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Fault Analysis of Practical Distribution System with and without Distribution Generation units

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Abstract— The number of distributed generation (DG) units is increasing rapidly. Combined heat and power (CHP) plants and wind turbines are most often installed. Integration of these DG units into the distribution grid leads to planning as well as operational challenges. Distributed generation (DG) is an emerging concept in the electricity sector, which represents good alternatives for electricity supply instead of the traditional centralized power generation concept. This paper presents the basic principles of integrating distributed generation technologies in low voltage networks and particularly focuses on the economics of DG installations and the impact that DG may have on voltage control leading to improved power quality.

Keywords- Distributed generation (DG); distribution grids; grid planning; protection; voltage control

I.INTRODUCTION

The term distributed generation is often used to depict a small-scale electricity generation. But what exactly is small-scale electricity generation. Currently, there is no consensus on how the distributed generation should be exactly defined. As shown by the survey conducted by CIRED [1], there is no consensus on the definition of this term [2]. Some countries define distributed generation on the basis of the voltage level, whereas others start from the principle that distributed generation is connected to circuits from which consumer loads are supplied directly. Other countries define distributed generation as having some basic characteristic (for example, using renewable, cogeneration, being non-dispatchable, etc.).

The task of defining the scope of distributed generation has also been taken by many academics. [6] defines distributed generation as a small source of electric power generation or storage (typically ranging from less than a kW to tens of MW) that is not a part of a large central power system and is located close to the load. [7] in turn defines distributed generation as relatively small generation units of 30MW or less, which are sited at or near customer sites to meet specific customer needs, to support economic operation of the distribution grid, or both

A very good overview of the different definitions proposed in the literature is given in [8], where the authors conclude that they prefer the definition proposed by [9], which is defining the distributed generation in terms of connection and location rather than in terms of generation capacity. Everyone seems to agree on at least the small-scale generation units connected to the distribution grid to be considered as part of distributed generation. Moreover, generation units installed close to the load or at the customer side of the meter are also commonly identified as distributed generation. This latter criterion partially overlaps with the first, as most of the generation units on customer sites are also connected to the distribution grid. However, the latter might also include somewhat larger generation units, installed on customer sites, but connected to the transmission grid 1. As these views are also shared by the authors of this report, the term distributed generation will be further used to depict an electric power generation source connected directly to the distribution network or on the customer side of the meter. The combination of utility restructuring, technology evolutions, recent environmental policies provide the basis for DG to progress as an important energy option in the near future. Utility restructuring opens energy markets, allowing the customer to choose the energy provider, method of delivery, and attendant services. The market forces favour small, modular power technologies that can be installed quickly in response to market signals.

II. DISTRIBUTED GENERATION BACKGROUND

A. AN ELCTRIC POWER SYSTEM

Generally, the term Distributed or Distributed Generation refers to any electric power production technology that is integrated within distribution systems, close to the point of use. Distributed generators are connected to the medium or low voltage grid. They are not centrally planned and they are typically smaller than 30 MWe (DTI 2001) [3] The concept of DG contrasts with the traditional centralised power generation concept, where the electricity is generated in large power stations and is transmitted to the end users through transmission and distributions lines (see figure.1). While central power systems remain critical to the global energy supply, their flexibility to adjust to changing energy needs is limited. Central power is composed of large capital-intensive plants and a transmission and distribution (T&D) grid to disperse electricity.

