Distribution Network Schemes Analysis with Distributed Generation

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Abstract – **Nowadays, medium voltage distribution networks are planned and managed for unidirectional power flows. The marked increase in Distributed Generation (DG), expected in the next years, will require a correct integration of the generators in distribution networks to guarantee safety and reliability of the electric system, with respect to the operation constraints.**

This paper proposes a synthesis of various types of distribution networks, for those are pointed out characteristics and problems related to the DG interconnection. Moreover the presented results are obtained by simulations carried out by using different network types. The goal of this analysis is to get the allowable generation limits.

Index Terms – **Distributed Generation, Radial, Loop and Meshed Distribution Network.**

I. Introduction

ELECTRIC power is supplied to final users by means of Medium Voltage (MV) and Low Voltage (LV) distribution networks: their structures and schemes can differ significantly according to loads location. Overhead lines with short interconnection capabilities are mostly employed in rural areas, whilst cables with a great number of lateral connections for alternative supplies are widespread used in urban areas.

In real situations there are a lot of different types of MV distribution networks that are chosen according to loads density and location; the choice is taken in order to achieve these goals:

- good quality of power supply;
- possibility to expand the system;
- simple and cheap construction and management.

Radial structure of distribution systems was often preferred to in respect to other configurations because of its cheap construction and management simplicity. Against, it offers a restricted possibility to expand the system and a poor power quality. DG introduction leads to a redistribution of power flows that may cause overvoltages at the generator connection point and may determine a different lines load factor [1]. Moreover, under fault conditions, the DG contribution to the short circuit current can cause untimely operation of protection devices and an increase of the outage for final users. So, considering high DG levels, it is appropriate to evaluate other distribution network structures which can improve the quality of power supply [2].

In this work a synthesis of some possible types of distribution networks is proposed, considering the operation characteristics and problems related to the DG interconnection. Thus it has been defined some network models obtained by suitably simplifying the Italian distribution network, which some simulations have been carried out on in order to evaluate the maximum power that can be injected from DG regarding different network constraints.

II. Network Model

The study has been carried out on a network model (Figure 1) obtained by suitably simplifying a typical Italian distribution network.

The network is made up as follows:

- two 132 kV HV networks with the same short circuit power A_{sc} of 6000 MVA;
- two HV/MV substations, comprising each a 132 kV HV busbar, a 132/20 kV 40 MVA transformer with Under Load Tap Changer (ULTC) at primary side and a 20 kV MV busbar;
- a feeder, subdivided in three line sections (L_{01}, L_{12} and L_{23}) of 3 km each, which will be connected DG in (DG1, DG2, DG3 and DGu);
- a series of a further passive overhead feeders;
- link lines between various feeder (L_{m1}, L_{m2} and L_{m3});
- configuration switches (I_{m1}, I_{m2}, I_{m3}, I_{p1} and I_{p2}).

The main data used in this work are reported in Table 1.

Tab. 1 Main Simulated Network Data

HV/MV Transformer					
A_n [MVA]	K [kV/kV]	P_{cc} [%]	v_{cc} [%]	P_0 [%]	I_0 [%]
40	132/20.8	0.437	15.5	0.065	1

Synchronous Generator					
P_n [MW]	r_s [pu]	x_d [pu]	x_q [pu]	x_d'' [pu]	x_q'' [pu]
0.66 ÷ 20	0.001	2	2	0.15	0.15

MV Overhead Line							
Size [mm²]	r_d [Ω/km]	x_d [Ω/km]	C_d [nF/km]	r_0 [Ω/km]	x_0 [Ω/km]	C_0 [nF/km]	I_{LT} [A]
Al-Acc 150	0.226	0.384	10	0.374	1.518	4	350

