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Application of Risk Analysis in Circuit Breaker Allocation 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 re-closers. The presence of distributed power generation causes the researches in this area to be considered more daily. One of the most interesting topics is this area is the protection of distribution networks that are connected to distributed generators. Recent trends in distributed generation (DG) and its useful advantages perfectly can be achieved while the relevant concerns are deliberately taken into account. Up to now, many papers have been published in this area, and in each paper some conflicts that DGs may make in the operation of protection system in distribution networks have been investigated. Also, some solutions have been presented in some other works. In this paper, a new method for optimal placement of circuit breakers (CBs), which are one of the main protective devices in distribution networks including DG, has been presented. In the proposed method, risk analysis is used to optimize the location of circuit breakers on the distribution feeders.

Keywords: Distributed Generation, Distribution System, Reconfiguration, Protection, Risk Analysis

INTRODUCTION

Traditional electric distribution systems are radial in nature, and are supplied through a main source, therefore it is simple to design protection scheme for such networks. Recently, great attention has been paid to applying Distributed Generation (DG) throughout electric distribution systems, and presence of these generation units results in not having a radial distribution network, consequently raises some problems such as losing coordination of protection devices. [1]-[8]

Presence of distribution generation and applying renewable energies in distribution networks has been one of the most noticeable subjects for electrical engineers in recent years. DGs are distributed generation units of electric power that are connected to distribution network. Compared with large generators and power plants, they have smaller generation capacity and run at lower operational costs. Application of DGs has many advantages like enjoying economic considerations in comparison with development of large power plants, reducing environmental pollution, having high efficiency, improving the quality of supplying consumers with electricity, reducing loss in distribution systems, improving voltage profile, freeing network capacity and so many other advantages. Hydro and wind turbine, solar thermal, photovoltaic arrays, fuel cells, biomass gasification, micro-turbines, battery storage, string engine and geothermal are the most significant technologies for distributed generation. Due to small generation capacity, it is not economical to transfer their energy productions through the power transmission lines. So, DGs are generally connected to distribution systems. [9]

When DG units are connected to a distribution network, the system will be radial no longer and this means losing the existing coordination among network protection devices. The extent in which a DG affects protection coordination depends on DGs' capacity, type and installation location of them. Due to generation capacity and installation location of DG, there are ranges in which protection coordination is maintained and in some cases no protection coordination can be achieved. [10]

Generally, problems that arise due to application of DGs are: false tripping in feeders, false tripping in generation units, protection blinding, increasing and decreasing short circuit levels, undesirable network islanding and preventing automatic and asynchronous reclosing [9]-[12]. Appearance of these problems depends on the characteristics of network and DGs and in most cases network protection scheme must be thoroughly changed in order to avoid the mentioned difficulties. Such changes may be complicated, since it is needed to model whole distribution system including distribution network in addition to DG, consequently obtaining the best protection scheme is still difficult. [13]-[15]

Recently, many papers have been published in this area, and in each paper some conflicts that DGs may make in the operation of protection system in distribution networks have been investigated. Also, some solutions have been presented in some other works. [1]-[12], [16]-[28]

A new protection scheme for distribution systems in presence of DGs is proposed in [1]. In the proposed scheme, system's protection is carried out through a computer-based relay which is installed in sub-transmission substation. The relay determines system's status after it receives the required network data, and in the case of fault occurrence it diagnoses its type and location using some trained MLP neural networks, and finally issues the proper commands for protection devices to clear the fault and to restore the network [1].

The field of risk analysis has assumed increasing importance in recent years given the concern by both engineers and scientists in most technical issues [29]-[37]. Risk analysis encompasses three interrelated elements: risk assessment, risk perception and risk management [29].

Risk assessment encompasses studies that estimate the chances of a specific set of events occurring and/or their potential consequences. Scientists and engineers need to provide the users of these data with a picture of what we know regarding the nature of a particular risk and the degree of uncertainty surrounding these estimates. They also have to be sensitive to their role as assessors of these estimates [30].

Traditional risk assessment focuses on losses that are often measured in monetary units. Risk perception is concerned with the psychological and emotional factors that have been shown to have an enormous impact on behavior [31].