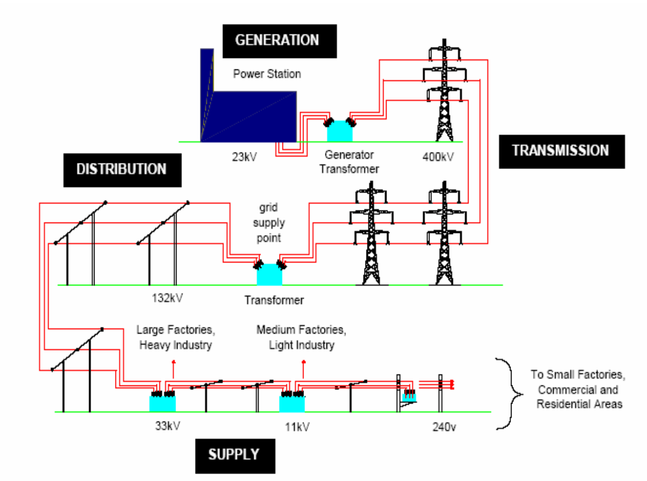

Fig.1 An electric power system

B. *DISTRIBUTED ELECTRICITY SYSTEM*

A distributed electricity system is one in which small and micro generators are connected directly to factories, offices, households and to lower voltage distribution networks. Electricity not demanded by the directly connected customers is fed into the active distribution network to meet demand elsewhere. Electricity storage systems may be utilised to store any excess generation. Large power stations and large-scale renewables, e.g. offshore wind, remain connected to the high voltage transmission network providing national back up and ensure quality of supply. Again, storage may be utilised to accommodate the variable output of some forms of generation.

The non-traditional operating model of DG has drawn strong interest because of its potential to cost effectively increase system capacity while meeting the industry restructuring objective of market driven, customer-oriented solutions. These distributed generation systems, capable of operating on a broad range of gas fuels, offer clean, efficient, reliable, and flexible on-site power alternatives. This emerging portfolio of distributed generation options being offered by energy service companies and independent power producers is changing the way customers view energy. Both options require significant investments of time and money to increase capacity. Distributed generation complements central power by (1) providing in many cases a relatively low capital cost response to incremental increases in power demand, (2) avoiding T&D capacity upgrades by locating power where it is most needed, and (3) having the flexibility to put power back into the grid at user sites.

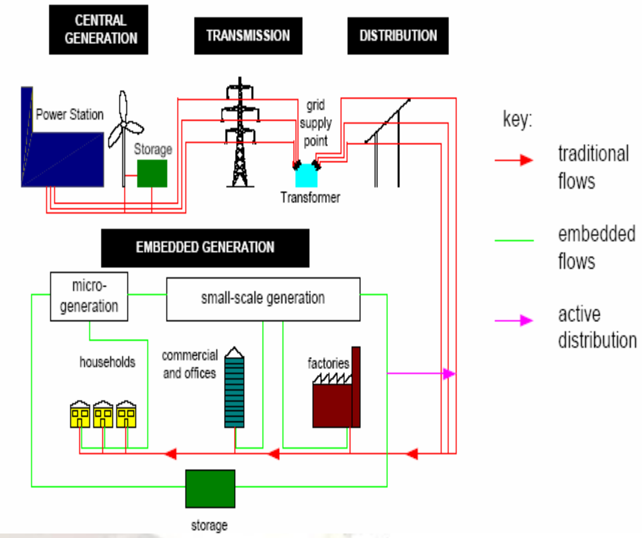

Fig.2 Distributed Electricity System

III. EFFECT OF DG ON DISTRIBUTION GRID OPERATION

Large scale integration of DG units in the distribution grid not only affects the grid planning but also has an impact on the operation of the distribution grid. Aspects which are influenced by the connection of DG units are [5] as follows:

- voltage control;
- power quality;
- protection system;
- fault level;
- grid losses.

The effect of DG units on these quantities strongly depends on the type of DG unit and the type of the network. DG units can be either directly connected to the distribution grid, such as synchronous and asynchronous generators, or via a power electronic converter. In all cases, the power flow in the distribution grid as well as the grid losses and the voltage control are affected. Synchronous generators contribute a large short-circuit current influencing the protection scheme and the fault level. DG units connected via power electronic converters hardly contribute to the fault current making the effect on fault level and protection system negligible

The Dutch distribution grid consists of cables only and covered distances are relatively short compared to many other countries with overhead line feeders. Different conductor type and much shorter distances cause the Dutch distribution grids to have much lower impedances compared to distribution grids consisting of long overhead lines. This difference strongly determines what impact DG has on the distribution grid operation

A.VOLTAGE CONTROL

For the power system and customers' equipment to function properly the voltage level of distribution grids must be kept within specific range [5]. This voltage range is well defined in international standards. Grids are confronted with varying loads and voltage fluctuations will occur. Varying loads create a changing current through the resistance and reactance of the feeder causing a changing voltage drop along the feeder.