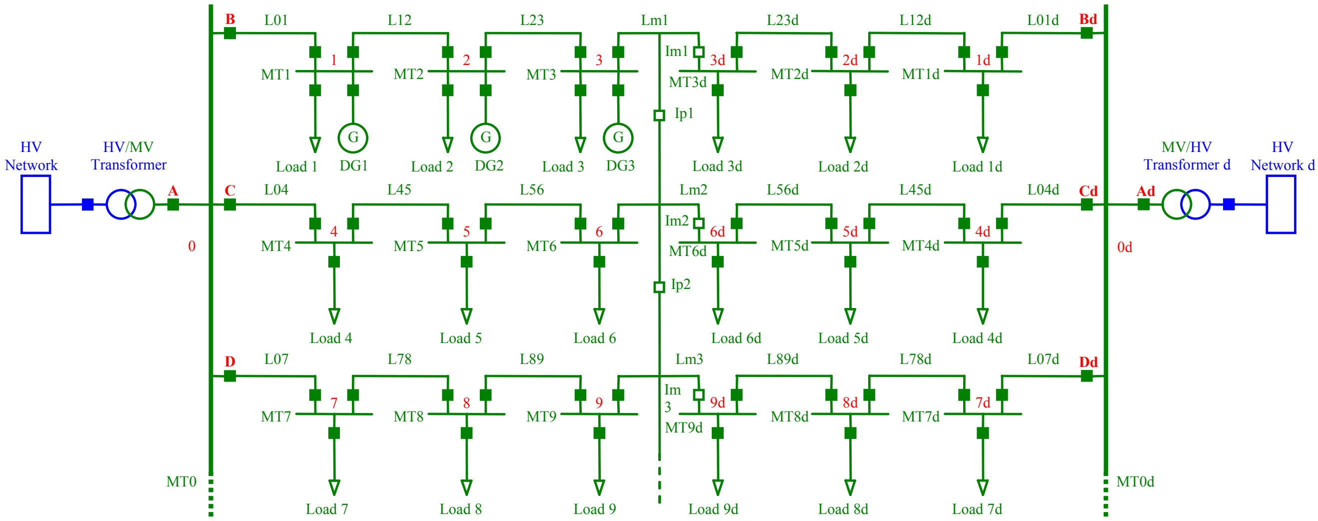

Fig. 1 Distribution test network.

The transformers adopted are equipped with ULTC for voltage regulation placed at HV section. In order to obtain more comparable results, it is assumed that this regulator controls continuously the voltage on the MV busbar, maintaining the same nominal value in each load condition.

The system has been analysed in two load conditions:

- Maximum load: lines are loaded at 60% of their thermal limit corresponding to I_{LT} in Table 1 (P_L = 6.75 MW, Q_L = 3.37 Mvar, cosφ = 0.9^{lag});
- Minimum load: this is about 25% of the maximum load, thus equal to 15% of the thermal limit (P_L = 1.68 MW, Q_L = 0.84 Mvar, cosφ = 0.9^{lag}).

Power generation has been modelled by means of a single synchronous isotropic machine directly connected to the network. This can represent the equivalent of one or more generators connected to the same node. In addition, the interface transformer between the network and the generator has been ignored. This assumption should be considered conservative, particularly in the short circuit analysis, where only the sub-transient reactance x''_d of the machine has been taken into account. Four cases have been studied, with DG concentrated alternatively at busbars 1, 2 and 3, and uniformly distributed (DG_u consists of three generators of equal power connected to busbars 1, 2 and 3).

Various machine sizes have been taken into consideration, between 2 and 20 MW for concentrated generation. In DG uniformly distributed case the total generation capacity has been subdivided between the three nodes. In all cases, the generator power factor[1] has been chosen equal to 0.9^{lag}. Finally, the loads have been assumed to be balanced, each of 2.25 MW in maximum load condition, with power factor of 0.9^{lag}.

Three different network configurations have been examined:

- radial configuration: this is the most used because it is cheaper. This structure is obtained with all the configuration switches open;
- loop configuration: this configuration presents a ring made by two feeders starting from the same substation. This structure is obtained with the configuration switch I_{p1} (I_{p2},…) closed;
- meshed configuration: it is achieved by interconnection of feeder starting from two different substations. This type of network is obtained by closing the configuration switch I_{m1} (I_{m2},…).

