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Investigating the Smart Grid Reliability in the Presence of Distributed Generation Resources and Its Impact on the Profitability and Network Stability

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Abstract: *The electric power industry is considered as an infrastructure industry, which plays an important role in the economic development and community welfare. The absences of power blackout and service continuity are the main expectations of electricity subscribers caused by increasing dependence of society on electrical energy. Implementing a secure, reliable and efficient distribution grid on the current network requires moving towards smart grids. Self-healing capabilities are considered as one of the important features of smart distribution grids. Self-healing concept in smart grid is one of the critical issues, due to high cost of resolving power blackout and its role in reducing costs. The emergence of smart grids and distributed products has led to numerous changes in various study concepts and the exploitation of the power system. This thesis investigated the reliability of smart grids by taking into account the effects of distributed generation sources. After presenting an appropriate model for analyzing the given problem, results of its application to the sample system have been analyzed using simulation of reliability indices in MATLAB software and the effect of different parameter changes on the indicators has been reported with the aim of improving the performance of the power system. One of the key features of this study was examining the impact of layout system elements changes. It was indicated that the self-healing ability has a positive effect on reducing the time needed for electrical energy reconnection and its reliability.*

Keywords: *Distributed generation sources, Reliability, Self- healing, smart grids.*

INTRODUCTION

Power outage or blackout refers to the short or long term loss of electric power in a region. There are many factors that cause the blackout in an electricity grid. Some of these factors include (electrical) errors in power stations, damage to electrical energy transmission lines, electrical substations, or parts of the distribution system, and the occurrence of a short connections or overhead in electrical systems.

A power outage, especially in areas and facilities that put public and environmental safety at risk, are critical. Institutions such as hospitals, sewage disposal plants and, mines usually have backup power resources such as emergency power systems that are automatically launched when power is cut off. Other important systems, such as telecommunication systems, also require emergency power systems.

The issue of using distributed products to provide electrical resources has long been the subject of debate on energy generation and extensive research has been conducted in this area. Given many benefits of supplying energy through the above-mentioned method, some of its capabilities have been investigated, which can be considered the main subject of academic research. Due to the government officials' concern about the continuous energy supplying for subscribers and minimizing the power failure problem, issue of reliability to this type of energy supply gain significant attention. In this study, the reliability of smart grid in distributed energy generation and the amount of trust to his type of energy generation method is considered and the amount of this capability is investigated. In fact, investigating the validity of this method is considered in this study.

On the other hand, the self-healing smart grid was concerned in this study, which all above-mentioned points emphasized the reliability of these resources. The experimental method of analyzing the system performance is one of the main methods used for measuring this concept. However, this method requires time and cost; therefore, it is not within the scope of the study. The other method that can be used for this kind of analyzing, is simulating the performance of smart grid in the program, and conducting other simulation steps that can be considered as a shortcut for practical research. Therefore, with the advancement of science and knowledge, the test-and-error method is considered as an incorrect way and science should replace the trial-and-error method. As a result, with the proper simulation of the problem in the software, as well as the use of a scientific, rigorous and documented relationship, the reliability of the smart power grid should be predicted with two self-healing and distributed generation approaches.

Due to the issue of blackout or power outage and the huge economic losses in many parts of the country caused by it, the solutions presented in this study are particularly important in this context. The general dependence of the most industries to electricity increases the importance of reliability feature and it is essential to research about the concept of reliability.

Many studies and statistical analyses have been conducted on the power outage and, in some cases, reliability. Extensive researches have been carried out on the reliability field, each of them were helpful in preventing power outage. Many researches have been conducted in the field of renewable energies as well, which can be considered as pillars of distributed generation. Major new energy projects and products are available on a large scale, but new energy can be used on small scale as well (small off-circuit power stations or small closed-circuit power stations).This is because renewable energy resources are available all over the world, In the margins and in remote areas, while fossil fuels (oil, gas, and coal) are found only in certain countries. Only a few studies have been conducted about the effect of self-healing capability on reliability or were able to present an appropriate model. Thus, it is possible to consider this issue as a research flaw and provide a more complete investigation in this concept. Accordingly, the most important aims of this study include investigating the enhancement of reliability in the presence of distributed energy generation resources in the case study, to study the effect of self-healing with the distributed generation resources, and simulating the results through the given software.

