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An adaptive protection scheme to prevent recloser-fuse miscoordination in distribution feeders with distributed generation units, a case study

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Abstract:*Many power companies tend to adopt protection policy based on the fuse saving rule in order to avoid prolonged interruptions in their distribution networks. According to the rule, when a fault occurs, before operating the fuse, feeder is going to be withoutelectricity by several cycles of fast reclosing. By presenting distributed generation (DG) to a normal distribution network changes the timing of fuse and recloser operations, causes a miscoordination between these devices and interferes with declared rule. In this paper, an adaptive modification of recloser time dial setting (TDS) is proposed to address this problem. The proposed method is tested by simulating an actual distribution feeder located in Abarkuh, Yazd in multiple scenarios assuming different capacities and positions for the DG unit. This simulation is conducted usingDigSILENT and MATLAB softwares. This paper also uses BBO algorithm to optimize the location and capacity of two DG units assumed to be added to the studied feeder. This optimization is focused on minimizing losses while maintaining the recloser-fuse coordination as well as other operational constraints. The obtained results indicate the effectiveness of the proposed method in ensuring proper recloser-fuse coordination.*
Keywords: *BBO algorithm, distributed generation, distribution network, recloser-fuse coordination.*

I. Introduction

As the time passed by, developing technology and having alacrity to move toward industrialization have made increasing demand for electricity. As a result, development of new power sources and interconnected current electrical grids are now considered inevitable. Meanwhile, the increased public awareness about environmental protection, magnitude of energy consumption and shortage of energy resources has increased the tendency toward the use of renewable energies which has led to increasing use of distributed generation (DG) systems.

Integration of new DG systems with the existing networks has created several technical, economic, and regulatory challenges. Connecting a new DG system to a normal distribution network enhances the fault current and may has adverse effects on the performance of circuit breakers, protective relays, reclosers, and fuses designed for mentioned network [1, 2].

Presence of set of DGs in distribution network have a great potential to affects in various ways on the fault current, mostly depending on the type of DG. When detecting a fault, some types of DGs immediately cut their connection with the network and do not contribute to its fault current variations; these DGs are often based on power electronic devices [3, 4]. Another group of DGs use induction generators and this type of generators contribute to the fault current as much as several times their nominal current, although for a short period [5].Another group of DGs use synchronous generators to produce electrical energy. These DGs are able to contribute to the fault current as much as several times their nominal current and duration of this contribution is extremely high, unless protective stuff cut them from the circuit [3]. Connecting DG units to a distribution networks and changing the range of current variations in that network (both in normal mode and at the time of fault) can interfere with the functions of fuses and reclosers. When a temporary fault occurs, the recloser acts faster than the fuse; but the additional current generated by DG and decreased current at the feeder may cause the fuse to melt before the recloser can do its designated task. Therefore, the presence of DG in distribution systems may lead to repeating instances of burned fuses caused by recloser-fuse miscoordination in addressing temporary faults, which hampers the basic functions of both equipment and highlights the importance of ensuring proper network protection in the presence of DG.

In this paper, first of all, protective equipment had been used in distribution network has been reviewed and then its performance characteristic curves have been used to examine the effect of DG on the recloser-fuse coordination. An idea based on adaptive digital relay, has been used to achieve a proper coordination between the fuse and the recloser. After that, the proposed method would be simulated on a model of an actual network built in DIgSILENT environment. To perform a more complete study on the issue, the location and capacity of two DG assumed to be added to the studied feeder has been optimized; this optimization has been aimed at reducing the losses and reaching a proper recloser-fuse coordination.

II. Protective equipment used in distribution networks

The most important protective equipment used in distribution networks include fuses, overcurrent relays, recloser and sectionalizer, a brief introduction on each device is presented in the following.Low cost and simplicity of overcurrent (OC) relay have to prevalent use of protective equipment. There are several types of these relays including definite time OC relay, inverse time OC relay, instantaneous OC relay, directional OC relay, and earth-fault relay; Using each type or a combination of several types of relays depends on the level of voltage and radial or annular layout of the network. Sectionalizer is installed in series with the line and fuses. This device is installed in series with reclosers or power switches with reclosing cycles but in a location farther from the power source than those devices. Considering the function and the normal current of reclosers, these devices can be essentially considered as low capacity power switches. Reclosers are often installed on important branches of distribution feeders in series with other cut-out devices. Recloser switches are designed to remain open after performing a certain number of reclosing cycles. So any short circuit causes the recloser to open its switch; if this fault is momentary recloser automatically closes its switch and waits for the next event; but when this fault is persistent recloser repeats the reclosing cycle a few times and then switch permanently to (OFF) state. These devices are often configured to perform three reclosing cycles before switching to OFF state [6]. Switches and reclosers are usually equipped with inverse time overcurrent trip devices whose characteristics can be expressed as equation (1):

$$t = \left[\frac{A}{(MP)^{p} - 1} + B\right] \times TDS \quad (1)$$

wheret is the protective device operating time and TDS is its time dial setting ; MP is s current ratio which is equal to $I_{f(CTS)}/I_{pickup}$ (the ratio of the current measured by the protective component to the relay’s current set point). A, B and p are the constants that must be determined with respect to status of the OC relay characteristic curve; the standard values of these constants are listed In Table 1 [7].

Table 1.Constants of inverse time current characteristic curve

Characteristic curve	A	B	P
Inverse	0.0515	0.1140	0.02
Very Inverse	19.61	0.491	2
Extremely Inverse	28.2	0.1217	2

The purpose of the fuse is to interrupt a persistent fault by isolating the faulty section of the network from the healthy section. Each fuse is designed to melt within a specified time at a specified value of fault current. Current-time characteristic of a fuse can be determined with two curves:

- Minimum Melting Time (MMT)
- Maximum Clearing Time (MCT)

MMT curve expresses the minimum time it takes for a fuse to melt at a specified current and MCT curve expresses the maximum fault clearing time. Fig. 1 shows the MMT and MCT curves [6].

