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# Calculation of maximum DG's capacity according to their location for remaining the protection coordination in distribution networks

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**Abstract**

Traditional electric distribution systems are radial in nature. These networks are protected by very simple protection devices such as over-current relays, fuses, and reclosers. Recent trends in distributed generation (DG) and its useful advantages perfectly can be achieved while the relevant concerns are deliberately taken into account. For example, penetration of DG disturbs the radial nature of conventional distribution networks. Therefore, protection coordination will be changed in some cases, and in some other cases it will be lost. In this paper, a new approach is presented for determining the maximum capacity of DG for maintaining the coordination of distribution system's protection devices. In the suggested approach, the contribution of DGs in fault current is limited through considering mathematical equations of characteristics of protection devices. All steps from the beginning to the end were implemented on a simple distribution network using MATLAB and DIgSILENT Power Factory and finally the numerical results are presented in order to confirm the authenticity of suggested approach.

**Keywords:** Distribution generation, Energy, Recloser, Protective device**,** Power.

## Introduction

Distributed Generation (DG) is defined as energy sources connected to distribution systems. The growing usages of the distributed generation resources in distribution networks are considered recently because of its useful benefits such as: cost reduction of energy generation and high efficiency, loss reduction, increasing of power quality and network's reliability, as well as environment considerations, *etc.*, Micro turbines, small hydro power plants, wind power plants, fuel cells, photo voltaic arrays are the main types of distributed generation (Javadian & Haghifam, 2008; Seyed Ali Mohammad Javadian & Maryam Massaeli, 2011; Navid Khalesi & Seyed Ali Mohammad Javadian, 2011; Seyed Ali Mohammad Javadian & Mahmood Reza Haghifam, 2011).

Although presence of such generation units has many useful advantages, it challenges distribution systems with variety of problems that certainly deserves closer considerations such as complicated control, operation, protection effects (Javadian & Haghifam, 2008). These distinguished difficulties are as follows: a). False tripping of feeders (sympathetic tripping), b). Nuisance tripping of production units, c). Blinding of protection, d). Affecting short circuit levels, e). Unwanted islanding, f). Prohibition of automatic reclosing, g). Unsynchronized reclosing.

Hence there is a need exploring the effects of the DG's penetration on protection system of the distribution networks. The impact of distributed generation on distribution networks depends on location, type and size of DGs, and presence of these kinds of energy resources will change the protection coordination range in some cases, and in some other cases it will result in losing it (Barker & de Mello, 2000).

Upgrading the protection system of distribution networks in order to have perfect operation in presence of DG is a very difficult job and so many efforts have been made in this area, but nobody can surely diagnose the best protection scheme up to now (Brahma & Girgis, 2001).

Protective devices may need to be changed or have new settings but requires large investment, and cannot be established in a short period. In this paper, the protective devices and protection coordination is discussed. Then, a new approach is presented for determining the maximum capacity of distributed generation for maintaining the coordination using the equations of general characteristics of protective devices. The maximum injected DG current should be calculated for the worst case of fault occurrence in the feeder. In order to distinct the career a typical distribution feeder is implemented using DIgSILENT Power Factory.

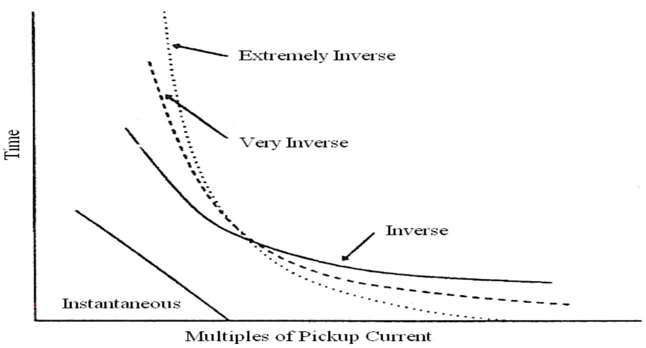
## The conventional protection system

### *Protection devices and characteristics*

A wide variety of equipment is used to protect distribution networks. The particular type of protection used depends on the system element being protected and the system voltage level. The devices most used for distribution system protection are over-current relays, reclosers, and fuses. Relays operate when the current reaches a predetermined value and based on relay operating characteristics, over-current relays can be classified into two main groups: instantaneous and inverse time. The characteristic curves of these types are shown in Fig.1.