Literature review

In 2016, in a research conducted about the distributed supply, the optimal location for switching in a radial distribution grid was proposed for improving the reliability (Ray, Bhattacharya and Bhattacharjee, 2016). In this study, a multi-objective function has been proposed by providing a suitable algorithm based on the differential search approach. All aspects of switching implementation were investigated by considering several effective loops. In another study on reliability purposed solutions, the use of distributed generation systems, such as wind and solar power stations, along with energy storage systems were proposed as backup systems in the distribution grids (Serincan, 2016). The structure was able to succeed in providing the required system power in response to 256 power outages out of 260 total blackouts. So, the reliability is estimated about 98.5%.

In another study, reliability was evaluated based on the customer satisfaction. This study emphasized on the relationship between consumer satisfaction and reliability of transmission distribution grids (Li et al., 2016). In 2012, (Vahedi, Gharehpetian and Karrari, 2012) it was stated that in the performance of energy islands in the presence of distributed generation resources, by considering the security and safe performance of the new distributed generation systems for the separating various events, requires a proper diagnostic system. Davda et al. (2012) in their study suggested that the proper positioning of distributed generation resources due to the growing is important for distribution systems due to the growing demand for energy. In 2013, in a study on distributed sources, a real 9.3 MW distribution grid was analyzed in Gujarat, India (Wang et al., 2013). It was indicated that, the distribution generation obtained from a renewable energy source, such as wind power and solar power, located at optimal points from the distribution feeder, can reduce energy losses and improve the voltage profile.

In 2013, in a study, because the consumption of electric energy is not a fixed amount in a residential building and is dependent on the climate changes, seasons and types of consumers, a grid independent distributed power generation system was proposed with proper size in order to meet the required power needed for given consumption (Ipinnimo, Chowdhury and Chowdhury, 2012). In 2016, a computer-controlled Peak Demand Decommissioning program has been investigated in a smart power grid and simultaneously analyzed power and power management (Powroźnik, 2016). In another study in 2016, a specific modular model Transformation based on the state of the transformer was designed for smart grids (Pinto, Mendes and Silva, 2016).

In another study on Libya, a smart grid concept is presented and the importance of its implementation is described (Solomon and Krishna, 2011). In another study on self-healing, an appropriate model was optimized and the voltage and power loss rate was determined at each point (ZakiEl-Sharafy and Farag, 2016).

Methodology

The single-line diagram of the studied system is shown in Figure 1.

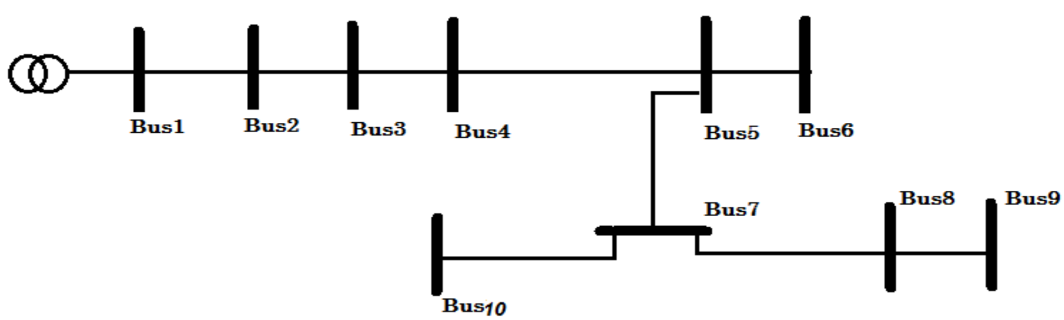

Figure 1: The studied single-line diagram

Table 1: Summary of the applied relationships

Relationships	Description
$\lambda_s = \sum_{i \in A} \lambda_i (f\ / yr)$	One of the reliability indicators is the average error rate
$U_s = \sum_{i \in A} \lambda_i r_i$	One of the reliability indicators is the Mean blackout
$r_s = \frac{U_s}{\lambda_s}$	One of the reliability indicators is the average annual blackout time
$ENS_i = \sum \lambda_i r_i L_c$	One of the reliability indicators is the average energy that was not sold for each subscriber
$SAFI = \frac{\sum N_i \lambda_i}{\sum N_i}$	Average number of system blackout index
$SAIDI = \frac{\sum N_i U_i}{\sum N_i}$	Average system blackout time index