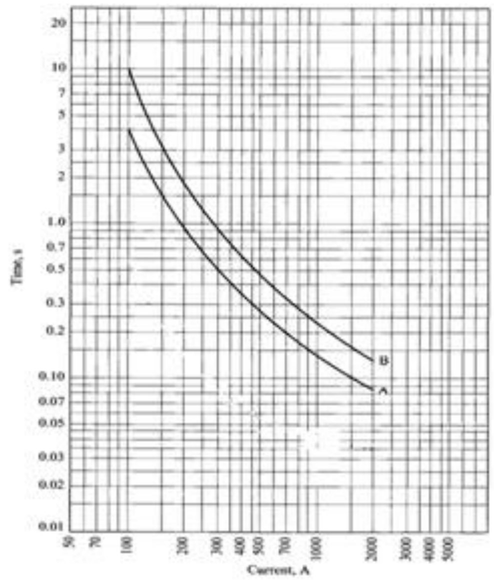


Fig. 1 MMT characteristic (A) and MCT characteristic (B) of a given fuse

The fuse has inverse time-current characteristic. The general equation describing the fuse characteristic curve is as follows:

$$\log(t) = a \times \log(I) + b \quad (2)$$

where I and t are the corresponding current and time respectively, and a and b are the constants that determine the curve. Constant a is the slope of the line I^2tin log-log plot. The value of this parameter is fixed for all fuses installed in the same system. This condition ispractically acceptable because all fuses in the system shouldbe of the same type. But constant b has a different value for each fuse. Constant b must be calculated by using parameter a and the coordinates of an operating point of the fuse (fault current passing through the fuse and its operating time).

The fault current passing through the fuse would be obtained by performing short circuit calculations. At the time of a short circuit, operating time of the fuse can be obtained by dividing the time range of recloser (i.e. the time difference between operating time of the slow and fast operating modes)by there the number of fuses in the fault path; the following equation can be used for this purpose [8]:

$$t_{fuse-i} = t_{rec-fast} + \frac{i \times (t_{rec-slow} - t_{rec-fast})}{n+1} \quad (3)$$

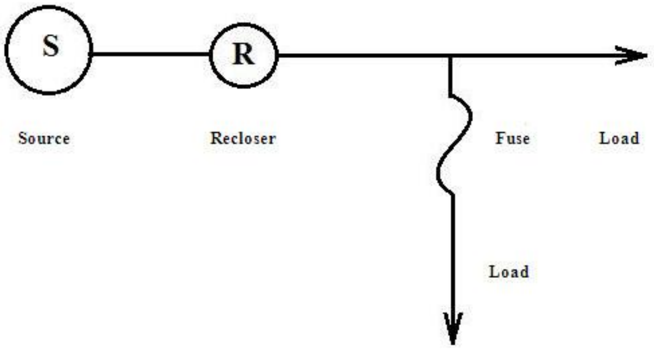
where t_{fuse-i} is the operating time of i-th fuse at the fault path (the closest fuse to the fault is i=1); n is the total number of fuses at the fault path; $t_{rec-slow}$ is the recloser operating time at slow-mode and $t_{rec-fast}$ is the recloser operating time at fast-mode.

III. The distributionnetwork's equipment protection coordination rules

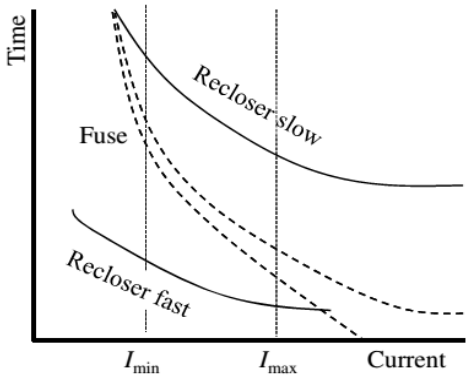
Equipmentprotection coordination is the process of selecting overcurrent protection equipment and configuring their time-current settings with the aim of clearing the fault and equipment according to a pre-determined order of operation. Two protective devices are called coordinated when they have a specific order of operation to deal with a fault and do not interfere with each other's functions. The device that is configured to operate first is known as primary protection and is usually closer to the fault location. Other stuff of equipment provides the backup protection and only operates when primary protection fails to operate.

3.1. Fuse- Recloser coordination

Fig. 3(a) shows a distribution feeder that is connected to a load. This feeder protected by a fuse. So fuse only acts against a permanent fault. For temporary faults, recloser must cut off the circuit in fast-mode and give the fault a time to be cleared. As a result, fuse will not blow by all temporary faults, and slow-mode reclosing remains as the fuse backup protection.



a) Fuse- Recloser coordination



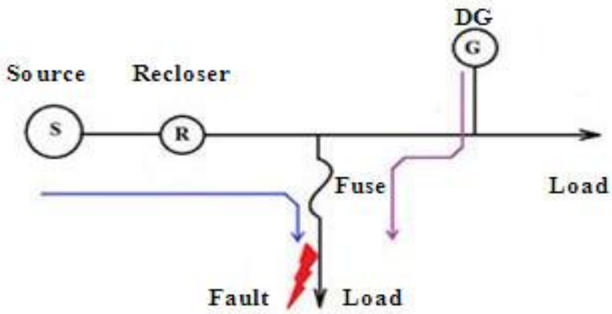
b) Recloser-Fuse coordination range [3]
Fig. 3 Recloser-Fuse coordination in a simple network