In developing risk management strategies for reducing future losses there is a need to incorporate the data from risk assessment studies and the factors that have been shown to influence risk perception. Since a number of studies indicate that people have difficulty processing data regarding uncertain events, this poses challenges as to how one can effectively communicate information on the risk to the public. The use of exceedance probability curves can indicate the uncertainties surrounding a particular risk [32].

Following, the proposed protection scheme in [1] is described first, and then, the suggested method for optimal placement of protective devices is explained. For explanation of the proposed method, a sample distribution network including one DG is considered and all steps of the method are implemented on it.

The Protection Algorithm

The general idea of the proposed scheme is based on dividing the distribution system into several zones. Zoning is done through considering locations and generation capacities of DGs along with network loads. After network zoning and determining zones' boundaries, some switches which are capable of operating repeatedly and quickly and are also able to receive remote signals, are placed between each two zones of the system. These switches must also be equipped with check-synchronization relays. To implement the protection scheme, it is required to place a computer-based relay with high processing power and large storage capacity in supplying substation (sub-transmission substation) of the distribution network. The computer-based relay installed in sub-transmission substation holds the main responsibility of system protection and operates through steady monitoring of the currents flowing through some specific points of network. The specific points of network that their currents must be measured and monitored continuously are:

1. All currents flowing through all DGs and main supplying source;
2. Currents flowing through isolating switches of zones;
3. Currents flowing through all network laterals excluding those laterals containing DGs;

In addition to the currents that are measured online and the relay is provided with them continuously, the following data must also be provided and stored in relay's memory as permanent specifications of network:

1. Technical specifications of all network's equipment such as distribution substations, transmission lines, existing protection devices and DGs;
2. Estimated hourly load curve for all loads of network;
3. All data regarding network zoning and the locations of isolating switches;
4. All data regarding operation of relay for different faults;

Network Zoning Approach

For applying the zoning procedure in the distribution system, it is considering one zone for each DG, starting from the beginning of feeder, and each zone extends to the end of feeder as long as the DG within that zone is capable of supplying average load of that zone. When average load of substations located in the zone exceeds generation capacity of zone's DG, zone border finishes, and two circuit breakers are installed in the beginning and in the end of zone points. In the case that there exists a second DG located within the supplying limit of first zone's DG, and as long as zone's average load does not exceed generation capacity of first DG, while moving towards end of feeder, the second DG is regarded within the same zone and zone border extends as far as the zone's average load does not exceed summation of two DG's capacity.

Fault Location Determination

In [1], through offline calculation, 4 MLP neural networks are trained with the proper input data which is gathered by system modeling and performing short circuit calculations in different locations and with various fault impedances. Then, in case of a fault occurrence, through online calculation, the accurate type and location of the fault are determined by the main relay.

In order to determine the fault type, only the 3 phase current of the main source is used. At this point, there is no need to ANN and it can be determined with normalizing 3 phase output current of the feeding substation.

After recognizing the fault type, its location should be determined. In this paper, MLP neural network is used for specifying exact location of the fault.

After recognizing fault type by its corresponded unit, the trained neural network of this kind of fault is activated and receives the input data which has been prepared by the input data preparation program. The output of the neural network will be the fault distance from all DGs and the main source [1].

Isolation of the Fault

To achieve the maximum load restoration in [1], disconnection signal is sent to all circuit breakers placed in faulty zone and its downstream zones after diagnosis of location and type of the occurred fault. Also, to cut off supply of faulty zone in the case that there are DGs inside that zone, relay sends disconnection command to all DGs inside that zone. In this condition, faulty zone faces power cut thoroughly, its electrical connection with other parts of network is cut off, and upstream zones continue their synchronous operation with the global network. It is obvious that upstream zones are supplied through main source and their own DGs. Downstream zones, are supplied through island operation of their DGs, if they have any, otherwise their supply is disconnected. To perform re-closing operation, the switch that links zone of fault to upstream network is used and the operation is coordinated with the characteristics of the faulty lateral's fuses through software process done by central relay installed in sub-transmission substation. To carry out this, relay reinvestigates network status after each re-closure attempt and in the case that fault still exists, re-opens the circuit breaker and if fault is cleared, restores the network. To restore the network, relay sends re-closing signal first to zones isolating circuit breakers as well as synchronizing signal from the beginning to the end of feeder, and then brings back DGs located in the faulty zone to network. [1]