$CAIDI = \frac{\sum N_i U_i}{\sum N_i \lambda_i}$	Average subscriber blackout time index
$ASAI = \frac{\sum N_i T - \sum U_i N_i}{\sum N_i T}$	Average Energy Access Index
$ENS_C = \sum ENS_i$	The energy that was not sold to subscribers
$G - L = M \Rightarrow \frac{G}{L} - 1 = \frac{M}{L} \Rightarrow GLR = 1 + \frac{M}{L}$	Normal density function
$\mu_m = \mu_g - \mu_l$	Average normal density
$\delta_m^2 = \delta_g^2 - \delta_1^2$	normal density standard deviation
$ENS_c = (\sum_{i \in f} \lambda_i r_i + \sum_{i \in \gamma} \lambda_i P_L T_a + \lambda_{up} P_M T_a) \mathrm{L}_c$	The energy was not delivered to subscribers with the presence of overproduced resources

The information needed to simulate the system is described in the following tables.

Table 2: Information on distributed generation sources

Distributed generation source	Minimum power	Maximum power	Breakdown rate	Duration
Partial solar power station	0	40	0.003	2
Fuel cell	13	240	0.004	1.5
Solar panel	0	55	0.005	2
Wind power station	0	70	0.004	1.25
Small gas station	0	46	0.000034	2

Table 3: Information on network load points

Bus	1	2	3	4	5	6	7	8	9	10
P	100	120	15	10	75	25	20	90	85	15
Q	135	160	60	45	95	65	70	140	130	60
Number of subscribers	120	140	35	28	85	45	45	115	107	40

Table 4: Network line information

	Line 1	Line 2	Line 3	Line 4	Line 5
Breakdown rate	0.0001	0.0001	0.00015	0.00015	0.0005
Repair time	2	2	2	2	2
R_{ohm}	0.176	0.176	0.153	0.153	0.078
X_{ohm}	0.045	0.045	0.121	0.121	0.063

Table 5: various reliability parameters at network load points before adding distributed generation sources

Load points	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
λ	0.001	0.0011	0.001	0.0012	0.0008	0.0015	0.001	0.0012	0.0013	0.0014
R	3.2	1.2	3.3	4.3	2.3	6.4	2.3	1.2	8.3	3.2
U	0.004	0.005	0.0043	0.009	0.0044	0.0034	0.0033	0.0043	0.0033	0.0065
ENS	0.5	0.9	0.2	0.2	0.3	0.4	0.3	0.3	0.2	0.12

Table (5) indicates the various parameters of reliability in the network load points before the addition of distributed generation sources.

Table 6: Load points information after adding distributed generation resources

Load points	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
λ	0.000095	0.0001	0.0001	0.0002	0.0002	0.0005	0.0003	0.0002	0.0003	0.0003
R	1.3	0.6	2.1	1.2	1.1	3.2	1.01	0.7	1.2	2.1
U	0.0002	0.0003	0.0003	0.0002	0.0002	0.0001	0.0001	0.0012	0.0002	0.0002
ENS	0.4	0.8	0.1	0.1	0.12	0.22	0.12	0.12	0.11	0.01

C) Including smart and self-healing capabilities

In this situation, three scenarios were analyzed as follows:

Scenario 1: In this scenario, it was assumed that there is no switch or source of distributed generation on the feeder of this study, and then the values of reliability parameters are calculated for the sample feeder. In this case, if an error occurs in each part of the network, the feeder is disconnected from the source. In fact, we plan to examine the lack of distributed source state and compare it with the specified values. Hence, we take into account the specific state of without distributed generation source and use its specific information for further measurement purposes. This is further discussed in the next discussion. If the network is fed from a large source, the processing ability will be fed from the large source, which is called the mother source. If an error is occurred in the process of power transmission, the feed from the source should be disconnected, which will reduce the reliability of the device.

Scenario 2: In the second scenario, it is assumed that the sample feeder is a smart grid, so that the feeder components are automated to the highest possible level. Under these conditions, each section has a detachable switch and a remote connection, and an error occurs in the process, only the relevant suction will be turned off. For these conditions, the values of system reliability parameters have been calculated. It is worth mentioning that there is no manual switching in this scenario, because the smart grid is cleverly cleansing the error. In fact, smartening was done in this case, which part of it was conducted mechanically and the main part was designed by the computer algorithm. In this case, the reliability would definitely goes higher, and in case on error occurrence, the power is turned off from a specific point within the grid.