Fuses are one of the most common forms of protection used to deal with excessive currents. A fuse has two characteristics: "Minimum Melting (MM) and

*Fig. 1. Operation characteristics of over-current relays*




Total Clearing (TC)". MM characteristic gives the time, in which fuse can be damaged for a given value of fault current. TC characteristic gives the fault clearing time of fuse for given value of fault current. Fuses contain inverse-time over-current characteristic. The straight line $I^2t$ log-log plot is usually expressed for the minimum melting and total clearing times for fuses. From the fuse characteristic on the log-log curve, it is better to approximate by the second order polynomial function. However, the interested range of the curve approaches a straight line within $I_{fmin}$ and $I_{fmax}$ which is called the coordination range. Moreover, a linear equation can be simply applied to reduce the calculation task. The general equation describing the fuse characteristic curve can be expressed as the following equation:

$$log(t) = a.log(I) + b \qquad (1)$$

where

t and I are the associated time and current, and the coefficients a and b can be known from the curve fitting (Chaitusaney & Yokoyama, 2005a,b). Circuit breakers and reclosers usually located at beginning and middle of main feeders. They are normally equipped with inverse-time over-current trip devices. The general characteristics of such devices can be shown as the following equation: (IEEE Std C37, 112-1996)

$$t(I) = \frac{A}{M^{\rho} - 1} + B \qquad (2)$$

where

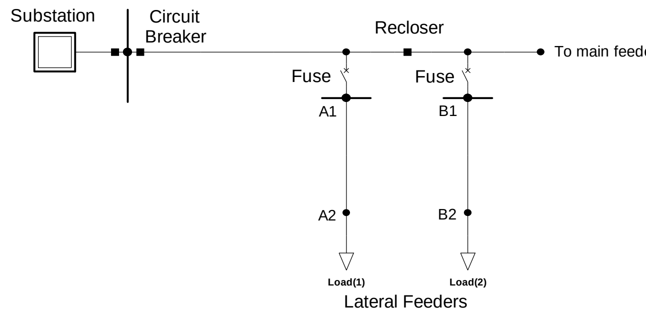
$t$ : Operating time of inverse-time over-current device; $I$ : Fault current seen by the device; $M$ : Ratio of $I/I_{pickup}$ ($I_{pickup}$ is relay current set point); $A, B, \rho$ : Constants for selected curve characteristics which are indicated in Table 1 from (IEEE Std C37.112-1996).

In typical distribution systems, all demand loads are supplied from a bulk supplying point, distribution substation, connected to transmission systems. Then, the electricity is transferred to distribution system via

*Table 1. Different over-current inverse time constants*

| Characteristic | A | B | $\rho$ |
|---|---|---|---|
| Inverse | 0.0515 | 0.1140 | 0.02 |
| Very Inverse | 19.61 | 0.491 | 2 |
| Extremely Inverse | 28.2 | 0.1217 | 2 |

*Fig. 2. A typical distribution feeder*




transformers. For distribution load points, the electricity is transmitted through normally radial distribution feeders and then through lateral feeders and transformers.

Fig.2 shows a typical radial distribution feeder with related protection devices simulated in DIgSILENT software in order to describe protection coordination scheme. This feeder will be utilized throughout the whole steps in this approach.

*Fuse-recloser coordination*

Fig.3 shows traditional fuse-recloser coordination in distribution systems. Fig.3(a) shows a fuse in lateral feeder after recloser located on main feeder. In order to have a correct operation, the fuse must be coordinated with upstream recloser on the main feeder. The coordination philosophy here is that the fuse should only operate for a permanent fault on the load feeder. For temporary fault, recloser should disconnect the circuit with fast operation and give the fault a chance to clear. Only if the fault is permanent, the fuse should be allowed to open. This way, the load feeder does not get disconnected for every temporary fault. Recloser also provides back up to fuse through slow mode.