Load Shedding

When network load is higher than average load and a fault occurs in system in this situation of network, as its result some zones go into island operation due to the disconnection signal issued by relay in addition to consequent opening of some of circuit breakers, it is required to perform load shedding operation during zones island operation. [1]

In the protection scheme, it has been proposed that to determine the load difference in each zone, summation of the active and reactive powers flowing through zones isolating switches at the time exactly before occurrence of fault.

$$\Delta P_L = \sum P_{CBi} \quad , \qquad \Delta Q_L = \sum Q_{CBi} \tag{1}$$

When for each zone ΔPL and ΔQL are known out of (1), it is possible to determine shortage or excess of load regarding generation capacity of each zone. Then, using estimated hourly loads curves of the zone, fault time, ΔPL and ΔQL, and loads degree of importance, load shedding can be done to the extent at which the balance between generation and consumption in each zone is maintained. Of course this operation is needed to be done in the zones that face overload at time of fault occurrence. In the case that at time of fault occurrence loads within the island zone are lower than generation capacities of zone's DGs, relay issues no disconnection signal in order zone's frequency control system decreases generation of DGs to have nominal system frequency. It must be mentioned that when load shedding is needed to be performed as well as determining which loads have to be shed, relay sends disconnection command to load break switch of the relevant distribution substation. [1]

The Proposed Method for CB Allocation

Deliberating the previously presented approach for zoning the network, it can be concluded that considering the average load for zoning may not be the optimum way. For example, in the peak load situation, if a fault happens, most of the loads which are located in DG zones may face power outage while they could be supplied through other zones of the network. On the other hand, the fault occurrence in the minimum load situation may reduce the power generation of DGs considerably.

In order to optimize the protection scheme, first, it should be calculated that how many CBs is required, and second, the optimum location of CBs should be determined. According to the presented protection scheme in [1], the number of CBs which are needed to be installed in the distribution network should be at last equal to the number of DGs.

In this paper, risk analysis has been used for optimizing the number of CBs. In the proposed method for each solution of CBs' location, the total risk of the system is calculated. Then, with comparison of system's total risk in all solutions and finding the solution in which the system risk has the least value, the optimum protection system for the distribution network can be determined.

For calculation of protection system risk, the probability of each fault multiple by its damage should be calculated. Then, by summation of system risk for each fault, the total risk of the network can be derived. In this paper, for calculating the damage of each fault, the total load that will be face power cut in case of that fault's occurrence is considered. This can be presented as follows:

$$R_i = \sum_{j=1}^{n} P_j . L_j \tag{2}$$

Where:
R_i: the risk of protection system in situation i;
P_j: the probability of fault happening on the line number j of the network;
L_j: the total load that will face power cut by outage of line j;

Because the loads of distribution network are variable in different hours of a day as well as different days of a year, this calculation should be done for the desired period of time by (3):

$$R_i = \sum_{k=1}^{m} \sum_{j=1}^{n} P_j . L_{j,k} \tag{3}$$

Where:
R_i: the total risk of protection system in situation i;
P_j: the probability of fault happening on the line number j of the network;
$L_{j,k}$: the total load that will face power cut by outage of line j and in time k;

In Fig. 1 a very simple distribution networks is illustrated which has only one DG and is being used for describing the proposed method for optimal CB placement in distribution network. For more clarifications, all steps of the suggested method are implemented on this network and the results are derived.

As it can be seen in Fig. 1, this distribution network has one DG which, in parallel with the distribution transformers, is feeding loads L1 to L4. To protect this network CB1 and CB2 have to be installed in order to cut the injected short circuit current of the upstream network and the DG. But, in order to permit the DG to operate in its island mode in case of fault occurrence in the network, one of circuit breakers CB3 , CB4, or CB5 can also been installed. In this network in order to performing risk analysis it is assumed that the probability of occurring fault on the line connecting buses B1 and B2 is P1. Similarly, P2, P3, and P4 are assumed for the probability of occurring fault on the line connecting buses B2-B3, B3-B4,

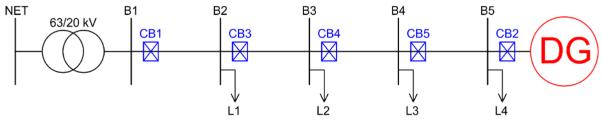

Fig.1. A Sample Distribution network

and B4-B5, respectively. Also, if is assumed that the generation capacity of the DG is 1.5 MW. For hourly load curve of all loads of the network, the load curve shown in Fig. 2 is considered

Calculating the risk in case of selecting CB3

Using CB3 for separating the protection zones from each other, the configuration of the network and its protection zones will be the same as Fig. 3.