Scenario 3: In this scenario, a single source of distributed generation is installed on the node. Selection of location, size and number of DGs is done by genetic optimization algorithm. In the next step, the values of reliability parameters are calculated with the assumption of DG. It should be noted that since the network is automation, in order to reduce the maximum reduction of not-distributed energy, the load switching is done in such a way that the maximum amount of possible load to be supplied by the distributed source, in case of error occurrence and placement of distributed generation source in the grid island. The genetic algorithm is determined in an optimized way and, therefore, the best location is determined. The importance of optimization in all sciences is clear. By having specific information in a field, a specific aspect of the planning capability can be customized. The three-dimensional procedures are mapped in this way and eventually the extreme points conduct the implementation capability. The genetic algorithm determines the relationship between the data and then easily determines the amount of extreme points.

Findings

Including smart and self-healing capabilities

The results of the study on the effects of three research scenarios on the various SAIFI, SAIDI, ASAI, ENS indices have been reported in Table (7).

Table 7: values calculated by the software for 3 scenarios

index	Scenario 1	Scenario 21	Scenario 3
SAIFI	26.65	4.983	4.219

SAIDI	15.455	3.447	2.141
ASAI	0.998578	0.999721	0.999757
ENS	121.213	18.571	13.513

The SAIFI index was improved significantly in the second and third scenarios compared to the first scenario. This means that by smartening the average distribution systems, the power outage or blackout will be significantly reduced. SAIDI index is improved in the second and third scenarios, compared to the first scenario. Therefore, the average period of the power outage in the smart system has been reduced as well. ASAI index has risen to a satisfactory level in second and third scenarios. The ENS index had the most relevant impact in this study. According to the results, the studied system was improved significantly after smartening the system, senario2, and after including the self-heal feature, senario3. According to the conducted analysis, the reliability was increased, the blackouts were reduced, and ultimately, customer satisfaction has improved. The amount of losses, which is the true part of impedance value in squaredpower flow, was about 400 kilowatts in the first scenario. However, after smartening the system, this amount reduced by 200 kilowatts.

Assessing the distribution grid profitability in the presence distributed generation source

According to the Table 7, the highest impact of smart and self-healing on the distributed resources was observed in ENS index. And the amount of this index, which is unsold energy, was reduced dramatically.

The ENS index is therefore important to us, because this indicator is directly related to the amount of losses that the distributing company suffered. If we want to calculate the amount of losses caused by the unsold energy, we have to calculate the energy that the company distributed among the subscribers within a given time period. To do this, we have to multiply the value of this indicator with the price of each kilowatt-hour of electricity and then multiply the result with the desired time period per given hour units. We want to calculate the effect of smart grids on self-healing feature on distributed generated resources on the reduction of losses. The distribution of company in one year was investigated.

We know that according to the international standards, the price of one kilowatt-hour electricity is 60 cents. As a result, the following chart shows the amount of losses suffered by distributing company in three above-mentioned scenarios, which was compared with each other.

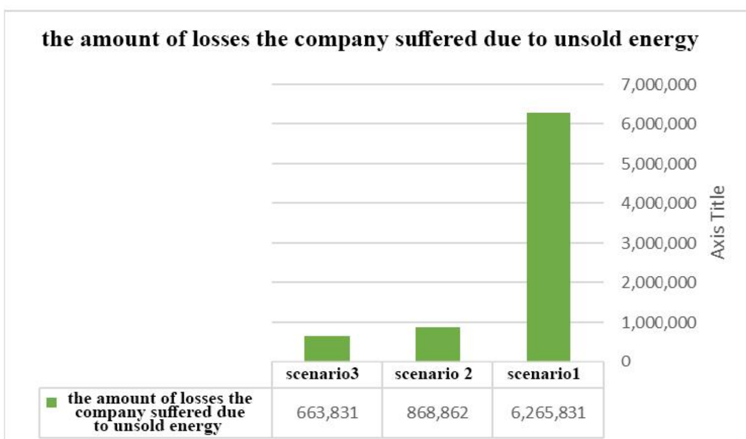

Figure 2: comparison diagram for the loss/damage amount

According to the Figure 2, the amount of loss/ damage is higher in scenario 1 compared to scenario 2 and 3. It means, the distributed system is a self-heal smarted grid, therefore, the return rate of self-heal grid with a distributed generation source is higher than other scenarios.