III. RADIAL NETWORK

In spite of the variety of possible schemes, distribution networks mostly operate leaving the radial structure. This one is constituted by an HV/MV substation from which several feeders start with unidirectional power flows to the loads. However, in MV distribution networks there is often the possibility of alternative path, in order to isolate an eventual faulted section without long interruptions of loads supply. Therefore in the network there are several line sections to connect each load in different ways; in other words, the network can be reconfigurated as necessary [3]. The system reconfiguration is a very important function in automated distribution networks. Its purpose is mainly to improve the quality of service, to reduce losses, and to boost the network reliability. Nowadays the process of network reconfiguration is carried out keeping the radial layout, because the actual protection devices do not allow right selectivity in other configurations. The line protections, indeed, are realized by using non-directional overcurrent relays placed at the beginning of every feeder [4]. The overcurrent protection threshold has generally a value of 1400 A for the instantaneous trip, one delayed of 250 ms with a value of 800 A and one delayed of 1 s with a value of 1.2 I_n; in this way the trip protection at the minimal fault current, i.e. in the case of short circuit at the end of the line, is guaranteed and

[1] For loads the passive sign convention has been employed while for generators the active one has been used.

the specific energy during the fault (I^2t) is smaller than the one tolerated by cable.

The main advantages in the employment of the radial configuration in distribution networks are:

- simple operation and fast faults location;
- clear distribution in the network of power flows and currents;
- simple and economic construction and installation.

Against, this topology presents:

- insufficient loads splitting between the lines;
- poor widening possibility;
- low quality of supply.

Indeed, an increase of power absorbed by feeder loads causes the overload only in interested line without the possibility to share the load between the other feeders. Moreover, when a fault happens, there is the temporary blackout of the feeder; this causes a short or long interruption, depending on the maintenance procedures adopted, also to the loads connected to unfaulted sections. However it is possible to isolate the fault by employing simple and economic protection systems. In the future, the use of automatic but still inexpensive devices and new communication systems for the remote control of the switches could solve these problems, so they will limit the duration of interruptions but not reduce their number.

The distribution networks aim is to transfer the produced energy to end users. Therefore, excluding rare exceptions, distribution networks do not have own generation systems. In this context the radial structure has always represented a good compromise between economy management and quality of supply. The DG development expected in the next years put the problem of the generators integration in the distribution networks, leaving the possibility to change the network schemes. In radial configuration, the main problems caused by DG introduction regard:

- voltage profiles variation: overvoltages in DG connection point;
- interference with voltage regulation systems in the HV/MV substation: if ULTC regulator implements the load compensation, The connected DG just downstream MV busbars may cause a reduction of load seen by the regulator and then an insufficient compensation;
- protection devices selectivity: untimely tripping of protections placed at the beginning of feeder with DG.

These problems are mostly due to the alteration of the power flows that the DG involves necessarily [5].

In MV distribution networks the voltage regulation is mostly carried out by varying the transformation ratio of the transformer in the HV/MV substation. This is made by employing transformers with winding sections that can be inserted or by using regulator units separated from the main transformer. In any case they need an Under Load Tap Changer (ULTC) that inserts or removes portions of winding maintaining the continuity of the network supply. This is important because it allows to carry out many regulations during the day, about seventy. Against, the ULTC is a delicate apparatus that requires several maintenance operations. The ULTC keeps the voltage of the MV busbar constant in the primary substation, so the downstream distribution network is designed in order to contain the maximum voltage drop (e.g. 4%·Vn) in all buses.

The introduction in the network of generators with variable power (as renewable source) could cause an increase in the ULTC manoeuvres number, and consequently its greater deterioration.

One of the main problems when a generator is inserted in a distribution network consists in selectivity and breaker capacity of protection devices [6].

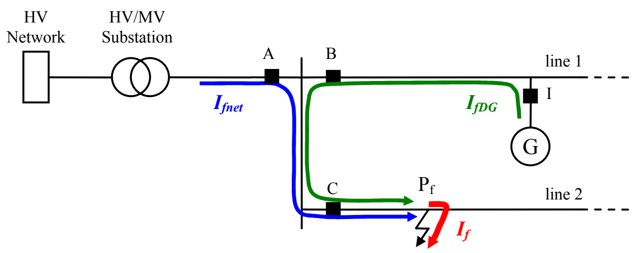

Fig. 2 Protection selectivity interference due to DG in radial network.