*Fig. 3(a). Fuse-recloser arrangement*

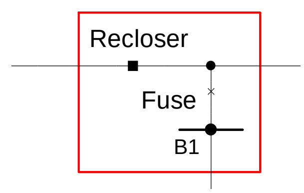
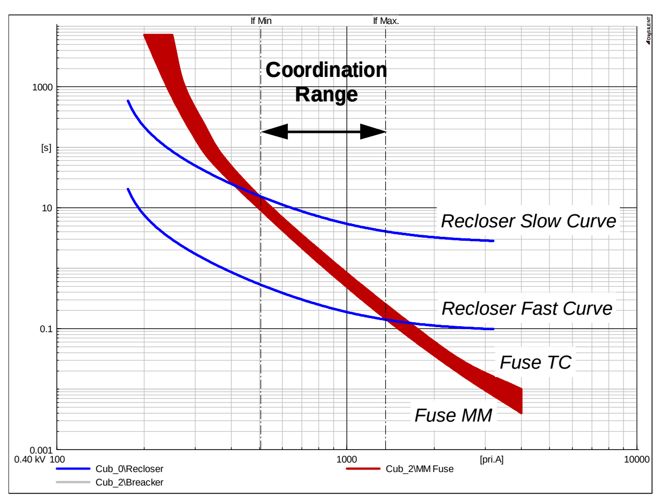



*Fig. 3(b). Fuse-recloser coordination range*



Since temporary faults constitute 70% to 80% of faults occurring in distribution system, this arrangement improves the reliability and decreases the maintenance cost. Fig.3(b) shows the fuse-recloser coordinated graph regarding the implemented feeder (Fig.2) for all fault currents within $I_{fmin}$ (minimum short circuit in B2) and $I_{fmax}$ (maximum short circuit in B1). This is called the coordination range. Therefore, as long as the fault current values for faults on lateral feeder are within coordination range, the fuse-recloser coordination is accepted. In Fig.3(b), we see that the fast characteristic of the recloser lies below the MM characteristics of fuse between $I_{fmin}$ and $I_{fmax}$ .Therefore, in coordination range the recloser operates in less time than the time sufficient to damage the fuse (Brahma & Girgis, 2001).

Typical operating sequence of a recloser is F-F-S-S (where F stands for fast and S for slow). There is an interval between each operation when the recloser remains open. If the fault is temporary, it will clear before the recloser closes after the second fast operation (if the 'open' time of recloser is assumed as one second, this time will be more than two seconds). If the fault persists after the recloser closes following the second fast operation, then the fault has to be a permanent one and hence fuse must operate to cut it off. As shown in Fig.3(b), the TC curve of the fuse is below slow curve of recloser in coordination range. Therefore, for a permanent fault, fuse will open before recloser operates in slow mode. If the fuse fails to operate, recloser will back it up by operating in slow mode and finally locking out. The coordination curves of recloser and fuse have to be modified (Brahma & Girgis, 2001; 2004).

**Effect of distributed generation**

Penetration of DG currents results in not having a radial distribution network, and consequently losing protection coordination. Fig.4 shows the main effect of DGs, which is contributing in fault currents. Hence, presence of these kinds of energy resources will change the protection coordination range in some cases, and in some other cases it will result in losing it. Maximum and minimum fault currents for a fault on the load feeder will change and for any fault on load feeder, fuse will see more current than the recloser. In addition, as conventional protection, a temporary fault, occurring mostly at lateral feeder, should be discriminated by the fast operation of recloser. However, this conventional scheme may not be held when DG is connected at the end of the feeder. It is possible that this temporary fault will be cleared by the lateral fuse, and be changed to a permanent fault. These undesirable operations of protective devices called "Fuse Blowing" (Fig.4) and certainly decrease the system reliability.