Also, according to the data presented in Tables 5 and 6, it is possible to compare the amount of losses/damages of distributing company caused by the unsold energy for each loading point in the grid.

Table 8: Losses due to unsold energy to subscribers

Bus	1	2	3	4	5	6	7	8	9	10
Losses before the DG	2628	4730.6	1051.2	1051.2	1576.8	2102.4	1576.8	1576.8	1051.2	630.72
Losses after the DG	2102.4	4204.8	525.6	525.6	630.72	1156.32	630.72	630.72	578.16	52.56

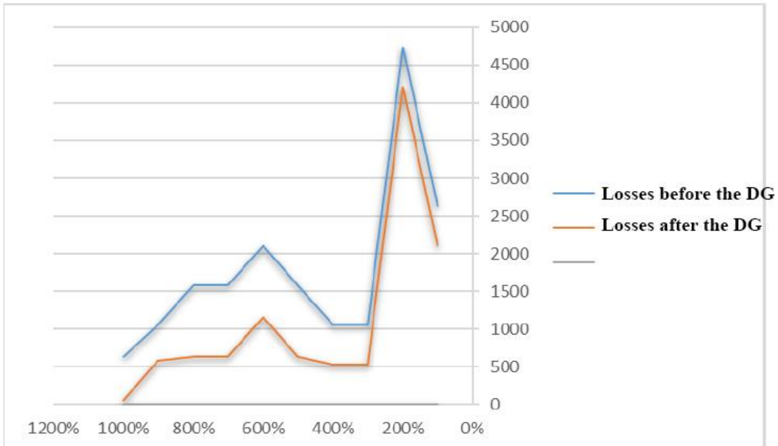

Figure 3: Comparison of losses amount caused by unsold energy before and after entering the distributed generation

Investigating the effect of distributed resources on the voltage profile

The Newton Raphson Method has been used through MATLAB software to load section. Voltage profile were examined in two state, after entering the distributed generation source into the energy grid and before entering the distributed generation source into the energy grid.

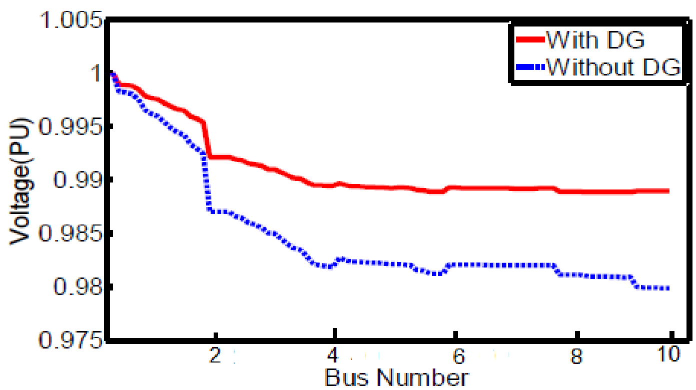

Figure 4: the effect of distributed generation source on the voltage profile

Figure 2 clearly shows the effect of distributed generation resources on voltage stability. The reliability will increase accordingly.

Investigating the effect of each element on reliability indicators according to modeling of uncertainties

According to the proven relationship in reference (5), which was expressed for the ENS index after entering the distributed generation resources with the assumption that the potential failure (PL = 1) does not exist and the probability of unwanted islanding of distributed generation resources was not considered as well (PM = 1). It can be concluded that the load factor and recovery time are effective on this indicator. This indicator is related to the profitability of the distribution grid. Therefore, by reducing this indicator, profitability would be increased. Therefore, it only examines the changes in these indicators. The effect of Ta and Lc parameters on the improvement of this index was examined. The amount of ENS can be reduced by controlling and reducing these two elements.

Because the presence of distributed generation resources in the network causes uncertainty, the numbers of these elements cannot be considered definitive. For this reason, for each of the numbers associated with these elements, a normal density distribution function is considered. However, remember that the probability of normal density in each of the repeat steps of the test is the same for all elements, so that the results can be compared with each other. This test is repeated several times (in this thesis the test was repeated 100 times), then, the results are sampled at each step, and finally a normal probability density distribution diagram for sampling results is plotted.