In particular, DG could cause selectivity interference of the protection relays in the event of fault on other feeders (Figure 2) in which DG is not inserted, since they are not directional. Without DG, if a fault occurs in P_f, the only contribution to the short circuit current I_f comes indeed from the HV network (I_{fnet}) and causes the trip of the protection placed in C; the relay placed in B is not involved. Vice versa, in the presence of DG, the current I_f is constituted by two contributions: the first one coming from the HV network (I_{fnet}) and the second one coming from the line which the generator is connected in (I_{fDG}). The current I_{fDG} causes the trip of the relay placed in B if it is greater than its instantaneous trip threshold. This phenomenon occurs, in particular, when synchronous generators are present because they can generate a high fault current for long time. Other types of generators, such as the asynchronous ones, generate a short circuit current only in the few cycles after the fault, but this contribution can be sufficient to cause the trip of the instantaneous relays. Finally, DG connected through power converters generally does not have this problem because the electronic interface limits the maximum fault current to a value less than two times of the nominal one.

IV. Loop Network

As a result of the increasing of small IPP (Independent Power Producer), it is possible to employ non-conventional structures in order to achieve better integration of DG in the network and to improve the quality of power for the final users.

The presence of lateral connections in the radial networks for alternative supplies to lines gives the opportunity to employ non-conventional MV distribution network topologies.

An example of these non-conventional structures is the loop network, formed by a closed ring supplied by a single primary HV/MV substation.

This configuration aims to split the power flows among two lines: this permits a more uniform load sharing and greater possibility to extend the network regarding that radial one. Another result, due to the load distribution, concerns the voltage profiles, that in this case are more flatter. From this point of view the loop network allows to inject more power and therefore to connect bigger generators.

If the loop structure offers better performances than the radial one during the normal operation of the network, in fault conditions problems can arise with respect to line protections. Nevertheless, in presence of extensive penetration of DG it could be necessary to adjust the protection system, so it can be advantageous to consider it.

In the network shown in Figure 1 the loop is realized by closing the switch Ip1. As in radial configuration, lines are protected by overcurrent relays installed at the respective beginning.

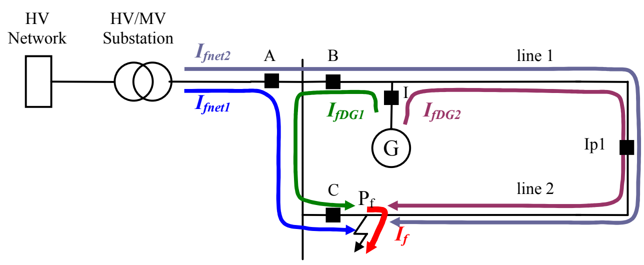

Fig. 3 Protection selectivity interference due to DG in loop network.

Let us suppose that a short circuit happens just downstream the circuit-breaker placed in C (Figure 3). Because of the loop forming, the short circuit current I_f results from two contributions: the first one incoming from upstream (I_{fnet1} + I_{fDG1}) and the second one that reaches from downstream (I_{fnet2} + I_{fDG2}). Since the short circuit is located at the beginning of line 2, the impedance upstream the fault is small so the first contribution is large and such to cause the tripping of switch C. After switch C has opened, the fault is fed through lines 1 and 2. In this case the impedance downstream the circuit-breaker B is the sum of the lines 1 and 2 impedances, so the short circuit current I_{fnet2} could be less than the minimum threshold (1400 A) of overcurrent protection placed in B. Moreover, the second contribution I_{fDG2} could result too small to cause the trip of the generator interface protection as well. However, even if the switch B opened, both lines will go out of service.

In order to get round this drawback it is possible to place an overcurrent protection (Ip1) in the point of connection between the two lines. This switch is located about in the middle of the ring and set on a lower and more selective threshold than that of relays placed in B and C. With respect to the previous example, the contribution (I_{fnet2} + I_{fDG2}) is sufficient to cause the instantaneous trip of the breaker Ip1 leaving closed the switch B; in this way only the out of service line 2 is cut off while the rest of the network remains supplied.

The same problem takes place symmetrically at breaker C for fault immediately downstream the switch B.

For faults outside the loop the same considerations developed in radial configuration are still effective, i.e. with DG, the protections placed in B, C and Ip1 could untimely trip. However it must be observed that, compared with the radial network structure, currents circulating in every branch constituting the loop are smaller, even if the total contribution to the fault current is greater.

