, control, and protection [28].

In proposed method, from data measured by the PMU are used for coordination of overcurrent relays, so that is satisfied the constraints related to the main and backup relays. On the other hand, PMU will have this advantage to systems that relays setting close to PMU, is done online for every fault. In other words, PMUs makes observability the amount of current and fault location. As a result, when location of the fault was identified by the PMU, a signal is sent to the Phasor Data Concentrator (PDC) and the setting value to be considered for it fault. With this task there is ability to change the relays settings and reduce their operating time during fault occurrence. But considering to the high cost of installation PMU on all network buses, initially the Optimal PMU placement is determined for full network observability. Therefore, the ultimate Objective function of problem is a two-objective function that includes the following functions: 1) determine the optimal location and number of PMUs 2) minimizing the operating time of overcurrent relays. Therefore, initially the Optimal PMU placement is determined for full network observability. Then, by using PMU measurements, the values of voltage and current phasor in the lines and buses power system are obtained for the desired fault. Now according to the location of PMU, the relays surrounding bus which PMU has been installed as online relays and the other relays as offline relays are considered. The settings of offline relays are fixed and the settings of online relays are obtained by using the real-time measured PMU data. This information is sent via communication links PMUs for the optimal coordination of overcurrent relays. Therefore, the dynamic changes of network will be observed by using wide area measurements based on PMU data.

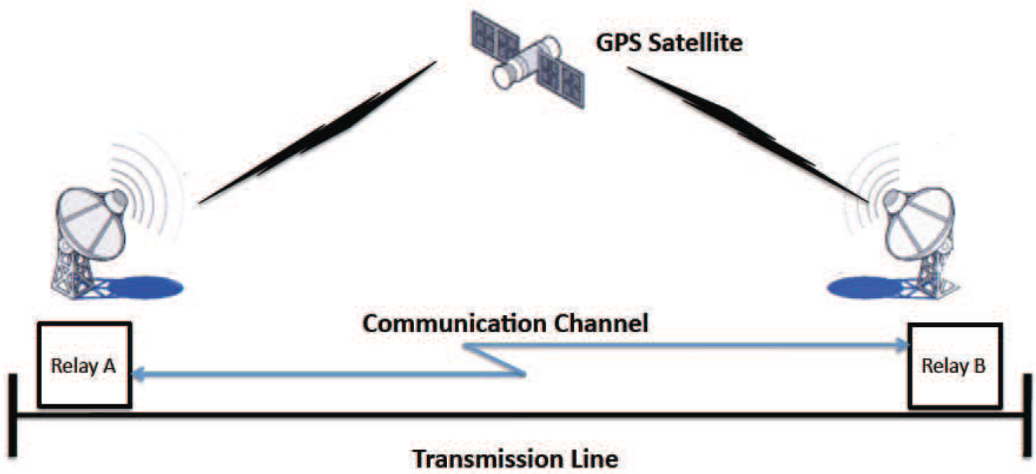

Figure 2. Phasor measurement units that function with the aid of GPS satellite

5. The Proposed Cuckoo Optimization Algorithm (COA)

This optimization algorithm is inspired by the life of a bird family, called Cuckoo. Special lifestyle of these birds and their characteristics in egg laying and breeding has been the basic motivation for development of this new evolutionary optimization algorithm. This novel evolutionary algorithm, is suitable for continuous nonlinear optimization problems. The effort to survive among cuckoos constitutes the basis of Cuckoo Optimization Algorithm. During the survival competition some of the cuckoos or their eggs, demise. The survived cuckoo societies immigrate to a better environment and start reproducing and laying eggs. Cuckoos' survival effort hopefully converges to a state that there is only one cuckoo society, all with the same profit values. Application of the proposed algorithm to some benchmark functions and a real problem has proven its capability to deal with difficult optimization problems [29].