According to Fig. 3(b), coordination between fuse and recloser is somewhat complex. The two vertical lines show the minimum and maximum fault current at the circuit downstream the fuse, and the curves must be coordinated for these currents. Two dotted curves are MMT (lower curve) and MCT (upper curve) of the fuse. The following rules must be applied to coordinate the fuse and recloser:

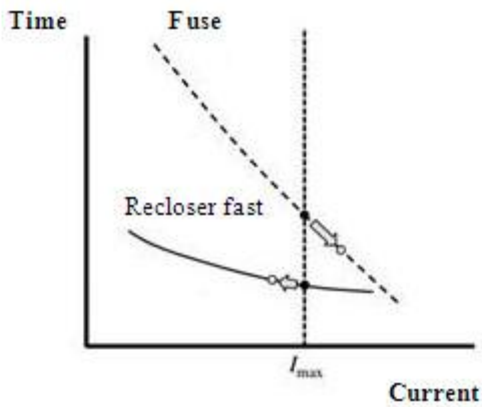
- MMT of the fuse must be greater than the recloser's fast-mode clearing time. The minimum distance between the curves must be maintained. Suggested minimum factors are: 1.25 times for one reclosing, 1.35 times for two fast reclosing with one second or more reclosing period, 1.8 times for two fast reclosing with half-second reclosing period.
- MCT of the fuse must be smaller than the recloser's slow-mode clearing time.

IV. The impact of DG on recloser-fuse coordination

Fig. 4(a) shows the effect of a generator in distribution feeder on recloser-fuse coordination. The main effect is that currents passing through the fuse and recloser are not the same. Fuse current is increased while reclosercurrent is reduced. Recloser current is reduced because the generator keeps a voltage fault at the beginning of the branch. This change in fuse and recloser currents decreases the margin of coordination. Fig. 4(b) shows this issue with the fast curve of recloser and MMT of the fuse.



a) A feeder with one recloser, one fuse, and one DG source



b) The impact of DG on coordination between the fuse and the recloser (fast-mode)
Fig. 4 The impact of DG on recloser-fuse coordination

Black circles in Fig. 4(b) show the feeder's clearing time and current in the absence of generator. In this state, recloser configuration the fuse selection must be with respect to this coordination margin.

Hollow circles show the clearing time and current in the presence of generator. In this state, currents are not the same and MMT of the fuse is affected. The difference between the recloser opening and fuse MMT is decreased. So fuse may melt or even cut off the current. Fuse meltdown without cut off will wear out the fuse and may cause unwanted cut offs in the future faults or at heavy loads. The presence of DG does not affect the coordination of recloser's slow-mode operation. Fuse acts faster and recloser acts slower which actually increase the coordination margin. But this margin added for slow-mode operation cannot be used to deal with fast-mode problems; because generator is not permanently under the fault condition and protection of distribution feeders should be coordinated in such a way that covers all situations.

V. Adaptive protection scheme

The adaptive relay used in this study, first stores the characteristics of fuse and recloser. After the determination of currents passing through the fuse and recloser by SCADA and distribution automation system, the maximum current passing through the fuse and recloser will be calculated. Then the ratio of recloser current to fusecurrent (I_R/I_F) will be calculated separately for each phase. If this ratio is equal to one, it is assumed that the fault has occurred after the fuse (or there is no fault at all) and at this stage DG has not been added to the circuit yet. When I_R/I_Fratio is greater than one, it is assumed that the fault has occurred at the path upstream the fuse. When this ratio is smaller than one, it is assumed that the fault has occurred at the path downstream the fuse; in this condition, DG contribution to the fault current can push this ratio to lesser than 1 and this contribution may even lead to recloser-fuse miscoordination. When I_R/I_Fratio is smaller than one, recloser's fast characteristic which is directly linked with TDS will be corrected by multiplying TDS of fast reclosing by I_R/I_Fratio. So the recloser's fast characteristic in the current-time plane will move downward and recloser will act faster than its previous state. Flowchart of the proposed adaptive relay is shown in Fig. 5.

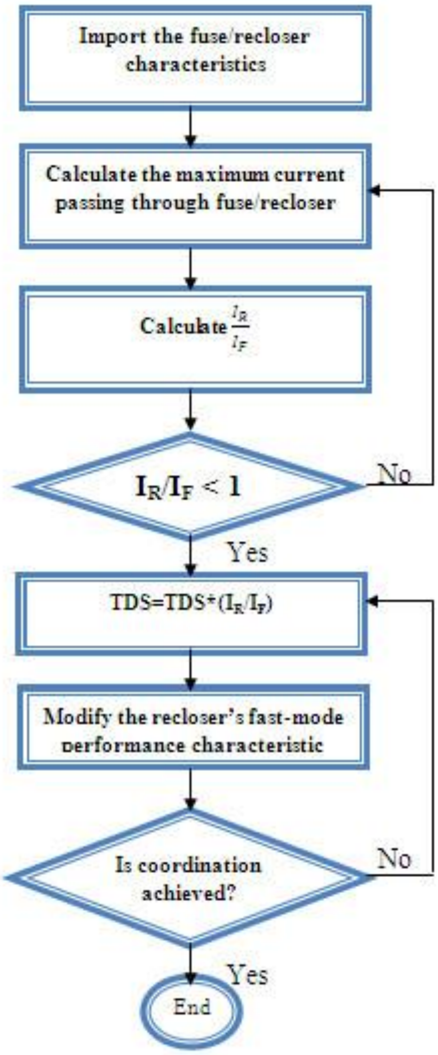


Fig. 5 Flowchart of adaptive relay for recloser-fuse coordination protection scheme

VI. Biogeography-Based Optimization

In 2008, Simon introduced a new algorithm called biogeography-based optimization (BBO) which can be effectively used to solve various optimization problems [9]. In this paper, this algorithm is used to optimize the capacity and location of DG in a real distribution feeder, by minimizing of losses and maintaining the recloser-fuse coordination while using the adaptive relay scheme expressed in the previous section. Some of the BBO features are similar to those of other biology-based optimization methods, such as genetic algorithm and particle swarm optimization (PSO). However, BBO has a few additional features that make this biology-based optimization method quite unique [9]. BBO is a powerful algorithm suitable for solving a variety of nonlinear optimization problems and therefore is selected to be used in this paper.