The connection of the DG along the feeder may affect proper voltage control of the distribution grid. The impact of the DG on voltage control is dependent on the power flow in the network. The voltage profile is not much influenced when the injected power by the DG is lower than or equal to the load of the feeder. In this case, the energy supplied by the grid as well as the current through the feeder are decreasing, resulting in a reduction of voltage drop. However, when the generated power exceeds the load of the feeder, voltage rise will occur. This voltage rise caused by the reversed power flow is a function of the power generated by the DG and the short-circuit power of the grid at the point of interconnection [7]. The effect of reversed power flow gets stronger when the DG injects reactive power as well

The effect of the DG on the voltage profile of a distribution feeder is demonstrated in the simulation of a 10-kV test feeder shown in Fig. 3.

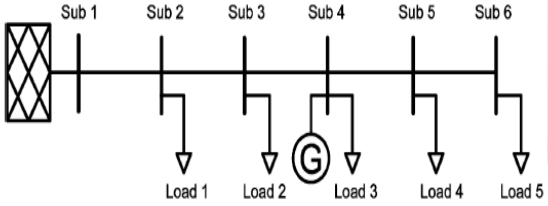

Figure.3 Overview of a test feeder including DG.

The total feeder length is 20 km and the substations are equally distributed along the feeder. The DG unit is connected to Sub 4 and generates 4 MVA. Table 1 gives an overview of the applied network data.

Different generation scenarios are applied to determine the voltage profile along the feeder as shown in Fig. 4.

Without active DG-power injection, an expected voltage profile occurs. The power flow through the feeder results in a smooth voltage drop from the beginning to the end of the feeder. A 1-MW DG-power injection helps to supply the local load, which reduces the flow from the source, and thus also reduces the voltage drop in the first part of the feeder. When the injected power starts to increase more loads are supplied locally further reducing the flow from the source

In Fig. 4, it can be seen that the voltage at Sub 4 significantly increases at an injected power of 3.2 MW. The simulations demonstrate that in a DG connection study all possible load/generation scenarios need to be studied to assess if the voltage profile will stay within the operational limits.

Keeping the voltage within the allowed limits can be achieved in several ways. One simple option is to reduce the primary substation voltage. This solution works well for those feeders with the DG connected. In feeders connected to the same substation, but without the DG, the voltage now may become too low. In most cases, voltage may be reduced to some extend without violating the lower voltage limit. Another solution is to increase the conductor diameter of the specific feeder to which the DG unit is connected. This is only possible when the distribution grid has to be extended due to the connection of the DG unit. An operational approach can be to constrain the DG unit at times of low demand and so expensive grid reinforcements can be prevented. This can be an attractive option when the DG unit is dispatched. New techniques are also available which are based on influencing the reactive power flow in the grid. DG units including a synchronous machine can absorb some reactive power and in this way can help reduce the voltage rise. Controlling the reactive power flow in the distribution feeder can also be done by a FACTS device named STATCOM. Because of the fast response time, it can provide a dynamic voltage control in the distribution grids [8]. However, controlling voltage level by controlling the reactive power flow only works for distribution feeders with a sufficient X/R ratio

Cable XLPE 400mm^2 A1	R=0.13Ω/km	X=0.124 Ω/km
Load	P=0.5MW	p.f=0.9
$S_{k.grid}$	200MVA	U_1=10kV
S_{gen}	4 MVA	P=3.2MW, p.f=1

Table.1 Network Data of the Test Feeder of figure.4

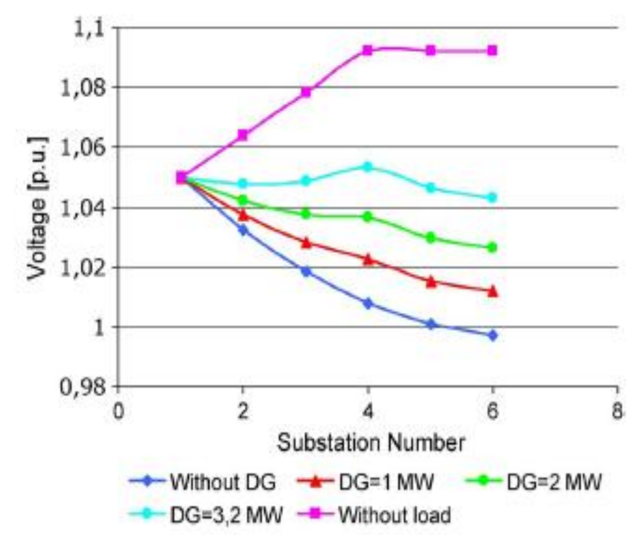

Figure.4 Voltage profile of the test feeder for different generating scenarios.