Considering the protection algorithm in this system, after a permanent fault occurrence on the line connecting busses B1 and B2, the protection relay will send disconnection command to CB1 and CB3 to isolate the fault zone (zone1) from other parts of the network. So, L1 will face power outage. On the other hand, zone2 will be still supplied through DG in its island mode.

In the peak load, because the power consumption of the zone is more than its power generation, the load shedding algorithm of the protection relay will shed L2 and L3 to maintain the balance between generation and consumption in zone2. As a result, in this situation loads L1, L2, and L3 will face power outage with the probability of P1.

In the average load, the load shedding algorithm of the protection relay will only shed L2 to maintain the balance between generation and consumption in zone2. As a result, in this situation loads L1 and L2 will face power outage with the probability of P1.

In the minimum load, DG has the capability of supplying all loads in its zone. So, in this regime just L1 will face power outage with the probability of P1.

So, the system risk can be calculated as follows:

$$R11=4P1.(L1p+L2p+L3p)+12P1.(L1a+L2a)+8P1.L1m \tag{4}$$

In case of fault happening on the other lines of the network, the protection relay will send disconnection command to CB2 and CB3 to isolate the fault zone (zone2) from other parts of the network. So, loads L2, L3, and L4 will face power cut. Therefore, the system risk can be calculated as follows:

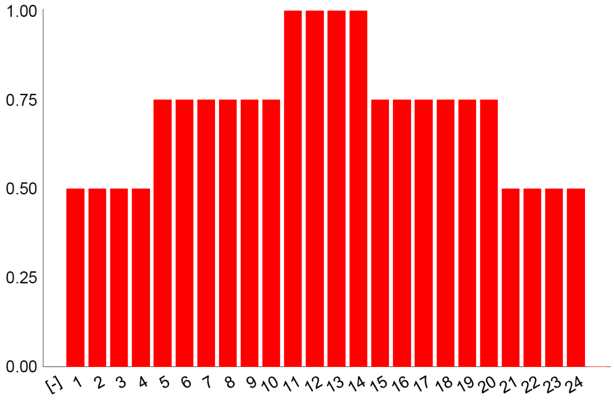

Fig.2. Hourly Load Curve of network loads

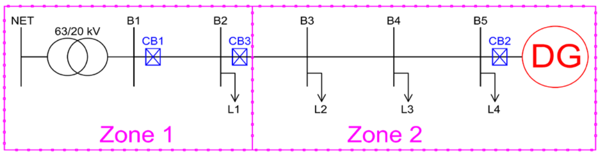

Fig.3. Distribution network configuration and its protection zones in case of selecting CB3

$$R12=4(P2+P3+P4).(L2p+L3p+L4p)+12(P2+P3+P4).(L2a+L3a+L4a)+8(P2+P3+P4).(L2m+L3m+L4m) \tag{5}$$

Finally, total risk of the system in this configuration can be calculated by summation of R11 and R12 as follows:

$$R1=R11+R12 \tag{6}$$

Calculating the risk in case of selecting CB4

Using CB4 for separating the protection zones from each other, the configuration of the network and its protection zones will be the same as Fig. 4.

Considering the protection algorithm in this system, after a permanent fault occurrence on the lines connecting busses B1-B2 or B2-B3, the protection relay will send disconnection command to CB1 and CB4 to isolate the fault zone (zone1) from other parts of the network. So, L1 and L2 will face power outage. On the other hand, zone2 will be still supplied through DG in its island mode.

In the peak load regime, because the power consumption of the zone is more than its power generation, the load shedding algorithm of the protection relay will shed L3 to maintain the balance between generation and consumption in zone2.