Figure 3 shows a flowchart of the proposed algorithm. Similar to other evolutionary methods, Cuckoo Optimization Algorithm (COA) starts with an initial population. These initial cuckoos have some eggs to lay in some host birds' nests. Some of these eggs which are more similar to the host bird's eggs have the opportunity to grow up and become a mature cuckoo. Other eggs are detected by host birds and are killed. The grown eggs reveal the suitability of the nests in that area. The more eggs survive in an area, the more profit is gained in that area. So the position in which more eggs survive will be the term that COA is going to point optimize.

5.1. Generating Initial Cuckoo Habitat

In order to solve an optimization problem, it's necessary that the values of problem variables be formed as an array. In GA and PSO terminologies this array is called "Chromosome" and "Particle Position", respectively. But here in Cuckoo Optimization Algorithm (COA) it is called "habitat". In a N_{var} dimensional optimization problem, a habitat is an array of $1 \times N_{\text{var}}$, representing current living position of cuckoo. This array is defined as follows:

$$Habital = [x_1, x_2, ..., x_{N\,var}] \tag{10}$$

Each of the variable values $(x_1, x_2, ..., x_{N\,\text{var}})$ is floating point number. The profit of a habitat is obtained by evaluation of profit function f_p at a habitat of $(x_1, x_2, ..., x_{N\,\text{var}})$. So

$$profit = f_p\,(habital) = f_p(x_1, x_2, ..., x_{N\,var}) \tag{11}$$

As it is seen COA is an algorithm that maximizes a profit function. To use COA in cost minimization problems, one can easily maximize the following profit function:

$$profit = -Cost(habital) = -f_c(x_1, x_2, ..., x_{N\,var}) \tag{12}$$

To start the optimization algorithm, a candidate habitat matrix of size $N_{pop} \times N_{\text{var}}$ is generated. Then some randomly produced number of eggs is supposed for each of these initial cuckoo habitats. In nature, each cuckoo lays from 5 to 20 eggs. These values are used as the upper and lower limits of egg dedication to each cuckoo at different iterations. Another habit of real cuckoos is that they lay eggs within a maximum distance from their habitat. From now on, this maximum range will be called "Egg Laying Radius (ELR)". In an optimization problem with upper limit of var_{hi} and lower limit of var_{low} for variables, each cuckoo has an egg laying radius (ELR) which is proportional to the total number of eggs, number of current cuckoo's eggs and also variable limits of var_{hi} and var_{low}. So ELR is defined as:

$$ELR = \alpha \times \frac{number\ of\ current\ cuckoo's\ eggs}{total\ number\ of\ eggs} \times (var_{hi} - var_{low}) \tag{13}$$

Where α is an integer, supposed to handle the maximum value of ELR.