B. POWER QUALITY

The effect of the integration of the DG on power quality concerns three major aspects [5], [9]:

- Dips and steady-state voltage rise;
- Voltage flicker;
- Harmonics.

I. Dips and Steady-State Voltage Rise

The DG can affect the quality of the supply voltage in several ways. Connecting the DG to a lightly loaded feeder the power flow can reverse and the voltage at the DG connection point starts to rise. This means that the supply voltage for customers connected nearby DG units starts to rise as well. This voltage rise is a steady-state effect and it strongly depends on the X/R ratio, feeder load, and injected power by the DG unit. However, the DG can also have a transient effect on the voltage level. A rapid load current variation of a DG unit causes a sudden increase or decrease of the feeder current and hence an effect on the feeder voltage. For instance, when the wind starts to blow, the wind turbine output rapidly increases until the rated power of the wind turbine is reached. The rapid output change of the wind turbine changes the power flow in the feeder and can cause a voltage transient. A sudden change in the output power can also occur when the wind exceeds a certain upper limit (25 m/s). At that point, the wind turbines have to be protected against overload and strong mechanical forces, and are disconnected and shut down [10]. This disconnection can cause an increase in the feeder current and hence a dip or a drop in the supply voltage.

II. Voltage Flicker

In the distribution grids, the most common cause of a voltage flicker is a rapid and regular variation of the load current. An example of a cause of regular load current variation is the tower effect of a fixed speed wind turbine. This effect is due to the wind shielding effect of each blade of a three-blade turbine as it passes the tower. When the blade passes the tower the injected electrical power of the wind turbines reduces, which has an effect on the grid voltage [10]. The tower effect causes a power oscillation with a frequency of three times the blade turning speed and hence voltage flicker with the same frequency. Conversely, some DG schemes contribute significantly to the fault level which gives a reduction of the network impedance. As a result, the changing load current caused by a changing load will lead to a smaller voltage variation and hence improved power quality.

III. Harmonics and Resonances

Inverter connected DG units might cause harmonics. The magnitude and the order of the harmonic currents depend on the technology of the converter and the mode of operation [5]. The injection of harmonic currents can distort the voltage waveform which can propagate throughout the distribution grid. Furthermore, apparently small voltage distortions can cause large harmonic currents at a series of resonance conditions of the cable capacitance and the supply inductance (transformer leakage and cable inductance) and have to be prevented. Especially for inverter interfaced DG, such as PV systems and micro CHP, parallel resonance of the parallel network capacitance (output capacitance of the inverter and the cable capacitance) and the supply inductance can lead to high-voltage distortion at the connection point [11].

These types of resonances are also found in [11] and [12] where practical measurements were performed on existing low-voltage networks including a large number of PV systems. The measurements especially show that parallel resonances occur which can trip the inverters due to a distorted supply voltage.

An ability to reduce the harmonic current injection is filtering of the output current. Modern power electronic converters are able to filter the injected current and reduce the injected harmonics. In [13], various harmonic reduction techniques are discussed and it is stated that harmonic reduction can be an ancillary service of grid connected converters. An overview and classification of all power quality phenomena and the effect of the DG on power quality can be found in

C. GRID PROTECTION

Distribution grid protection consists normally of a simple over current protection scheme since there is only one source of supply and the power flow is defined. The connection of the DG to the distribution grid leads to multiple sources of the fault current which can affect the detection of disturbances. The contribution of the DG to the fault current strongly depends on the type of the DG and the way the DG unit is connected to the distribution grid. As stated earlier, the converter interfaced DG hardly contributes to the fault current. To study the effect on distribution grid protection, the directly coupled DGs are considered here.

In [15]–[17], potential problems to the distribution grid protection are discussed. The main problems identified are:

- Prohibition of automatic reclosing;
- Unsynchronized reclosing;
- Fuse-recloser coordination;
- Islanding problems;
- Blinding of protection;
- False tripping.