In the average and minimum load conditions DG has the capability of supplying all loads in its zone. So, in these regimes only L1 and L2 will face power cut. So, the system risk can be calculated as follows:

$$R21=4(P1+P2).(L1p+L2p+L3p)+12(P1+P2).(L1a+L2a)+8(P1+P2).(L1m+L2m) \tag{7}$$

In case of fault happening on the on the lines connecting busses B3-B4 or B4-B5, the protection relay will send disconnection command to CB2 and CB4 to isolate the fault zone (zone2) from other parts of the network. So, loads L3 and L4 will face power cut. Therefore, the system risk can be calculated as follows:

$$R22=4(P3+P4).(L3p+L4p)+12(P3+P4).(L3a+L4a)+8(P3+P4).(L3m+L4m) \tag{8}$$

Finally, total risk of the system can be calculated by summation of R21 and R22 as follows:

$$R2=R21+R22 \tag{9}$$

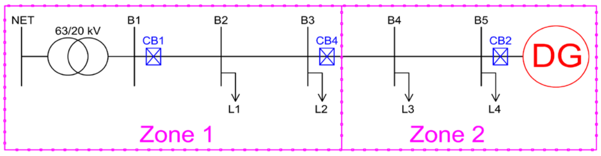

Fig.4. Distribution network configuration and its protection zones in case of selecting CB4

Calculating the risk in case of selecting CB5

Using CB5 for separating the protection zones from each other, the configuration of the network and its protection zones will be the same as Fig. 5.

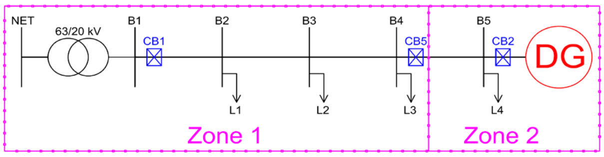

Fig.5. Distribution network configuration and its protection zones in case of selecting CB5

Considering the protection algorithm in this system, after a permanent fault occurrence on the line connecting busses B4 and B5, the protection relay will send disconnection command to CB2 and CB5 to isolate the fault zone (zone2) from other parts of the network. Therefore, L4 will face power outage.

In this situation, other loads of the network will supply from the upstream network. So, the system risk can be calculated as follows:

$$R32=4P4.L4p+12P4.L4a+8P4.L4m \qquad (10)$$

In case of fault happening on the other lines of the network, the protection relay will send disconnection command to CB1 and CB5 to isolate the fault zone (zone1) from other parts of the network. So, loads L1, L2, and L3 will face power cut. In this situation zone2 of the system will operate as an island and supply L4 by DG. Therefore, the system risk can be calculated as follows:

$$R31=4(P1+P2+P3).(L1p+L2p+L3p)+12(P1+P2+P3).(L1a+L2a+L3a) +8(P1+P2+P3).(L1m+L2m+L3m) \qquad (11)$$

Finally, total risk of the system can be calculated by summation of R31 and R32 as follows:

$$R3=R31+R32 \qquad (12)$$

Performing this procedure and calculating the total protection system's risk for each network configuration, and after that, comparing these values and selecting the minimum value, means the optimal placement of the required protectionCBs for designing the proper protection system in the network.

These calculations are done for the distribution network shown in Fig. 1 and with different values of fault probability for network's lines and its result is tabulated in table 1.

Table.1. Risk Analysis Results for the Sample Network of Fig.1

Probability Values	**R_1**	**R_2**	**R_3**	**Optimum Choice**
$P_1=P_2=P_3=P_4=0.01$	1.87	1.44	1.7	CB_4
$P_1=P_2=P_4=0.01$, $P_3=0.03$	2.89	2.12	2.72	CB_4
$P_1=P_2=P_3=0.01$, $P_4=0.03$	2.89	2.12	2.04	CB_5
$P_2=P_3=P_4=0.01$, $P_1=0.03$	2.55	2.2	2.72	CB_4
$P_1=P_3=P_4=0.01$, $P_2=0.03$	2.89	2.12	2.72	CB_4

As it can be seen in table 1, the probability of distribution lines has as important role as load profile and generation capacity in the optimal location of protective devices in distribution network.

Simulation Results

A 22-bus, 20 kV distribution network with three 3MVA diesel generators is considered as a test system for simulation. Single line diagram of this network is illustrated in Fig. 6. The technical data of the equipments are given in the Appendix. For simulation of distribution network, DIgSILENT Power Factory 13.2 software application is used.