V. Meshed Network

Often it happens that inside an area there are more than one HV/MV primary substation, each of them feeding a portion of MV network leaving the radial structure. However, in fault conditions, it is possible to supply some lines of an area from another primary substation; therefore, also in this case the interconnections between the several parts of the network already exist. The meshed distribution networks can be obtained by closing these links also during the normal operation. But this is possible only if the primary substations voltages have the same value and are in phase, otherwise power transfers from a substation to the other could take place and this would cause a useless lines overload and a consequent losses increase. Such conditions can be reached feeding the primary substations from the same HV line and acting on the ULTC in order to regulate the voltage value, otherwise inserting appropriate phase shifter transformers.

Compared with the loop network structure, the meshed network allows a better power flows distribution both in the lines and in primary substations, reducing possible network congestions. Nevertheless, because of the increase of the short circuit power due to the presence of two or more HV/MV transformers, also a rise of fault currents takes place which, in case of many interconnections between lines, can become intolerable for switches and cables. Indeed, as interconnections increasing, the equivalent impedance in the fault point aims at the parallel of all HV/MV transformers impedances: consequently, compared with the radial network structure, the short circuit current will be bigger.

Compared with the loop network structure, where the protection system presents some problems, the meshed network introduces further complications. Indeed, also in the absence of DG, there are always more contributions to the fault current incoming from different primary interconnected substations. Therefore, the protections selectivity can be guaranteed only by adding to overcurrent relays directional relays, because in the case of bilateral feeding of a line the power flows are not intrinsically unidirectional, but can go from one substation to the other one and vice versa. Also in presence of DG, directional relays allow a correct protection system selectivity between inside and outside fault avoiding the drawbacks developed previously. Nevertheless problems can rise when is necessary to place another overcurrent protection in the point of connection between the two lines which is set on the minimum short circuit current value (breaker Im1 in Figure 1). This relay is necessary in order to guarantee the protection against a short circuit immediately downstream the circuit-breaker B (and symmetrically downstream the circuit-breaker Bd). Indeed the relay threshold at the beginning of the feeder, usually employed in MV network, is too high to trip in the event of a fault to the other side of the line. Problems can arise when a fault occurs on a lateral feeder near the MV substation busbar. The contribution to the short circuit current incoming from Bd would be almost the same compared with fault downstream the breaker B, causing wrong tripping of relay Im1, while relay B would not trip because of the directional protection. A possible solution consists in suitably delaying the trip of the breaker Im1 so as to let the instantaneous protections release in order to clear the fault. Another possibility consists in letting relay Im1 trip only after that relays B or Bd released: in this case it is necessary to have a communication and coordination system between the several protections. Because of the low threshold of relay Im1, the introduced delay is such however to guarantee the electrical system safety and protection.

However, the lines protection against the line-to-ground faults and faults between phases can be obtained by replacing the protections installed with electronic devices nowadays. It could be advantageous, being technically correct, to employ protection devices equipped with hardware and software specific for meshed networks against the line-to-ground faults and overcurrent directional relays against faults between phases.

VI. Simulation Results

In order to study the DG impact in network configurations exposed above, parametric simulations have been made, as function of the connection point and the power delivered by DG, in which various constraints have been taken into account. The analysis has been carried out by varying the injected power by DG from 0 to 20 MW alternatively inserted in position 1, 2, 3 and uniformly distributed along the feeder. The maximum injected power value is 20 MW, equal to three times the total feeder load. This assumption is made considering an high DG penetration in the network, therefore, in the table 2, the value of 20 MW indicates that the constraint does not present particular limitations. The first constraint considered has regarded the voltage profiles along the feeder in which the DG is inserted. It has been supposed that:

- the voltage on the MV busbar of the HV/MV substation is maintained to its nominal value by the ULTC transformer;
- the voltage on MV busbars of the MV/LV substations can deviate maximum of ±4% from their nominal value.

At the end users the maximum voltage deviation permitted by International Standards is ±10% from the nominal value in the case of slow variations, i.e. not so fast to cause the flicker phenomenon [7]. However quality level of electrical supply that the distributor must guarantee to the end users must be better, both for the rising sensibility of loads to the voltage variations, and in order not to have an excessive voltage decrease in LV section due to voltage drop on the MV/LV transformer and lines of the LV distribution network.

Figure 4 shows the voltage profiles along the lines in which DG is inserted, both for the radial network and for the loop/meshed one, when the generator is connected in 3.