Reclosure problems, blinding of protection, and false tripping are further analyzed.

I. Recloser Problems

An automatic recloser is a protection device typically applied in distribution grids consisting of overhead lines. Most faults on these lines only last a short period of time, therefore it is not necessary to switch the line off permanently. The automatic recloser switches off the line for a short period of time to allow the arc to extinguish. After a brief time delay the line is energized again by the automatic recloser. When the fault is removed the line can stay in service otherwise the automatic recloser switches off the line again. In case of a permanent fault the line is switched off permanently after three or four unsuccessful reclosing actions.

The DG can disturb the automatic reclosing process significantly. During the open time of the recloser, the DG unit still energizes the feeder, thus energizing the arc and making the temporary fault a permanent one. The line will be unnecessary, often switched off permanently. Also, during the open time, a small island is created and the DG units tend to accelerate or decelerate, which results in unsynchronized automatic reclosing [16]. This can lead to a serious equipment damage. Because the automatic recloser is a powerful means to protect overhead line feeders, the DG units will have to disconnect before the recloser action takes place.

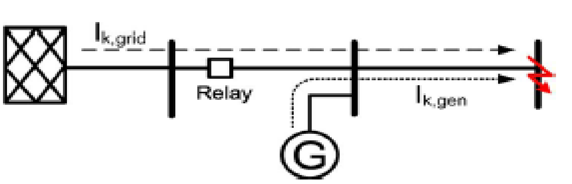

Figure.5 Principle of blinding of protection.

Besides unsynchronized reclosing the coordination between fuse and recloser can also be lost. Temporary faults will then be cleared permanently by the fuse instead of temporarily by the recloser. To restore the coordination of the fuse and the recloser a microprocessor-based recloser may be applied [18]. In the microprocessor, several trip curves can be programmed and the microprocessor keeps track of which curve is in use. The recloser is equipped with fast and slow curves. The fast curve should be programmed in such a way that this curve is selective with the lateral fuses, especially in the presence of the DG. To prevent unsynchronized reclosing, the DG first has to be disconnected, which brings the grid back in the situation without the DG. Hence, the fast curve has to be active only during the first reclosing action. In the second reclosing cycle, the slow curve, which is selective with the lateral fuses, is activated and the fault can be selectively cleared.

Overhead line feeders are widely used in the world. However, the Dutch distribution grid consists of cables only and all faults are permanent, therefore automatic reclosers are not applied. Blinding of protection and false tripping are independent of the type of feeder and will be discussed in the next sections.

II. Blinding of Protection

In Fig. 5, a distribution feeder including a DG is shown. When a short-circuit occurs at the indicated location, both the grid and the DG unit contribute to the fault current. The division of the current contribution depends on the network configuration, grid impedance, and power generated by the DG unit. Due to the contribution of the DG unit, the total fault current will increase. However, the grid contribution decreases. This can lead to a poor fault current detection. It is even possible that the short-circuit stays undetected because the grid contribution to the short-circuit current never reaches the pickup current of the feeder protection relay. This mechanism is called blinding of protection and is also known as protection under reach. To determine the impact of a DG on the short-circuit current a test grid, consisting of an external grid and three cable connected MV nodes, is defined and modelled in the simulation software. Busbar 2 connects a synchronous generator (see Fig. 7). The grid parameters are shown in Table 2. In the test grid, the location and the size of the generator are modified in repetitive calculations. The setup is explained by the flowchart in Fig. 7.

The flowchart contains two loops: one loop to modify the location and the other loop to modify the size of the generator. The location of busbar 2 is adjusted by 10% of the total feeder length, which is kept as a constant. In this way, node 2 shifts from node 1 towards node 3 and the effect of the location of the generator can be observed. After the modification of the location (the distance to the substation and the distance to the feeder end), the second loop is entered performing a three-phase fault calculation at busbar 3 with increasing generator size in 2-MW steps to a maximum of 10 MW. The short-circuit calculation is based on the well-known IEC 909 method. For each loop run, the grid contribution specific for that short-circuit current is stored. When the power generation loop is completed, the first loop is entered again moving the location 10% and the process starts all over.