*Fig. 4. Fault currents contribution*

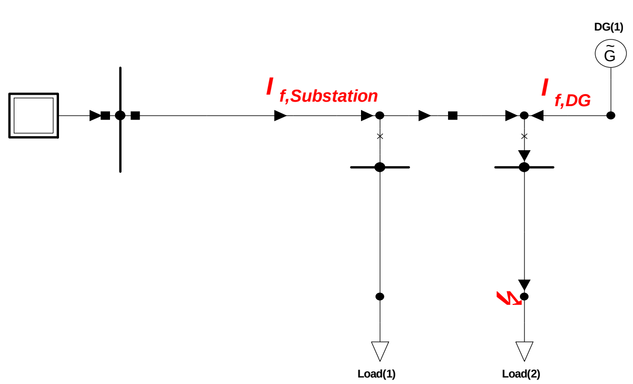
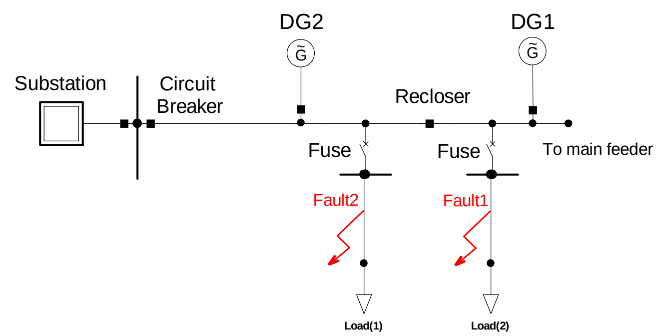



*Fig. 5. Alternative cases*




For clarifying and explaining in consequence of injected current, different options depend on placement of DG toward the recloser, four cases are considered which have indicated in Fig.5 & Table 2. In the table, the notation IR and IF mean fault current seen by recloser and fuse respectively, and $I_S$ and $I_{DG}$ mean fault current flowing from utility substation and DG respectively.

*Table 2. Alternative cases*

| Case | DG Unit | Fault location |
|---|---|---|
| 1 | DG 1 | Fault 1 |
| 2 | DG 1 | Fault 2 |
| 3 | DG 2 | Fault 1 |
| 4 | DG 2 | Fault 2 |

In case 1, fault current seen by the fuse is vector summation of both fault currents from the substation and the DG. It means that the problem will occur whenever both DG source and fault position are located behind the recloser. This is the case of fuse blowing above mentioned.

In case 2, DG is after the recloser and the fault location is before it. In this case, reverse current flows through the recloser. The fuse should operate first. Thus, if the recloser was not equipped with the directional over current relay, DG size should be considered in such a way that recloser fast curve does not disconnect the rear circuit.

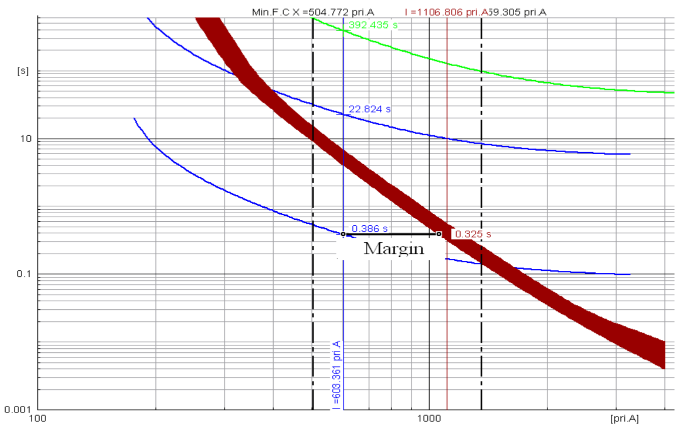
For case 3, the same fault current flows through the recloser and the fuse. Therefore, increasing the current will result in changing the coordination range, and no longer will maintain the coordination protection. It should be taken into consideration.

At last, in case 4, DG and fault location both are in the rear of recloser and the fault current from both, the substation and the DG, will flow to fuse directly and the recloser will detect nothing. Fuse blowing will not occur in this case. As a result, only fuse blowing from cases 1, 2, and 3 will be investigated.

**Calculating the maximum capacity**

It is true that protective devices may need to be changed or have new settings. However, this requires large investment, and cannot be established in a short period. One of the solutions regarding the fuse blowing is limiting the contribution of DG, instead of replacement or new settings. In the following, a method considering set of protection equation constraints will be discussed to keep the existing devices unchanged.

*Fig. 6. Coordination margin after connecting DG*




As shown in Table 2, there is a difference between current flowing through the fuse and the recloser because of contributing the DG in feeding the fault location. Naturally, the disparity between these currents will depend on the size and type of DG and its placement on the main feeder. The larger DG size, the more fault current. Fig.6 illustrates the currents flowing through recloser and fuse in the typical distribution feeder mentioned in Fig.2. If the difference between $I_R$ and $I_F$ exceeds the margin, for a certain fault current, fuse will be blown before the first closure attempt of the recloser and consequently the coordination will be lost.