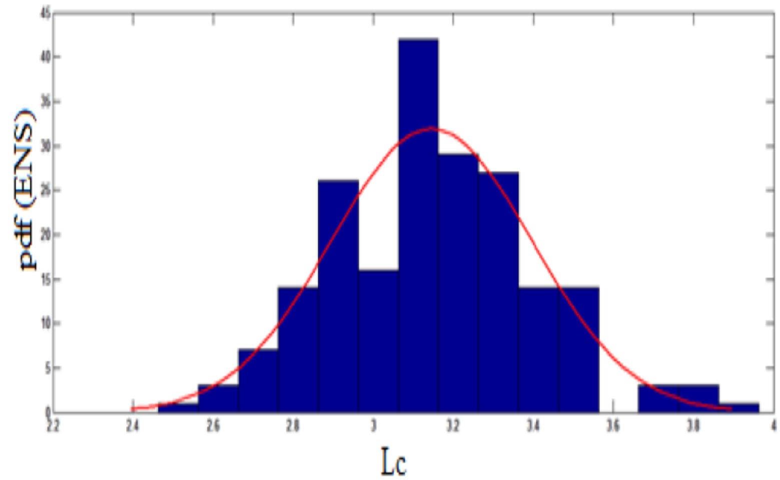

Figure 5: Effects of Lc on the ENS reliability index before the arrival of distributed generation sources.

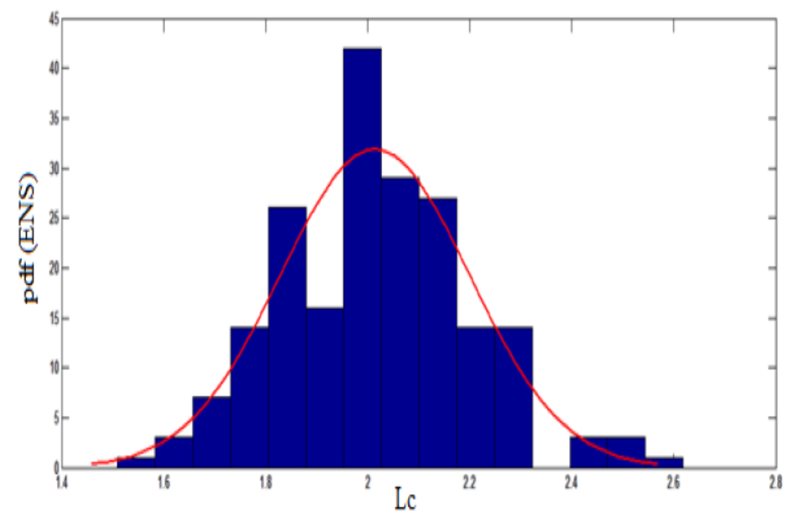

Figure 6: The effects of Lc on the ENS reliability index after the arrival of distributed generation sources.

Distributed generation resources reduce network load and cause the loss of Lc. As shown in the diagrams above, this reduction would decrease the ENS as well. This amount has been improved to a satisfactory level.

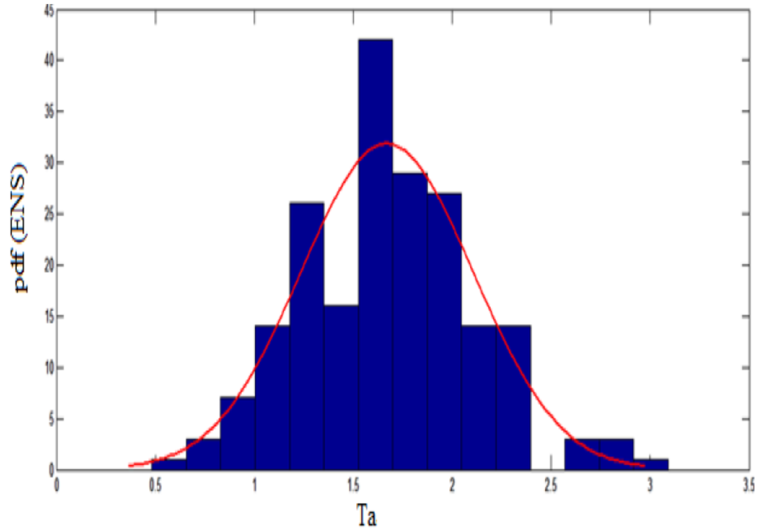

Figure 7: The effect of Ta changes on ENS Reliability Index before the entrance of distributed generation sources