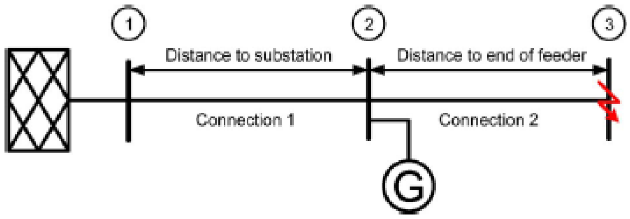

Figure.6 Test feeder blinding of protection

The grid contribution determination tests are run for three-phase and two-phase faults. The results are shown in Fig. 9(a) and (b). In both situations with two-phase as well as three phase faults, it can be clearly seen that the generators have an effect on the short-circuit contribution by the grid itself.

As expected, large size generators influence the grid contribution more than small size generators. The graphs also show that the effect of the generator is most significant near the centre of the feeder. To determine if blinding of protection occurs, the minimum grid contribution has to be compared with the pickup current of the over current protection. Normally, the pickup value is set to 50% of the minimum end of the line two-phase fault current [19]. In the test feeder, the minimum end of the line two-phase fault current without a DG contribution is 2.1 kA, and the pickup current of the over current protection is set to 1.05 kA. In Fig. 8(a) and (b), the minimum grid contributions are 1.75 and 1.58 kA. It can be concluded that in this case blinding of protection will not occur. So, integrating DG into a “sufficiently strong” distribution grid composed of cable feeders of a “moderate length” does not normally lead to blinding of protection.

Cable XLPE 630 mm^2 A1	R=0.063Ω/km	X=0.109Ω/km
$S_{k.grid}$	200MVA	U_1=10 kv
Total feeder length	15 km	

Table.2 Network Data of the Test Feeder of Fig. 6

III. False Tripping

False tripping (also known as sympathetic tripping) may occur when a DG unit contributes to the fault in a adjacent feeder connected to the same substation. The generator contribution to the fault current can exceed the pickup level of the over current protection in the DG feeder causing a possible trip of the healthy feeder before the actual fault is cleared in the disturbed feeder. This is shown schematically in Fig. 9.

The DG unit provides a major contribution to the fault current when the DG unit and/or the fault are located near the substation. Especially in weak grids with long feeders protected by definite-time over current relays, false trip tripping can easily occur. In this case, the settings of the protection relays have to ensure that faults at the end of the feeder are also detected which leads to a relatively low pickup current.

In [15], it is discussed that in some cases false tripping can be prevented by finding another suitable relay setting. In practice, this means that the fault clearing time has to be increased rather than increasing the pickup current.

Increasing the pickup current results in a less sensitive feeder protection which probably may not clear all faults anymore. Changing the fault clearing time leads to disconnecting the faulted feeder first and preventing the healthy feeder from false tripping