For placement of CBs in this network, there are 21 locations that have the possibility of installing CB. These locations are on all distribution lines of the network. Because there are 3 DGs connected to the network, at last, 3 CBs can be installed. But, the protection system with less than3 CBs may have lower risk. So, the previously explained method for risk analysis should be done for all cases of protection system with 3 CBs, protection system with 2 CBs, and protection system with only 1 CB.

These calculations have been done by considering the value of 0.01 for the probability of fault occurrence on all lines of the network and its output results are presented in table 2.

As it can be seen in table II, the minimum risk value is for the network with 2 CBs when these CBs installed on lines connected buses 6 to 7 and 4 to 14. The network configuration in this situation as well as protection zones is shown in Fig. 7.

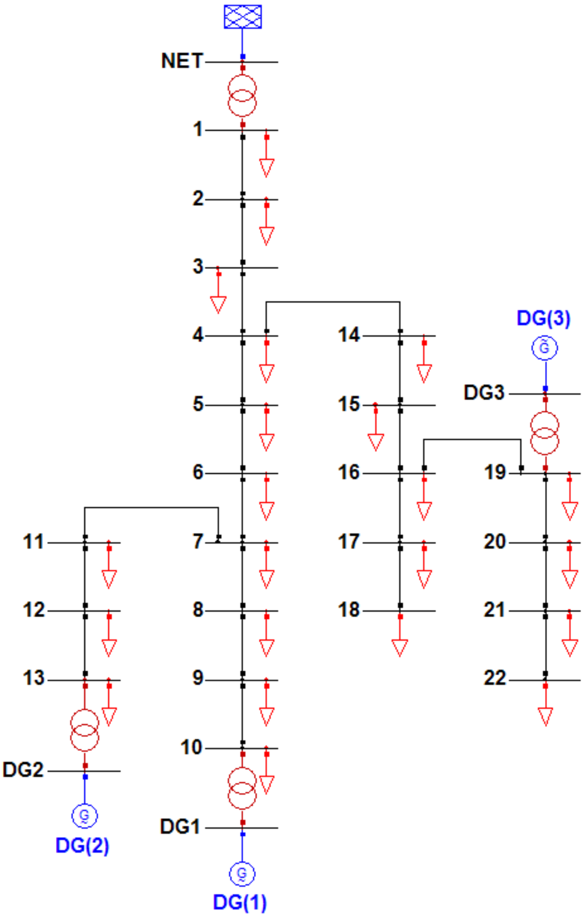

Fig.6. Single Line Diagram of Simulated Network

Table.2. Risk Analysis Results for Simulated Distribution Network

Situation	**Minimum Risk Value**	**Optimum Location of CB(s)**
Network with 3 CBs	15.68	B_5-B_6,B_7-B_{11}, B_{15}-B_{16}
Network with 2 CBs	14.91	B_6-B_7, B_4-B_{14}
Network with 1 CB	16.87	B_6-B_7