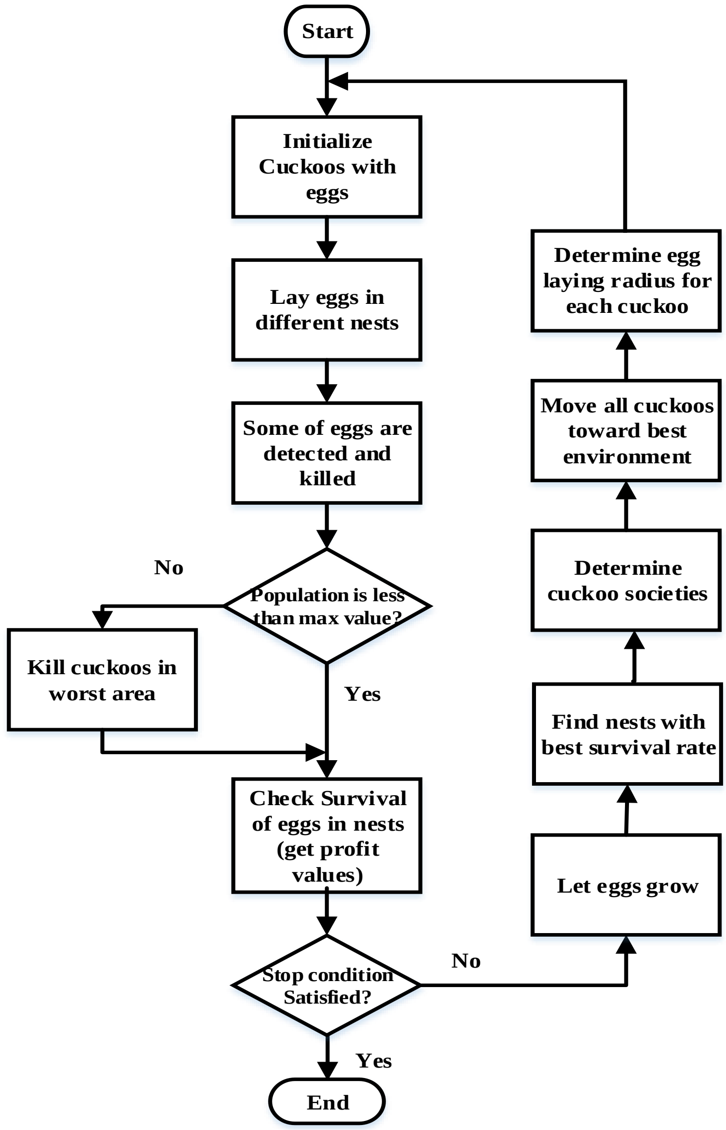

Figure 3. Flowchart of Cuckoo Optimization Algorithm

5.2. Cuckoos' Style for Egg Laying

Each cuckoo starts laying eggs randomly in some other host birds' nests within her ELR. Figure 4 gives a clear view of this concept.

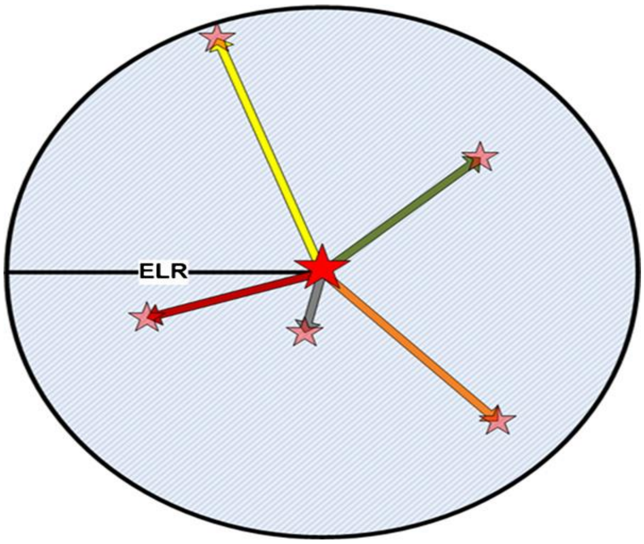

Figure 4. Random egg laying in ELR, central red star is the initial habitat of the cuckoo with 5 eggs; pink stars are the eggs' new nest.

After all cuckoos' eggs are laid in host birds' nests, some of them that are less similar to host birds' own eggs, are detected by host birds and though are thrown out of the nest. So after egg laying process, p% of all eggs (usually 10%), with less profit values, will be killed. These eggs have no chance to grow. Rest of the eggs grow in host nests, hatch and are fed by host birds. Another interesting point about laid cuckoo eggs is that only one egg in a nest has the chance to grow. This is because when cuckoo egg hatches and the chicks come out, she throws the host bird's own eggs out of the nest. In case that host bird's eggs hatch earlier and cuckoo egg hatches later, cuckoo's chick eats most of the food host bird brings to the nest (because of her 3 times bigger body, she pushes other chicks and eats more). After couple of days the host bird's own chicks die from hunger and only cuckoo chick remains in the nest.

5.3. Immigration of Cuckoos

When young cuckoos grow and become mature, they live in their own area and society for some time. But when the time for egg laying approaches they immigrate to new and better habitats with more similarity of eggs to host birds and also with more food for new youngsters. After the cuckoo groups are formed in different areas, the society with best profit value is selected as the goal point for other cuckoos to immigrate.

5.4. Convergence

After some iterations, all the cuckoo population moves to one best habitat with maximum similarity of eggs to the host birds and also with the maximum food resources. This habitat will produce the maximum profit ever. There will be least egg losses in this best habitat. Convergence of more than 95% of all cuckoos to the same habitat puts an end to Cuckoo Optimization Algorithm (COA).