6.1.The Basics of biogeography

In [9], Simon has modified the mathematics of biogeography so that they can be used for engineering optimization problems. Mathematical models of biogeography use mathematical equations to show how a biological entity migrates from one habitat to another, grows and multiplies, and how it goes extinct. Geographical areas with favorable conditions for the species have high Habitat Suitability Index (HSI). A habitat with higher HSI has higher number of species that experience limited immigration to nearby habitats and restricted number of species that they host. Parameters λ and μ are immigration rate with a maximum value of I andemigration rate with a maximum value of E respectively, are function of number of species the habitat supports (S). BBO algorithm uses two operators: migration and mutation.

6.2. Formulation of DG capacity and location optimization problem with respect to protection issues

One of the advantages of incorporating distributed generation in distribution systems is the reduced losses. So the location and capacity of DG both play significant roles in the loss reduction; meanwhile the basic requirements of DG and distribution system should also be provided. Mathematical relationships of non-linear optimization problem which optimize the use of DG in distribution feeder (objective function) according to its operational conditions (constraints) are as follows:

$$\text{obj. Fun} = \min \sum_{i=1}^{n} \left(\frac{P_i^2 + Q_i^2}{V_i^2}\right) \times r_{i+1} \quad (4)$$

where n is the number of buses; Pi and Qi are the active and reactive power in the path between buses i and i + 1; r_{i+1} is the resistance in the path between buses i and i + 1.

Limits of voltage variation range are expressed as the following inequality constraint (in accordance with ±5% standard):

$$V_{min} < V_i < V_{max} \quad (5)$$

Where V_{min}, V_{max} are the minimum and maximum allowed voltages and V_i is the voltage of i-th bus.

Another constraint that adding a DG system necessitates is the constraint that limits the maximum load of the lines. This constraint is expressed as following inequality:

$$S_{i+1,i} < S_{i,i+1}^{max} > S_{i,i+1} \quad (6)$$

Where $S_{i,\ i+1}$ and $S_{i+1,\ i}$ are the apparent power at each side of the path between buses i and i + 1, and Smax is the maximum allowable power at that path.

Conditions and constraints of DG system are expressed as the two following inequalities:

$$S_{min}^{DG} < S_i^{DG} < S_{max}^{DG} \quad (7)$$

$$\text{p.f.}_{min}^{DG} < \text{p.f.}_i^{DG} < p.f._{max}^{DG} \quad (8)$$

Inequality (7) expresses the minimum and maximum power output of the generator, and inequality (8) expresses the minimum and maximum power factor of generator.

Another important issue in this optimization problem is the matter of recloser-fuse coordination after adding the DG system, so this coordination must be checked for each solution of this algorithm. If the coordination conditions are not met, the adaptive scheme must be used to modify the recloser-fuse coordination and if applying the adaptive scheme cannot guarantee the coordination, that solution is unacceptable.

VII. Simulation

In this paper, an actual medium voltage feeder located in Yazd power distribution network (Feeder 3 Abarkuh) was used for studies. Fig. 6 is the schematics of studied feeder in DIgSILENT environment. This figure shows the location of fuses (red dots) and 20 candidate locations for the installation of DG system (black squares).

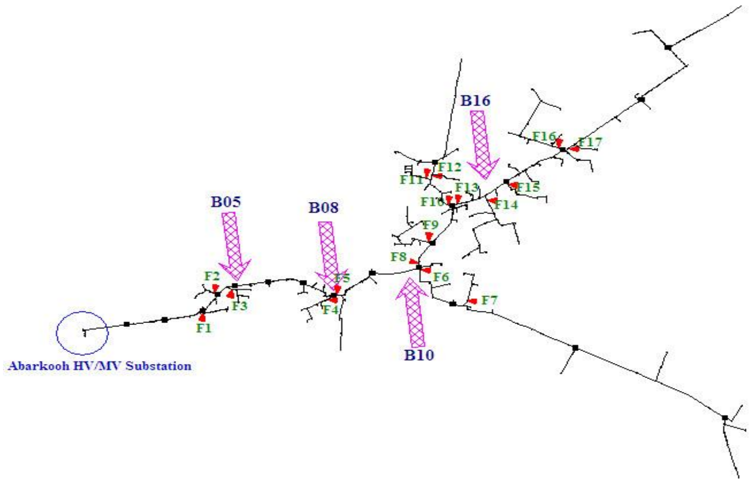


Fig. 6 Schematics of the studied feeder

7.1.Recloser characteristic

One recloser was located at the beginning of the feeder. Recloser characteristic was considered to be in the form of relationship (1). For recloser configuration, the relay was assumed to have extremely inverse characteristic. Current setting (MP) of OC relay (Ipickup) of recloser was defined as follows:

$I_{pickup} = OLF * I_n$ (9)

Where OLF is the overload factor which was considered to be 1.5 [8] and $I_n$is themaximum current passing through the recloser which can be obtained through load flow calculations.For the studied feeder this currents was calculated to 190 A.Therefore, I_{pickup} was calculated to 285 A. The time dial setting (TDS) of recloser was considered to be 0.5 for fast mode reclosing and1.5 for slow reclosing [8]. In this paper, TDS allowable range was considered to be 0.5 to 1 [8].