For determining the maximum capacity of DG, the following procedure can be applied: Based on equations 1 and 2, $I_F$ and $I_R$ can be calculated for each specified time. In compliance the coordination philosophy, described in section 2.2, considering recloser and fuse operation at the same time, $I_{fuse,margin}$ can be achieved by vector summation of DG and distribution substation currents. This value must not be more than the mentioned criteria. In other word:

$$I_S + I_{DG} < I_{fuse,\,margin} \qquad (3)$$

Where

$I_S$: fault current from utility substation; $I_{DG}$: fault current from DG;

$I_{fuse,margin}$: current seen by fuse, considering the margin

Replacing equation 1 in 3, and rearranging the following equation will be achieved:

$$I_{DG} < 10^{((\log(t)-b)/a)} - I_S \qquad (4)$$

Where depend on cases described in last section, time comes from (3). For the case 1, time, t, comes from (5) where the fault current seen by the recloser is equal with the fault current flowing from the substation.

$$t(I) = \frac{A}{(I_S / I_P)^P - 1} + B \qquad (5)$$

For the case 2, time, t, comes from (6) where the fault current seen by the recloser is just supplied by DG.

$$t(I) = \frac{A}{(I_{DG} / I_P)^P - 1} + B \qquad (6)$$

At last for the case 3, time, t, comes from (6) where the fault current seen by the recloser is the summation of the fault currents from both the substation and the DG.

$$t(I) = \frac{A}{(I_S + I_{DG} / I_P)^P - 1} + B \qquad (7)$$

From (4) together with (5), (6), or (7), the size of DG can be determined by the transformation of current to the apparent power limit or the size of DG. In this paper, short-circuit capacity (MVA) is assumed to determine the maximum capacity of DG (Chaitusaney & Yokoyama, 2005a,b).

$$Short-Circuit \quad MVA = \sqrt{3} \times V_{DG} \times I_{DG} \qquad (8)$$

By substituting (4) into (8), the maximum capacity of DG, $S_{DG}$, can be obtained as follows.

$$S_{DG} < \sqrt{3} \times V_{DG} \times \left(10^{((\log(t)-b)/a)} - I_S\right) \qquad (9)$$

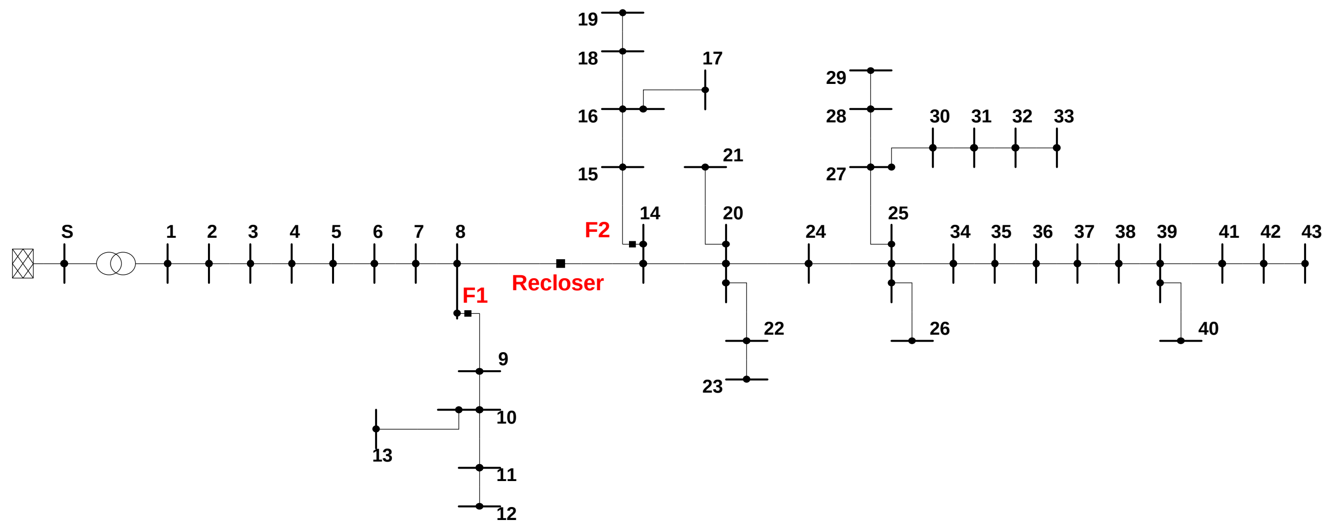
Where t , depends on the case comes from (5),(6) or (7).