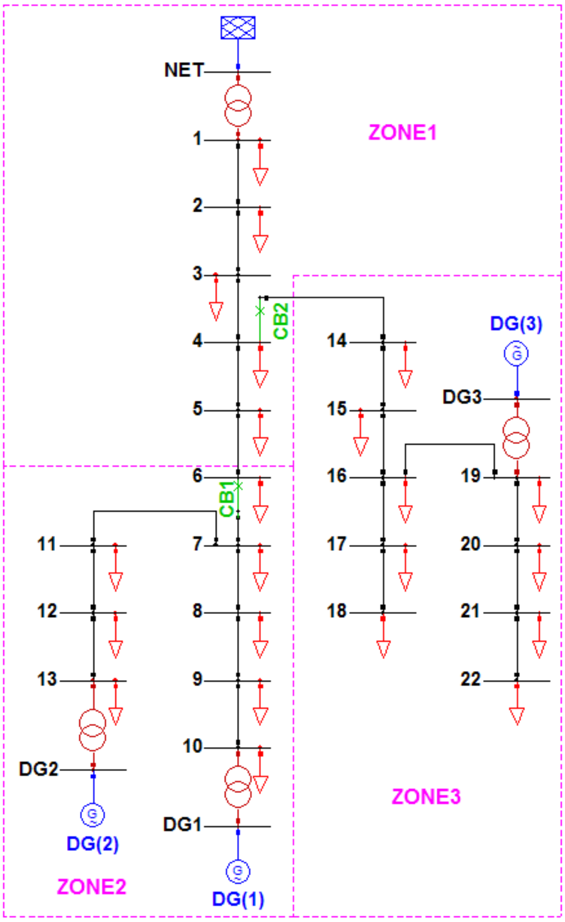

Fig. 7. Optimum Network Configuration for minimum risk of protection system

CONCLUSION

An optimization method for placement of protective circuit breakers in distribution networks based on risk analysis has been presented in this paper. In the proposed method, based on the previously presented protection scheme, the installation location of protective devices is calculated with the goal of minimizing the total risk of the system. The suggested method was implemented on a typical distribution network and its results were presented. The simulation results prove that previously ideas about placement of protection CBs may cause different risks for the network which usually are not the minimum value and the best solution. So, by calculation of the total risk of the system in each solution and minimizing it, the optimum location of protective devices can be derived.

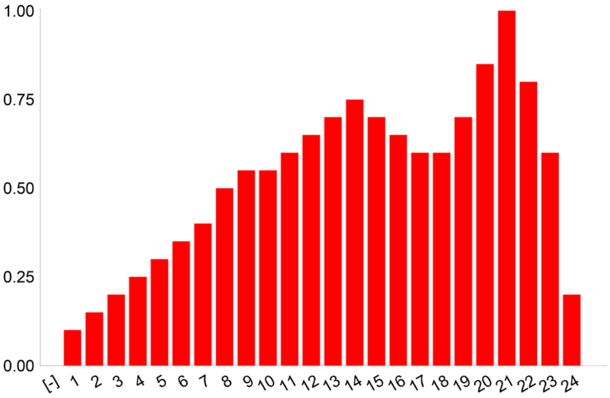

Fig.8. Hourly load curve of the simulated feeder's loads for a typical day

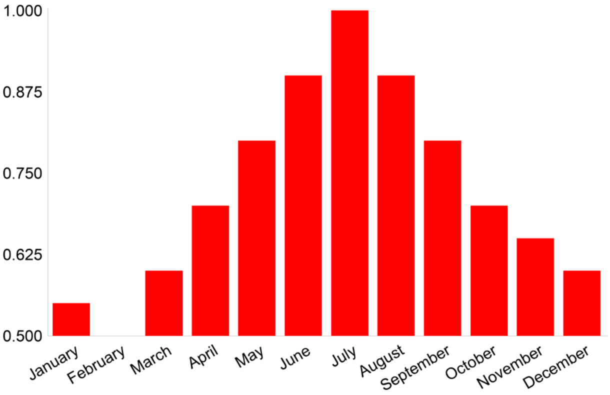

Fig.9. Monthly load curve of the simulated feeder's loads for a typical year

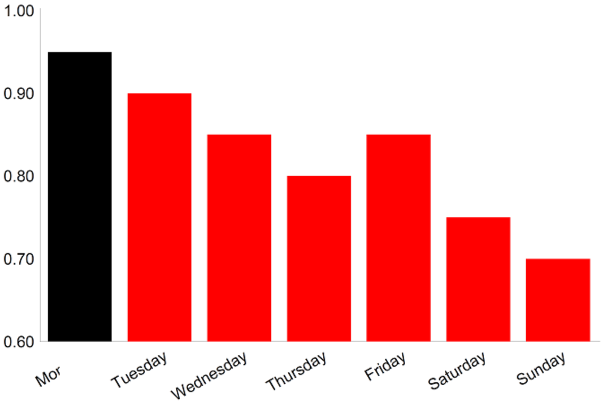

Fig.10. Daily load curve of the simulated feeder's loads for a typical week

Appendix

The peak load for all loads is 1 MW and the power factor for all of them and in every time is 0.92 (lag). Typical hourly load curve of network's loads is shown in Fig. 8. Also, monthly load curve of network's loads in year and their daily load curve in week are shown in Fig. 9 and Fig. 10 respectively.

All the distribution conductors used in simulation are HYENA with 500m length and technical information mentioned in table 3.

Technical data of DGs is presented in table 4.

Table.3. Technical data of distribution lines

Conductor Name	**Type**	**A**
HYENA	ACSR	126 mm^2
Technical Data	**R (Ω)**	0.303
	X (Ω)	0.3383
	R_0 (Ω)	0.4509
	X_0 (Ω)	1.5866
	I_n (A)	250

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