6. Apply COA Algorithm in Order to Optimal Coordination of Relays

Relay coordination problems, is an optimization problem with constraints and many local optimum points. In the usual methods, such as linear programming, non-linear programming and integer programming, since optimization start with initial point, the final answer depends heavily on that point and may lead to a local optimization. However COA starts the search from a population of initial points, therefore in the local optimum points the possibility of stopping this algorithm is very low. COA algorithm, problem's variables are encoded into strings, so each string represents an answer to the problem of coordination.

In the relays coordination problem, the decision variables are the TMS and I_{set} variables for each relay. Therefore, in the COA method a habitat is defined in the form of a string which contains both TMS and I_{set} parameters as discrete variables. Figure 5 shows structure of the habitat when the network consists of n overcurrent relays.

I_{set1}	TMS_1	I_{set2}	TMS_2	$\cdots$	$I_{set\,n}$	TMS_n

Figure 5. Structure of the habitat in the COA method.

The main objective function (OF) that is already used in most of the literature is the total weighted sum of operating times (OTs) of primary relays as follows [30]:

$$mim\, OF = \sum_{i=1}^{m} w_i . t_i \tag{14}$$

Where m is the number of relays, t_i is the operating time of the relay i^{th} per fault In front of the relay and w_i is the weight assigned for the operating time of the relay i^{th} and is usually set to one [30].This objective function has two problems. One of them is miscoordination and another is insensibility to avoid having large discrimination times in addition to CTI. To overcome the mentioned difficulties in [31], a new OF is proposed for coordination of OC relays, as follows:

$$O.F = \alpha_1 \times \sum_{i=1}^{m} (t_i)^2 + \alpha_2 \times \sum_{k=1}^{n} (\left|\Delta t_{mbk} - |\Delta t_{mbk}|\right| . t_{mk}^2 + (\Delta t_{mbk} + |\Delta t_{mbk}|).t_{bk}^2). \tag{15}$$

Where n is the number of P/B relay pairs, t_i is the operating time of the relay i^{th} and k represents each P/B relay pair and varies from 1 to n. α_1 and α_2 are used to control the weighting of $\sum_{i=1}^{N} (t_i)^2$ and $\sum_{k=1}^{P} (\left|\Delta t_{mbk} - |\Delta t_{mbk}|\right|).t_{mk}^2$ of the OF and Δt_{mbk} is the discrimination time between the main and backup overcurrent relays which is obtained from the equation below:

$$\Delta t_{mbk} = t_b - t_m - CTI \tag{16}$$

Where t_m and t_b are the operating times of the primary and backup relays, respectively. CTI is the coordination time interval that is equal to 0.3(sec).To describe the role of the new expression, consider Δt_{mbk} is positive, then the third term of the OF gains value. Because of multiplying by t_{bk}^2, the program tries to further reduce the operating time (OT) of the backup relay and therefore prevents the undesirable increase of the OT of the primary relay. However, the necessity of a method by which the mentioned problems could be solved completely, is sensed.

7. Simulation Results and Discussion

The proposed method is applied to an 8-bus, 9-branch network shown in Figure 6. At bus 4, there is a link to another network which is modeled by a short circuit capacity of 400 MVA. The parameters are used in the network is provided in reference [32]. The transmission network consists of 14 relays which their location are indicated in Figure 6. The TMS values can range continuously from 0.1 to 1.1, while seven available discrete pickup tap settings (0.5, 0.6, 0.8, 1.0, 1.5, 2.0 and 2.5) are considered. The generation size and population size is directly related to the chromosome length; for longer lengths, more chromosomes should be produced. The generation size and the population size are considered to be 1000 and 100, respectively.