On a necessary note, regarding the worst condition of the type and location of fault occurrence, maximum running current through the protective devices would be determined throughout the procedure in this approach. Therefore, the beginning of the feeder as location and symmetrical three-phase short circuit should be chosen in the equations.

**Case study**

To show the accuracy in operation of proposed approach, this part deals with real data of an existing distribution network which belongs to some part of a large distribution system of a city named Shiraz in Iran. The studied part of network in question has been simulated using Power Factory software application and authenticity of proposed approach has been investigated on this network. The sample distribution network is named "Sanayeh 4" which is a medium voltage feeder with 12335m in length and is supplied through a 63/20 kV sub-transmission substation named "Sanayeh Substation", located in a large city in south of Iran, named Shiraz. The sub-transmission substation is located near to "Sanayeh Square" in Shiraz and it's forth feeder supplies three parts of Shiraz named "Moali Abad", "Shahrak-e-Bahonar", and "Farhang Shar". This feeder supplies 34 distribution substations, including 3 ground and 31 aerial ones.

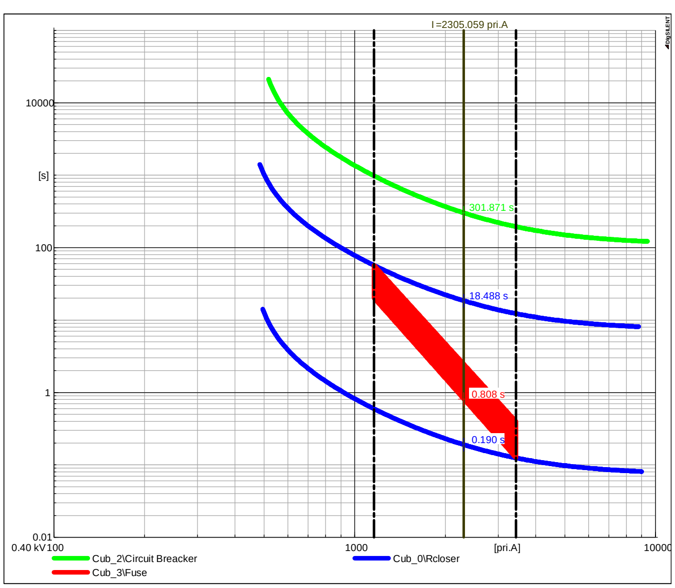
*Fig. 7. Simulated single line diagram of the studied distribution feeder in Power Factory*




All the data of this sample network has been extracted from MODEC software. MODEC stands for "Mechanization and Optimization of Distribution Electrical Calculations" and is a large software application, targeted at performing engineering calculations and optimizations of distribution networks, as its name suggests. The application has been developed in Ghods Niroo Consulting Engineering Company, a well-known consulting engineering company in Iran, active in consultancy projects throughout the country and adjacent countries in the fields of generation, transmission, distribution of electric power, hydro power and dams, oil and gas.

Fig.7 shows the single line diagram of this feeder that has been implemented by Power Factory for simulation purposes of performed studies.

*Fig. 8. Coordination range before connecting DG*




In order to determine the maximum capacity for the DG, cases 1 and 2 among the different cases in table 2 must be taken into consideration. The numerical implementation in compliance with the operational characteristics which are driven in (1) and (2), has been applied on the simulated feeder and the following equations is obtained (descending, recloser fast, fuse MM, and fuse TC characteristics):

$$t(I) = \frac{2.8395}{(\frac{I}{450})^2 - 1} + 0.0745 \qquad (10)$$

log(t)= -4.564×Log(I) + 15.893 (11)

log(t)= -4.497×Log(I) + 15.932 (12)

Fig.8 shows the coordination scheme in the case of fault occurrence before injecting DG's current into the feeder carried out by Power Factory.