7.2. Fuse characteristic

Fuse characteristic was considered to be in the form of relationship (2). In this relationship, constant a was considered to be -1.8 [10]. for all fuses; the parameter b corresponding to each fuse was calculated separately by using relationships (2) and (3) and the method explained in section 2. These calculations were carried out without adding DG to the system. Assuming fault at different locations leads to the calculation of different (b)s for each fuse, therefore the highest calculated value should be selected for that fuse, otherwise the fuse with smaller b may operate sooner than recloser or other fuses. The time margin for fuse and recloser functions was considered to be 0.1 second [8]. Table 2 shows the values of b for each fuse.

Table 2.The values of constant b for the fuses in feeder 3 Abarkuh

Fuse name	i	n	Isc (A)	t-fast (s)	t-slow (s)	t-fuse (s)	B
F01	1	1	4934.394	0.108045	0.324134	0.216089	5.982
F02	1	1	4430.025	0.11945	0.35835	0.2389	5.942
F03	1	1	4001.737	0.132732	0.398196	0.265464	5.908
F04	1	1	2354.102	0.270585	0.811755	0.54117	5.803
F05	4	4	1032.946	1.222676	3.668027	3.178957	5.928
F06	2	3	1375.213	0.693602	2.080807	1.387204	5.791
F07	1	3	1375.213	0.693603	2.080808	1.040404	5.666
F08	3	4	1034.732	1.218341	3.655022	2.680349	5.855
F09	1	3	1576.04	0.537515	1.612546	0.806273	5.662
F10	1	3	1367.676	0.700913	2.10274	1.05137	5.667
F11	1	4	1222.546	0.871149	2.613447	1.219609	5.643
F12	1	4	1210.398	0.888456	2.665367	1.243838	5.644
F13	2	4	1034.732	1.218341	3.655022	2.193013	5.768
F14	1	4	1243.432	0.842661	2.527983	1.179725	5.642
F15	1	2	1167.464	0.954375	2.863126	1.590625	5.723
F16	1	3	1032.946	1.222676	3.668027	1.834014	5.689
F17	1	3	1034.732	1.218341	3.655022	1.827511	5.689

7.3. Simulation method

The contribution of DG units to the fault current depends on their type and electrical specifications. In this paper, we decided to use synchronous generator due to its continuous contribution to the fault current and also imported the DG and transformers parameter and specifications from a real DG system.

Three different scenarios are assumed for this simulation. Each scenario assumes a different capacity and location for the DG added to the studied network. According to Fig. 6 the following three scenarios are investigated:

Scenario1: 2 MW DG located at B05
Scenario1: 3 MW DG located at B10
Scenario1: 4 MW DG located at B16

The main task of DG is to produce active power, so the power factor of DG is assumed to be 0.95 for all scenarios. Also, all load flow calculations are based on the assumption that DG operates in PQ mode.

In all scenarios mentioned above, a short-circuit fault must be simulated for all the points downstream of each fuse, and then currents of fuse and recloser must be recorded. The relationships (1) and (2) must then be used to calculate and obtain the fuse operating time and the recloser's fast curve(if TDS value has been supposed equal to 0.5), and subsequently the difference between the operating time of recloser's fast-mode and that of fuse. The time margin for recloser-fuse coordination is 0.1 second, so a less than 0.1 value for this difference indicates the lack of recloser-fuse coordination, because in this situation ambient conditions such as temperature may cause the fuse to operate sooner, or fuse may get damaged and malfunction in later temporary faults.

The absence of an appropriate time margin between the operating time of the fuse (closest to the fault) and that of Recloser's fast-mode necessitates a change in TDS. Therefore, in accordance with the recloser-fuse coordination adaptive protection scheme presented in section 5, TDS must be multiplied by I_R/I_F ratio to get new TDS value.

In the case that this multiplication does not lead to an appropriate time margin, newly acquired TDS must again be multiplied by I_R/I_F ratio. The process must continue until reaching an appropriate time margin between fuse function and recloser function.

Tables3, 4 and 5 show the results of these steps for each defined scenario. Those fuses that had not a proper coordination margin (dark colored) were modified by adaptive protection scheme. The TDS of 4^{th} step, which was acquired by multiplying the TDS of 3^{rd} step by I_R/I_F ratio, led to an appropriate coordination margin for the fuse F1.

Table 3. The steps of adjusting TDS settings for the first scenario, 2 MW DG located at B05