In proposed method, by using the PMU measurements, phasor information can be obtained continuously at any node where PMUs are installed in the power grid. This means that, the dynamic changes of network will be observed by using wide area measurements based on PMUs data. For this purpose initially the Optimal PMU placement for full network observability is determined by using COA algorithm and with the aid of equation 2, which is shown in Figure 7. Then, by using PMU measurements, the values of voltage and current phasor in the lines and buses power system are obtained for the desired fault. Now according to the location of PMU, the relays surrounding bus which PMU has been installed as online relays and the other relays as offline relays are considered. By detecting fault location by the PMU and declare it to Phasor Data Concentrator (PDC), the values of online relays setting is determined for the desired fault. Finally this information is sent via communication links PMUs for the optimal coordination of overcurrent relays and the relays can decide whether and when to trip a transmission line. With this task there is ability to change the relays settings and reduce their operating time during fault occurrence.

According to the results obtained, the optimal location of PMUs is on the buses 1, 4 and 6, as shown in the Figure 7. Therefore, according to Figure 6, the relays 2, 8 and 14 (relating to the PMU bus-1), the relays 4 and 10 (relating to the PMU bus-4) and the relays 6, 7 and 12 (relating to the PMU bus-6), are member of the online relays. The remaining relays (i.e. the relays 1, 3, 5, 9, 11 and 13) are component the offline relays. The setting of offline relays is fixed and the setting of online relays is obtained by using the real-time measured PMU data. This setting is sent via communication links PMUs for the optimal coordination of overcurrent relays.

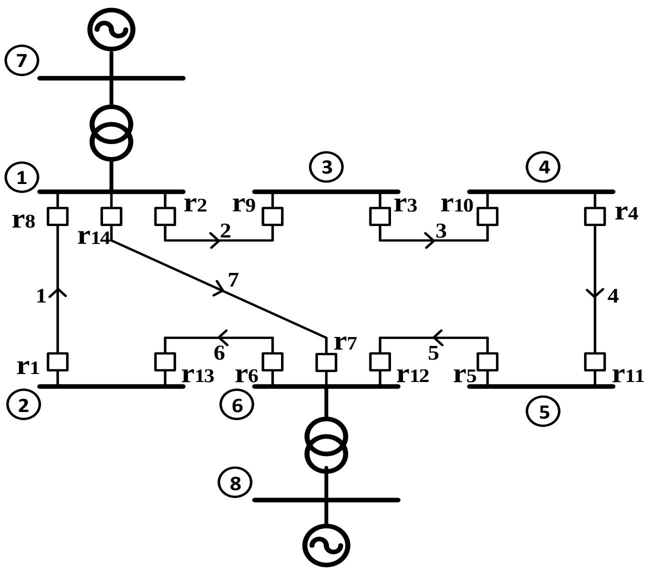

Figure 6. Single line diagram of the 8-bus system

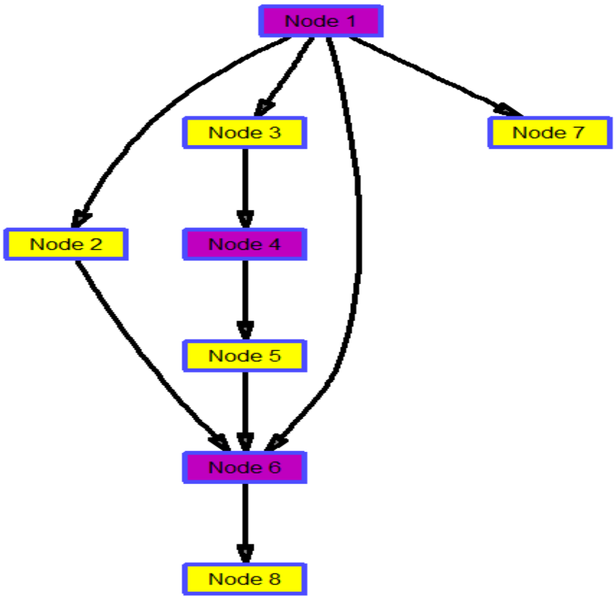

Figure 7. The optimal location of PMUs in the IEEE 8-Bus Test System

Table 1 shows the primary/backup (P/B) relay pairs and corresponding fault currents passing through them for fault in front of the main relay and fault on bus away the main relay. This matrix contains 20 rows and two columns. The first column is the number of the main relay and the second column is the number of backup relay. Then, for a short circuit in front of the main relay the fault currents passing through the primary/backup (P/B) relay pairs is calculated and is stored in the IP and IB matrix respectively, as shown in Table 1. Obviously, when the system topology is changed the presented data in Table 1 should be updated. The current setting of relay is obtained by using the power flow. Then, I_{set} and TMS overcurrent relays have been obtained using COA, DE-GA, GA, PSO and DE algorithms, as shown in the Table 2.