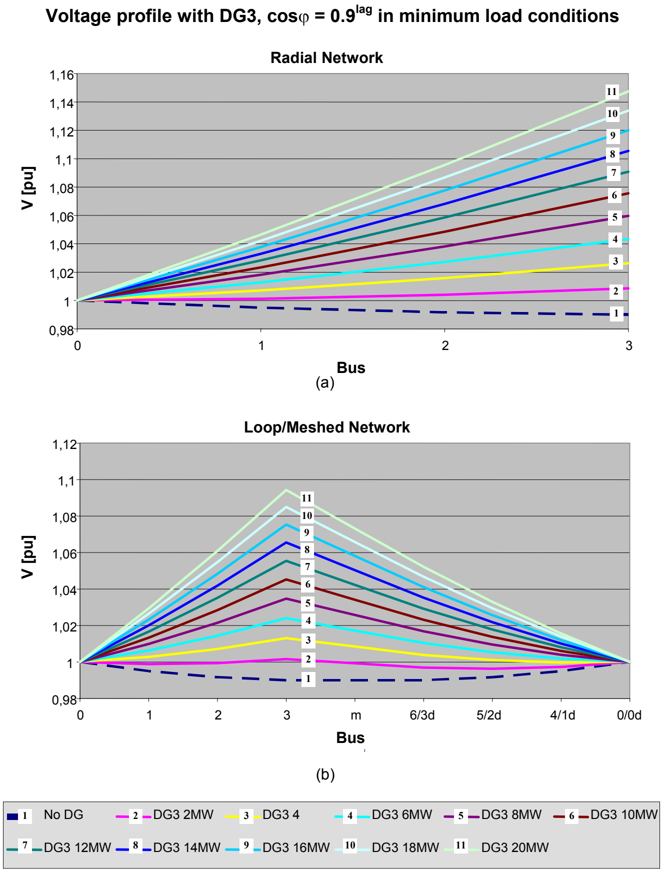

Fig. 4 Voltage profile with DG3 for radial (a) and loop/meshed (b) network.

It can be observed that the redistribution of power flows due to the loop closing causes a lower overvoltage in the DG connection point, consequently the injectable power in that node is greater. This redistribution is greater when the DG connection point moves towards the end of the feeder [8]. This fact is more evident by observing the lines load factor in Figure 5, in which it can be noticed that the loop closing permits a more uniform currents sharing in the lines. Moreover the reduction of the line load factor obtained by the loop scheme allows to reduce the losses in the network [9].

In the case of meshed network voltage profile and lines load factor are the same as the loop one, since the ULTC transformers maintain the same voltage at the beginning of the lines.

The presence of DG connected to the public network causes an increase in short circuit power. This fact gives a greater robustness to the grid to disturbs, but it demands the verification that, in case of fault, the short circuit current does not exceeds the maximum values for which the system components have been designed. This verification allows to obtain the maximum value of injectable power in the network. The problem is to establish the way of how to share the existing margin among several DG systems that ask for a connection to the public network.

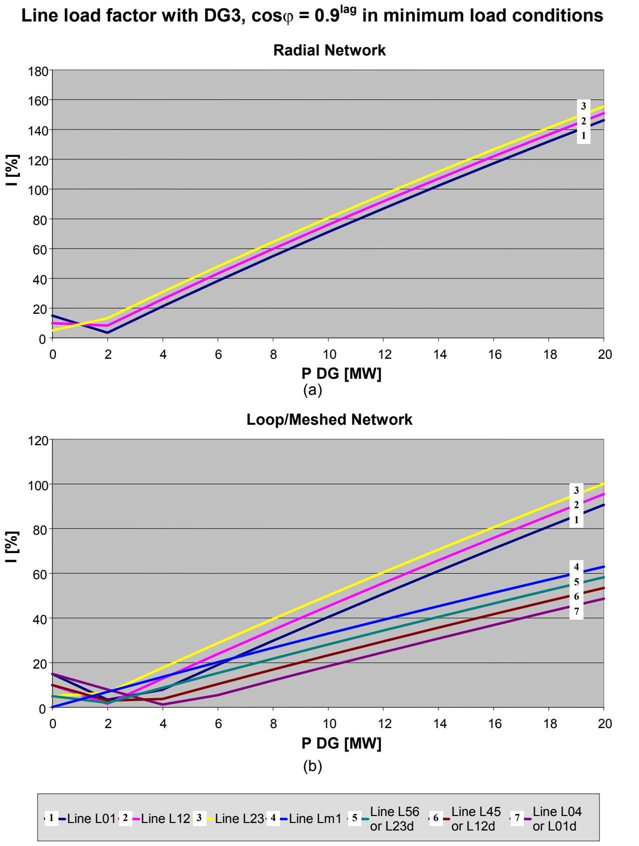

Fig. 5 Load factor of the lines with DG3 for radial (a) and loop/meshed (b) network.