Faulted Bus	I-recl	I-fuse	t-fuse	t-recl	dt1	TDS-new1	t-recl-new1	dt-new1	TDS-new2	t-recl-new2	dt-new2	TDS-new3	t-recl-new3	dt-new3
F01	4930.147	5525.449	0.176	0.108	0.07	0.45	0.097	0.079	0.4	0.087	0.089	0.36	0.078	0.098
F02	4427.971	5031.531	0.19	0.12	0.07	0.44	0.105	0.085	0.39	0.093	0.097	0.34	0.081	0.109
F03	3999.473	4593.973	0.207	0.133	0.07	0.44	0.117	0.09	0.38	0.101	0.106	0.33	0.088	0.119
F04	2232.404	2575.054	0.461	0.294	0.17	0.43	0.253	0.208	0.37	0.218	0.243	0.32	0.188	0.273
F05	2240.56	2584.463	0.611	0.293	0.32	0.43	0.252	0.359	0.37	0.217	0.394	0.32	0.187	0.424
F06	1620.717	1869.48	0.798	0.511	0.29	0.43	0.439	0.359	0.37	0.378	0.42	0.32	0.327	0.471
F07	1255.718	1448.457	0.947	0.827	0.12	0.43	0.711	0.236	0.37	0.612	0.335	0.32	0.529	0.418
F08	1591.803	1836.128	0.955	0.528	0.43	0.43	0.454	0.501	0.37	0.391	0.564	0.32	0.338	0.617
F09	1450.329	1672.94	0.724	0.627	0.1	0.43	0.539	0.185	0.37	0.464	0.26	0.32	0.401	0.323
F10	1248.472	1440.1	0.959	0.836	0.12	0.43	0.719	0.24	0.37	0.619	0.34	0.32	0.535	0.424
F11	1109.729	1280.061	1.122	1.057	0.07	0.43	0.909	0.213	0.37	0.782	0.34	0.32	0.676	0.446
F12	1098.182	1266.742	1.146	1.079	0.07	0.43	0.928	0.218	0.37	0.799	0.347	0.32	0.691	0.455
F13	1238.648	1428.768	1.228	0.849	0.38	0.43	0.73	0.498	0.37	0.628	0.6	0.32	0.543	0.685
F14	1129.599	1302.981	1.084	1.019	0.07	0.43	0.877	0.207	0.37	0.754	0.33	0.32	0.652	0.432
F15	1057.466	1219.776	1.471	1.165	0.31	0.43	1.002	0.469	0.37	0.862	0.609	0.32	0.746	0.725
F16	930.793	1073.66	1.712	1.52	0.19	0.43	1.307	0.405	0.37	1.124	0.588	0.32	0.972	0.74
F17	932.4652	1075.589	1.706	1.514	0.19	0.43	1.302	0.404	0.37	1.12	0.586	0.32	0.969	0.737

Table 4. The steps of adjusting TDS settings for the second scenario, 3 MW DG located at B10

Faulted Bus	I-recl	I-fuse	t-fuse	t-recl	dt1	TDS-new1	t-recl-new1	dt-new1	TDS-new2	t-recl-new2	dt-new2	TDS-new3	t-recl-new3	dt-new3
F01	4928.2992	5558.7346	0.174	0.108	0.07	0.44	0.095	0.079	0.39	0.084	0.09	0.35	0.076	0.098
F02	4427.6826	5073.0421	0.187	0.12	0.07	0.44	0.105	0.082	0.38	0.091	0.096	0.33	0.079	0.108
F03	3999.0862	4655.3788	0.202	0.133	0.07	0.43	0.114	0.088	0.37	0.098	0.104	0.32	0.085	0.117
F04	2349.0264	3045.7128	0.341	0.272	0.07	0.39	0.212	0.129	0.3	0.163	0.178	0.23	0.125	0.216
F05	2362.0025	2362.0025	0.718	0.269	0.45	0.5	0.269	0.449	0.5	0.269	0.449	0.5	0.269	0.449
F06	1743.8939	2483.6514	0.478	0.448	0.03	0.35	0.313	0.165	0.25	0.224	0.254	0.18	0.161	0.317
F07	1270.8991	1810.0129	0.634	0.807	-0.17	0.35	0.565	0.069	0.25	0.404	0.23	0.18	0.291	0.343
F08	1720.194	1720.194	1.074	0.459	0.62	0.5	0.459	0.615	0.5	0.459	0.615	0.5	0.459	0.615
F09	1572.4928	2328.4719	0.399	0.54	-0.14	0.34	0.367	0.032	0.23	0.248	0.151	0.16	0.173	0.226
F10	1364.2639	2138.7964	0.471	0.704	-0.23	0.32	0.451	0.02	0.2	0.282	0.189	0.13	0.183	0.288
F11	1164.0967	1824.9884	0.593	0.96	-0.37	0.32	0.614	-0.021	0.2	0.384	0.209	0.13	0.25	0.343
F12	1148.3614	1800.3198	0.609	0.986	-0.38	0.32	0.631	-0.022	0.2	0.395	0.214	0.13	0.256	0.353
F13	1357.4517	1357.4518	1.346	0.711	0.64	0.5	0.711	0.635	0.5	0.711	0.635	0.5	0.711	0.635
F14	1236.7294	2015.2548	0.495	0.852	-0.36	0.31	0.528	-0.033	0.19	0.324	0.171	0.12	0.204	0.291
F15	1162.2105	1950.6618	0.632	0.963	-0.33	0.3	0.578	0.054	0.18	0.347	0.285	0.11	0.212	0.42
F16	967.3503	1623.6072	0.813	1.401	-0.59	0.3	0.841	-0.028	0.18	0.504	0.309	0.11	0.308	0.505
F17	969.9333	1627.9424	0.809	1.393	-0.58	0.3	0.836	-0.027	0.18	0.502	0.307	0.11	0.307	0.502

Table 5. The steps of adjusting TDS settings for the third scenario, 4 MW DG located at B16