Base on described approach and substituting (10), (11), and (12), the following inequality obtained. Consequently, solving depends on different cases, the maximum capacity is determined.

$$I_{DG} \le 10^{\left[\frac{Log(559912.5 - 0.0745 I^2_R) - Log(I^2_R - 1) - b}{a}\right]} - I_S \qquad (13)$$

Finally, acceptable value for $I_{DG}$ in each case can be calculated by substituting $I_S$ according to $I_{DG}$ and consequently solving the inequality.

Candidate points for installation of DG in above mentioned network contain buses 12, 23, and 40, and the aim is determining maximum capacity of DG based on given options. Obviously, considering bus 12 as a candidate location, all above mentioned calculation procedure for case 3 should be done and considering buses 23, 40 as candidate buses, calculation procedure for case 1 and case 2 should be done. For example, the maximum installed capacity in bus 12, for maintaining the existing recloser-fuse coordination in the network is obtained from (14), and the maximum installed capacity in bus 40, (15), (16) should be calculated and then, minimum value is defined as acceptable value.

$$I_{DG} \leq 10^{\left[\frac{Log(559912.5-7.45I^2_{DG})-Log(100I^2_{DG}-1)-11.435)}{-4.497}\right]} \quad (14)$$

$$I_{DG} \leq 10^{\left[\frac{Log(559912.5-6.0345I^2_{DG})-Log(81I^2_{DG}-1)-11.329)}{-4.564}\right]} \quad (15)$$

$$I_{DG} \leq 10^{\left[\frac{Log(559912.5-0.0745I^2_{DG})-Log(I^2_{DG}-1)-11.435)}{-4.497}\right]} \quad (16)$$

All above mentioned stages have applied on the simulated feeder using Power Factory for simulation, load flow study and short circuit analysis, and MATLAB for mathematic calculations. The result of study revealed that the maximum capacity for installing DG in the studied feeder is 591 KVA in bus 40, which is approximately 12.5 percentage of the network's total peak load.

*Fig. 9. Coordination range after installing calculated capacity*

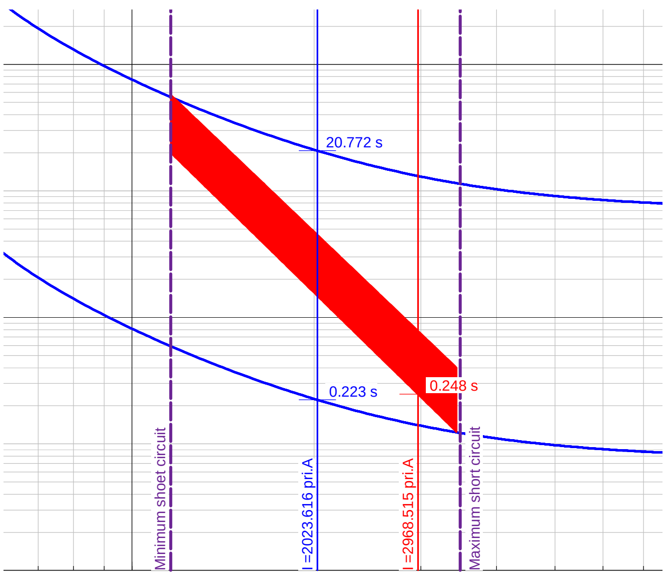



Fig.9 shows the protective devices coordination, after replacing calculated size, carried out by Power Factory software in a logarithmic diagram. As shown in the figure, for a three-phase short circuit at the beginning of the feeder, the recloser disconnects the current in 0.223s which is smaller in comparison with the fuse minimum melting time (0.248s).

**Conclusions**

After a brief overview on protection coordination between fuse and recloser, the effect of DGs on this coordination has been analyzed and restriction of DG sources has been suggested in order to keep the coordination in conventional distribution systems. Finally, the authenticity of applied method has been verified by Power Factory software. Numerous algorithms have been demonstrated to discover the optimum placement of the distributed generation resources in distribution systems. Considering the mentioned equations the suggested approach can play a supplementary role in sizing and locating of DGs. Implementing the suggested approach, allocating DGs at the end of distribution feeders is recommended.

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