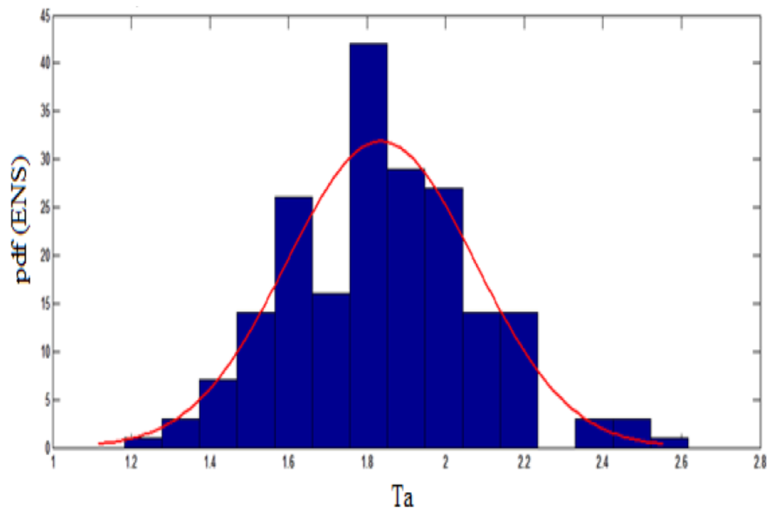

Figure 8: The effect of Ta changes on ENS Reliability Index after the entrance of distributed generation sources

By looking at the diagrams, it is clear that the entrance of the distributed generation resources causes the Ta amount to be reduced appropriately, and will reduce the amount of ENS and improve it.

Investigating various states for the amount of distributed generation resources and consumption

The amount of power generated by distributed generation resources should be in line with the load on the grid so that to be not cause network instability. In this section, the relationship between the supply of distributed generation power and the demand for the network has been examined.

In this case, the stated cases are implication of the mean and standard deviation and are used in determining the reliability indices. In the density diagrams, the goal is to consider the amount of load impact in different ratios. The growth rate of movement toward the negative part is proportional to the amount of GLR ratio increases. The supported area or section is the areas where M is greater than zero (green) and the distributed production sources that discharge their load, feature M lower than zero (red).