Faulted Bus	I-recl	I-fuse	t-fuse	t-recl	dt1	TDS-new1	t-recl-new1	dt-new1	TDS-new2	t-recl-new2	dt-new2	TDS-new3	t-recl-new3	dt-new3
F01	4926.8383	5668.2321	0.168	0.108	0.06	0.43	0.093	0.075	0.37	0.08	0.088	0.32	0.069	0.099
F02	4427.2267	5189.6593	0.18	0.12	0.06	0.43	0.103	0.077	0.37	0.088	0.092	0.32	0.076	0.104
F03	3998.546	4781.0973	0.193	0.133	0.06	0.42	0.112	0.081	0.35	0.093	0.1	0.29	0.077	0.116
F04	2347.5578	3215.5437	0.309	0.272	0.04	0.37	0.201	0.108	0.27	0.147	0.162	0.2	0.109	0.2
F05	2362.0025	2362.0025	0.718	0.269	0.45	0.5	0.269	0.449	0.5	0.269	0.449	0.5	0.269	0.449
F06	1742.0894	2693.5805	0.413	0.449	-0.04	0.32	0.287	0.126	0.21	0.188	0.225	0.14	0.126	0.287
F07	1241.0344	1918.8603	0.571	0.846	-0.28	0.32	0.541	0.03	0.21	0.355	0.216	0.14	0.237	0.334
F08	1720.194	1720.194	1.074	0.459	0.62	0.5	0.459	0.615	0.5	0.459	0.615	0.5	0.459	0.615
F09	1571.3934	2558.9031	0.337	0.54	-0.2	0.31	0.335	0.002	0.19	0.205	0.132	0.12	0.13	0.207
F10	1363.0855	2396.1882	0.384	0.705	-0.32	0.28	0.395	-0.011	0.16	0.226	0.158	0.09	0.127	0.257
F11	1144.9067	2012.6486	0.497	0.992	-0.5	0.28	0.556	-0.059	0.16	0.318	0.179	0.09	0.179	0.318
F12	1128.0208	1982.9645	0.511	1.022	-0.51	0.28	0.572	-0.061	0.16	0.327	0.184	0.09	0.184	0.327
F13	1357.4517	1357.4518	1.346	0.711	0.64	0.5	0.711	0.639	0.5	0.711	0.635	0.5	0.711	0.635
F14	1234.4305	2285.927	0.394	0.855	-0.46	0.27	0.462	-0.068	0.15	0.256	0.138	0.08	0.137	0.257
F15	1160.4588	2235.7777	0.494	0.966	-0.47	0.26	0.502	-0.008	0.13	0.251	0.243	0.07	0.135	0.359
F16	946.3244	1823.2196	0.66	1.467	-0.81	0.26	0.763	-0.103	0.13	0.381	0.279	0.07	0.205	0.455
F17	949.1403	1828.6446	0.656	1.458	-0.8	0.26	0.758	-0.102	0.13	0.379	0.277	0.07	0.204	0.452

7.3.1.Simulation results of recloser-fuse coordination

The previous section defined three different scenarios for adding a hypothetical DG to a real feeder. These scenarios considered different capacities and location for that DG. The studied feeder had seventeen fuses at different locations and one recloser at the beginning of the feeder. Locations of the short circuit were selected in such a way that results can almost be generalized to all parts of the feeder because the highest possible fuse fault currents were there. These points included the nearest bus downstream of a fuse so that under the fault condition that fuse would experience the maximum short circuit current. After performing the short circuit calculations for different parts of the feeder, the new fast reclosing TDS setting that ensured the minimum recloser-fuse coordination time margin was obtained.

Modern distribution systems that are equipped with advanced distribution automation are able to transfer data between measuring equipment, relays and control center. In these systems, intelligent electronic devices (IED) report the occurrence of a fault and the currents passing through lines to the control center. Using this information, the system applies the necessary changes to the recloser fast curve TDS to maintain coordination between fuses and recloser, in order to control fuse behavior regard for fuse saving rule against temporary faults.

7.4. Optimization of DG capacity and location in order to maintaining recloser-fuse coordination

In this section, BBO optimization algorithms introduced in section (6) is used to optimize the capacity of DG and its location on the studied feeder to minimize the losses while maintaining recloser-fuse coordination. In this section, DIgSILENT software is used to carry out load flow and short circuit calculations and MATLAB is used for optimization and protection coordination processes.

7.4.1. Objective function, constraints and variables of BBO algorithm

The goal of objective function considered in this paper is to reduce the losses of distribution network in the presence of two DG unit. Constraints that must be adhered to are discussed in subsection 6.1. Considering the high number of buses (at 70-80 meters intervals) in the studied feeder, checking all buses by optimization algorithm cause the search space to grow significantly, leading to a very time-consuming operation. Therefore 20 buses of this network were selected (B01 to B20) and DGs must be connected to one of those. The maximum number of species (S_{max}) was considered to be 25. The maximum rates of migration (E and I) were considered to be 1, the maximum mutation rate was considered to be 0.01 and elitism rate (the rate by which algorithm keeps the best solutions) was considered to be 2 species per iteration. Habitats were initialized with random values. The maximum number of iterations was set to 50, and this number was defined as the stop condition.

7.4.2. Optimization Results

After running the BBO optimization algorithm and reaching the stop condition, algorithm reported the following results describing the optimum location and capacity of two newly added DG units for minimizing the losses while maintaining the recloser-fuse coordination:
Location of first DG: Bus B08
Capacity of first DG: 2 MW
Location of second DG: Bus B16

Capacity of second DG: 2 MW

The optimal locations of DG units in terms of maintaining the recloser-fuse coordination protection and also maintaining the operation constraints set by the BBO algorithm are shown in Fig. 6. Fig. 7 shows the curve expressing the process of obtaining the optimal solution.

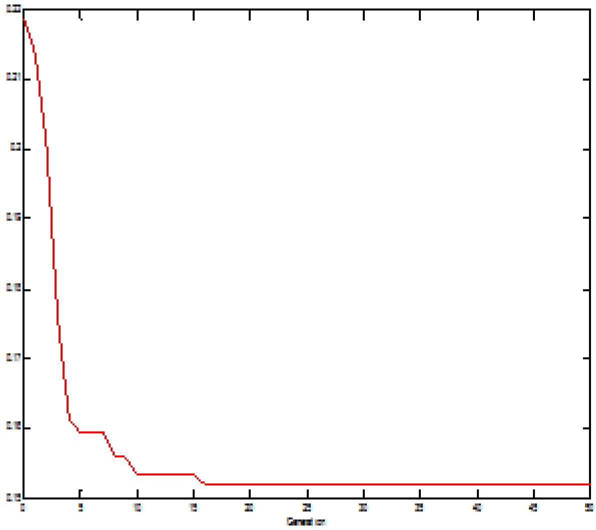


Fig. 7 The changes curve in the objective function value

7.4.3. Recloser-fuse coordination after optimization

Table 8shows the TDS settings for the fast reclosing operation that maintains the recloser-fuse coordination. According to the Table 8, it can be seen that when TDS is 0.5 only three fuses are coordinated with the recloser, and as the TDS value decreases the number of fuses that are coordinated with the recloser increases. Ultimately, multiplying the third TDS by I_R/I_Fratio gives the new TDS as 0.24 which increases the coordination time margin of the first fuse to 0.104 second.