Figure 8 illustrated comparative convergence performance of objective function. It is obvious that the Cuckoo Optimization Algorithm (COA) gave the accurate and convergence with faster computational time compared to other method. As a result, the COA algorithm has operation time and the fitness value less compared to other algorithms.

Table 1. P/B Relay pairs and the fault currents in the main network topology

P/B pair		Near-End Fault Currents(A)	
primary relays	backup relays	IP	IB
2	1	5910	993
14	1	5190	993
3	2	3550	3550
4	3	3780	2240
5	4	2400	2400
6	5	6100	1200
7	5	5210	1200
1	6	3230	3230
2	7	5910	1880
8	7	6080	1880
13	8	2980	2980
8	9	6080	1160
14	9	5190	1160
9	10	2480	2480
10	11	3880	2340
11	12	3700	3700
7	13	5210	985
12	13	5890	985
6	14	6100	1870
12	14	5890	1870

Table 2. Overcurrent relay settings regardless of distance relays

Relay No.	CT Ratio	The results of the program GA [15] Fitness=7.63		The results of the program PSO [18] Fitness=6.84		The results of the program DE [14] Fitness=6.29		The results of the program DE-GA [33] Fitness=4.05		The results of the proposed method (COA) Fitness=3.98	
		TMS	I_{set}	TMS	I_{set}	TMS	I_{set}	TMS	I_{set}	TMS	I_{set}
1	240	0.25	0.8	0.100	2.5	0.100	1.0	0.105	2.0	0.100	2.5
2	240	0.19	1.5	0.100	2.0	0.126	1.0	0.134	1.5	0.202	0.5
3	160	0.21	0.6	0.126	1.5	0.156	2.5	0.152	0.5	0.274	2.5
4	240	0.17	0.6	0.142	1.5	0.127	2.0	0.131	0.5	0.116	0.8
5	240	0.10	0.5	0.100	0.8	0.100	0.5	0.100	0.6	0.100	0.6
6	240	0.20	0.8	0.185	0.5	0.252	0.8	0.190	2.0	0.158	2.0
7	160	0.20	0.6	0.154	2.0	0.229	1.0	0.199	1.0	0.540	2.5
8	240	0.17	1.0	0.162	2.5	0.100	2.5	0.223	0.6	0.139	2.5
9	160	0.09	0.6	0.100	0.5	0.100	0.5	0.100	0.5	0.100	0.5
10	240	0.16	0.8	0.100	2.0	0.194	0.6	0.100	0.8	0.100	1.5
11	240	0.20	0.6	0.182	2.5	0.112	2.0	0.177	0.8	0.150	0.8
12	240	0.26	0.8	0.124	1.0	0.156	0.6	0.151	1.0	0.204	2.0
13	240	0.18	0.6	0.100	1.5	0.142	1.5	0.121	1.0	0.169	1.0
14	160	0.16	0.8	0.162	1.5	0.172	2.5	0.166	2.0	0.126	2.5