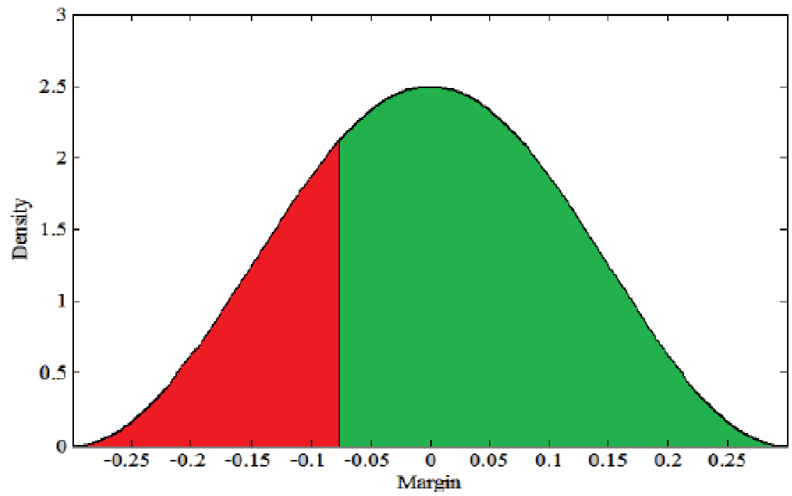

Figure 9: Density in relation to GLR = 1

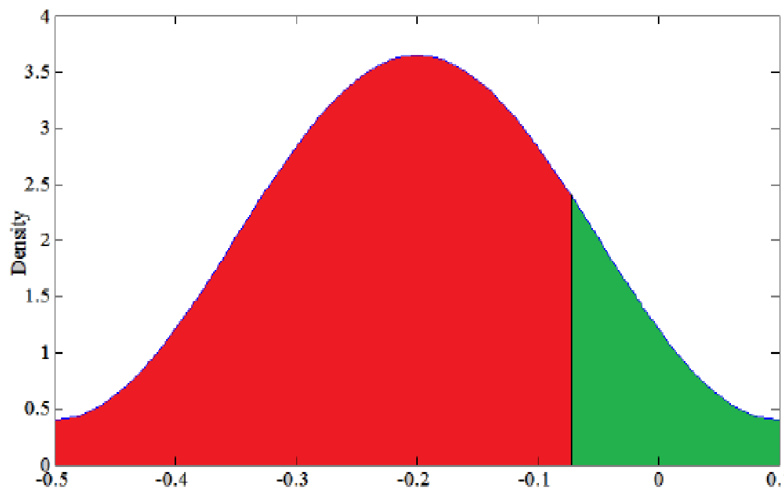

Figure 10: Density in GLR = 0.8

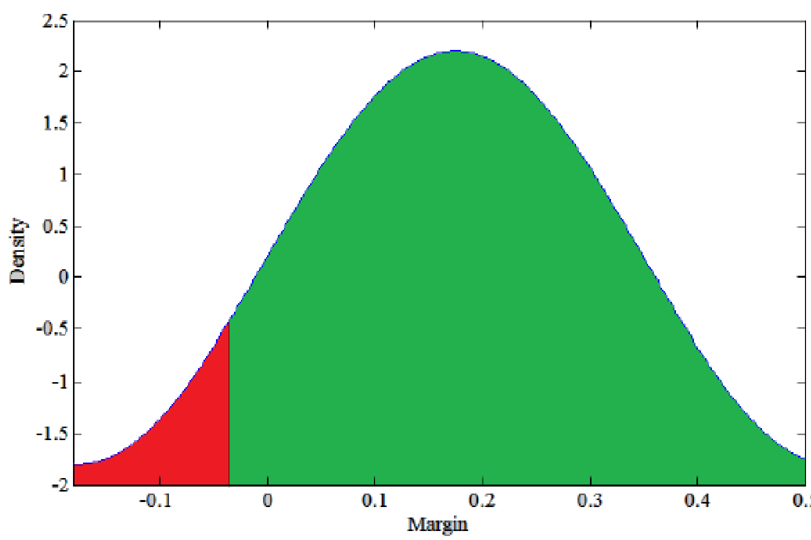

Figure 11: Density in GLR = 1.2

Due to the importance of supply and demand, a density less than 1 is shown in Figure 10 and values greater than 1 is shown in Figure 11. According to the analysis of the three above mentioned conditions, G's ability to improve the reliability of the distribution network is highly dependent on the ratio of production of distributed generation resources and load demand.

Conclusion

Distributed generation with flow injections and voltage improvements reduce the amount of losses. Hence, one of the significant issues in distributed power generation systems is to locate and connect a distributed generation system to a location that will benefit the power grid. Generally, another important issue in the network is the load of the network. The network load directly affects the flow of the network and indirectly influences on the power line and losses line through the power flow. Particularly, the type of load has a significant impact on the power loss calculation issues in the power system.

Micro grids are able to supply the subscribers with more reliable and better quality electrical energy. It also brings various benefits to electricity distribution companies and the community. Providing safety and security features in micro grids and their implementation is one of the most important concerns of power distribution companies. In this way, it seems that energy measuring and management in distribution companies and using a distribution resources are the key to reach a smart micro grid implementation.

In this research, self-healing is considered as one of the important features of smart distribution grid. This feature was examined in the network related to the actual distribution feeder of Gol- Gohar Sirjan Mine by selecting three different scenarios. The results indicated that the reliability of the system was improved and the power outage was reduced when the smart grid turned on, and the results are further improved by adding the DG in a part of the grid.

The results of the studies confirm that the use of dispersed generation units in distribution networks can have a significant effect on reducing the duration of blackout by reducing the index r for load points and improving the reliability of distribution networks. Also, the amount of improvement at the system reliability caused by the installation of distributed generation units depends on the installation location, capacity and number of units.

An important point is that, ENS and CAIDI are similar to SAIDI. This phenomenon is due to the fact that when the error rate is constant, the CAIDI is only a function of SAIDI and when the load times of the load points is constant, ENS will only depend on the duration of the offset. As you can see, the SAIFI index remains unchanged.

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