Table 8. Recloser protection settings and operating times of fuse and recloser for the optimized DG units

Faulted Bus	I-recl	I-fuse	t-fuse	t-recl	dt1	TDS-new1	t-recl-new1	dt-new1	TDS-new2	t-recl-new2	dt-new2	TDS-new3	t-recl-new3	dt-new3
F01	4925.9696	5872.8432	0.158	0.108	0.05	0.42	0.091	0.067	0.35	0.076	0.082	0.29	0.063	0.095
F02	4426.5517	5401.2461	0.167	0.12	0.05	0.41	0.098	0.069	0.34	0.081	0.086	0.28	0.067	0.1
F03	3997.8148	4986.5807	0.179	0.133	0.05	0.4	0.106	0.073	0.32	0.085	0.094	0.26	0.069	0.11
F04	2347.4056	3398.9839	0.28	0.272	0.01	0.35	0.19	0.09	0.24	0.13	0.15	0.17	0.092	0.188
F05	2360.0105	2904.5512	0.495	0.27	0.23	0.41	0.221	0.274	0.33	0.178	0.317	0.27	0.146	0.349
F06	1658.4819	2560.1177	0.453	0.49	-0.04	0.32	0.314	0.139	0.21	0.206	0.247	0.14	0.137	0.316
F07	1201.4807	1854.6672	0.607	0.902	-0.3	0.32	0.577	0.03	0.21	0.379	0.228	0.14	0.252	0.355
F08	1630.4144	2006.6107	0.814	0.505	0.31	0.41	0.414	0.4	0.33	0.333	0.481	0.27	0.273	0.541
F09	1474.0665	2334.7518	0.397	0.608	-0.21	0.32	0.389	0.008	0.2	0.243	0.154	0.13	0.158	0.239
F10	1256.6039	2066.6036	0.501	0.825	-0.32	0.3	0.495	0.006	0.18	0.297	0.204	0.11	0.182	0.319
F11	1075.668	1769.0376	0.627	1.125	-0.5	0.3	0.675	-0.048	0.18	0.405	0.222	0.11	0.248	0.379
F12	1061.3816	1745.5422	0.643	1.156	-0.51	0.3	0.694	-0.051	0.18	0.416	0.227	0.11	0.254	0.389
F13	1248.1583	1536.1541	1.078	0.836	0.24	0.41	0.686	0.392	0.33	0.552	0.526	0.27	0.452	0.626
F14	1127.9758	1902.8875	0.548	1.022	-0.47	0.3	0.613	-0.065	0.18	0.368	0.18	0.11	0.225	0.323
F15	1052.5675	1810.8459	0.722	1.176	-0.45	0.29	0.682	0.04	0.17	0.4	0.322	0.1	0.235	0.487
F16	883.3885	1519.7889	0.916	1.699	-0.78	0.29	0.985	-0.069	0.17	0.578	0.338	0.1	0.34	0.576
F17	885.6173	1523.6233	0.912	1.69	-0.78	0.29	0.98	-0.068	0.17	0.575	0.337	0.1	0.338	0.574

VIII. Conclusion

Most electricity distribution companies tend to protect the fuses from temporary faults according to fuse saving rule by configuring the reclosers upstream of the fault to cut off feeders before any damage to their fuses. Adding a DG unit to a normal distribution network causes the distribution feeder fault current to increase and therefore interferes with the mechanisms protecting the fuses from temporary faults by causing miscoordination between fuses and reclosers. As a result, the issue of recloser-fuse coordination in the presence of DG units has become one of the major concerns of power distribution companies and grid integrity protection authorities.

In this paper, an idea based on adaptive digital relay was implemented to achieve proper fuses-recloser coordination in the presence of DG units in radial distribution systems. This idea is based on changing the time range of recloser by the use of I_{fuse} /$I_{recloser}$ ratio. Mentioned idea involved checking for recloser-fuse miscoordination at the time of a temporary fault in a DG-containing network and then multiplying the TDS by I_{fuse} /$I_{recloser}$ ratio to decrease the recloser fast-mode operating time. The process of changing TDS continues until reaching an appropriate margin between the fuse operating time and recloser fast-mode operating time. This method modifies the recloser's fast characteristic without any change in fuse characteristics, and therefore prevents the fuse from melting before recloser performs its fast-mode operation. The technique used in this paper leads to an improved recloser-fuse coordination margin.

This paper studied an actual feeder located in Abarkuh-Yazd to ensure that simulations would be more close to reality. Generators modeled in simulations were also based on actual specifications of DG units gathered from a manufacturer of small-scale generators. The described method for adaptive modification of recloser was then tested for different scenarios which assumed different capacities and locations for the DG unit. Results of these tests showed the possibility of applying adaptive modification scheme for all tested scenarios.

To perform a more thorough study on the issue, biogeography-based optimization algorithm (BBO) was sued to optimize the location and capacity of two DG units on the studied feeder. Objective of this optimization was to minimize the losses and it incorporated the recloser-fuse coordination as a constraint along with other operational constraints.

Using the technique described in this paper requires multiple measurements and the minimum number of measurements is as much as the number of fuses in the system. It should be mentioned that in the presence of DG units, maintaining the fuse protection rule requires the recloser to have synchronization checking equipment.

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