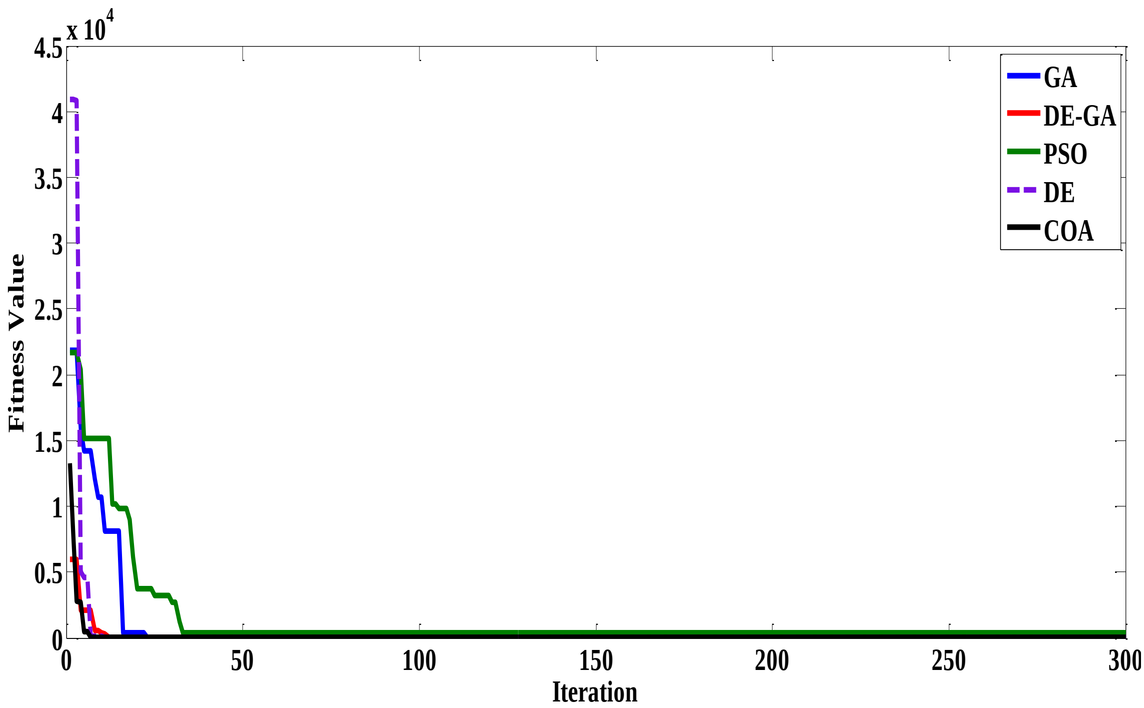

Figure 8. Comparison of objective function for 8-busbars test system

In order to assess the validity of the obtained settings, relays performance was evaluated caused by a short circuit fault per 40% of line the front of relay 7. In the ring networks, like the network Figure 6, the relays setting is complex in front of generator bus, like relays 5 and 9 which are backup relays for 6, 7 and 8, 14 respectively. When in the front of lines of relays 6, 7, 8, 14 a short circuit occurs, if the backup relays 5 and 9 are not set correctly, it is possible fault current passing through them be less than the current set, and thus does not operate as a backup of the primary relays. According to the table 2, in all the cases studied, relays 5 and 9 are set at the lowest values.

8. Conclusion

In this article, a novel protective logic based on phasor measurement unit data is proposed for optimal coordination of overcurrent relays. Compared to conventional relays, in coordination of overcurrent relays based on PMU are used from the real time wide area measurement system (WAMS). PMU utilizes powerful signal processing technology, have capable of measuring voltage and current phasors with high accuracy (less than 0.1% error) and very high speed (60 samples per second). Therefore, they can accurately detect and locate the initial disturbance in the system, as well as the system situation or state after the isolation of this disturbance. But considering to the high cost of installation PMU on all network buses, initially the Optimal PMU placement is determined for full network observability. Therefore, the dynamic changes of network will be observe by using wide area measurements based on PMUs data. Finally, this information is sent via communication links PMUs for the optimal coordination of overcurrent relays and the relays can decide whether and when to trip a transmission line. This can stop the propagation of failures and/or confine it to a limited small area. PMU will have this advantage to systems that relays setting close to PMU, is done online for every fault. The use of PMU for the Coordination of overcurrent relays can improve the decision making capability and performance of protective relays and help them to form a reliable and robust protection system. Also, in order to obtain the best solutions is used from COA algorithm. Results show the proposed method has significantly reduced the execution time of the algorithm while improving the accuracy of the output results in comparison with the other nature-inspired algorithms such as PSO and GA.

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