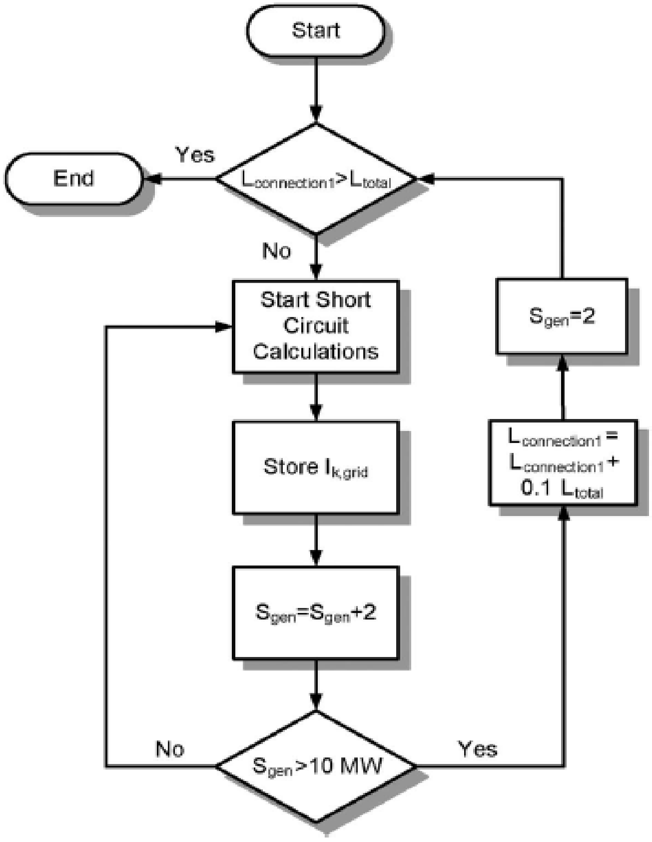

Figure.7 Flowchart to illustrate the repetitive calculations

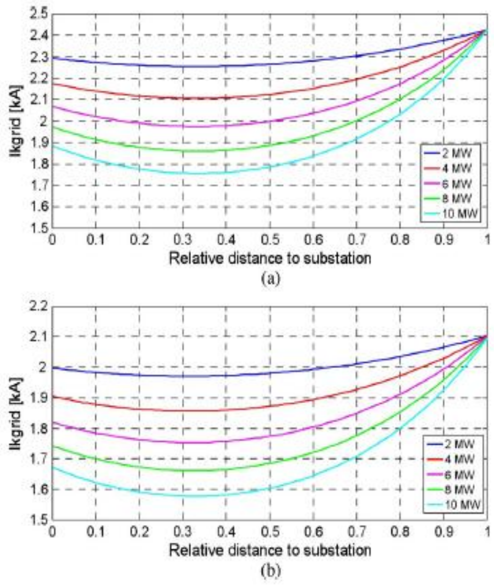

Figure.8 (a) Three-phase fault grid contribution varying generator size and location. (b) Two-phase fault grid contribution varying generator size and location.

IV. MATLAB/SIMULINK MODEL & SIMULATION RESULTS

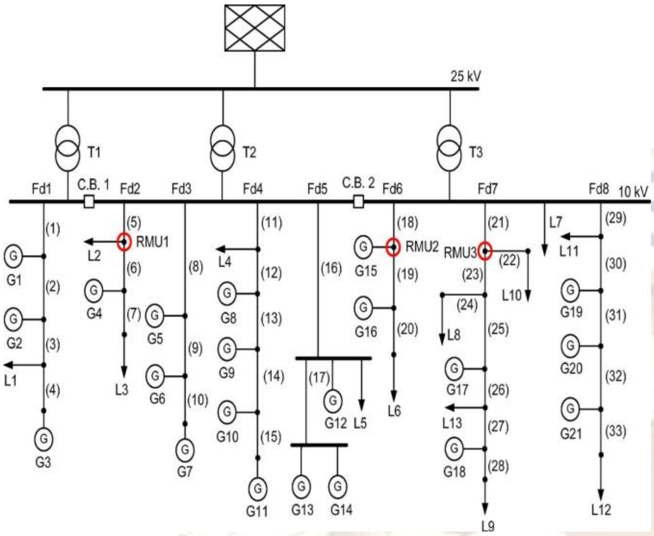

Fig. 9 simulated distribution grid.

	Nominal Voltage Values (V)	Fault Voltage Values (V)
F1	7750	1100
F2	7950	1110
F3	7718	1000
F4	4970	200
F5	8190	1123
F6	8000	1115
F7	7950	1000
F8	7990	650

Table. 3 Without DG

	Nominal Voltage Values (V)	Fault Voltage Values (V)
F1	9991	9990
F2	9830	9510
F3	9990	9987
F4	9998	9994
F5	9540	9440
F6	9977	9970
F7	9990	9960
F8	9965	8760

Table. 4 With DG

From the above tables it is clear that with DG voltage profile at various buses is improved.

V. CONCLUSION

In today's distribution grids the number of distributed generation (DG) units is increasing rapidly. Combined heat and power (CHP) plants and wind turbines are most often installed. Integration of these DG units into the distribution grid leads to planning as well as operational challenges. This paper deals with integration issues of DG units in medium voltage grids. The significant increase of integration of DG units in distribution grids can lead to major planning issues and conflicts with the legal and regulatory framework. Some approaches to overcome these planning issues are discussed. When integration of DG units in the distribution grid also causes expansion of the transmission grid, a prediction-based grid planning is recommended. Finally a Matlab/SImulink based model is developed and simulation results are presented with and without DG under various faults.

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