As previously exposed, the DG short circuit current contribution depends on the generator type employed: synchronous generators have high fault currents; asynchronous generators contribute to short circuit current only in the moments immediately subsequent the fault; if the generator is interfaced by means of electronic converters, the fault current can be limited by means of a suitable control of valves. In order to analyze the impact of the DG on the protection system and on the network components various three phase faults have been simulated.

The first one consists in a three phase short circuit downstream the breaker placed in C (Figure 1) in radial network configuration; the fault current incoming from the network and the DG contribution has been analysed. As far as this last one, it has been assumed a maximum value equal to 1.4 kA, i.e. the minimal trip threshold of maximum current protections usually installed at the beginning of MV lines. In order to guarantee the selectivity of protections, it is opportune that the contribution to the fault current due to the generator does not exceed such value. Otherwise, since non-directional protection devices are used on MV networks, it could occur untimely trip due to faults on other lines. It has been observed that the maximum value of the injectable power increases when the DG connection point goes away from the HV/MV substation. The lightly decreasing trend of curve 1 in Figures 6, representing the contribution to the short circuit current incoming from the HV network, is due to the variation of the transformation ratio of the HV/MV transformer.

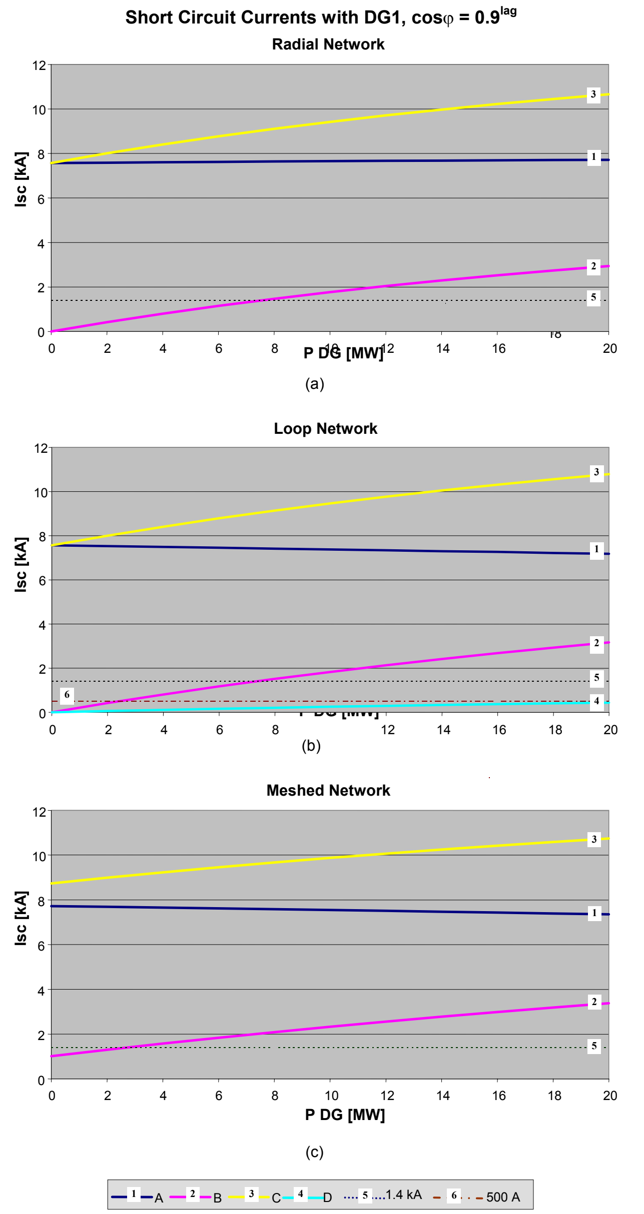

Fig. 6 Short circuit currents with DG1 in case of fault downstream breaker C for radial (a) and meshed (c) network, and in case of fault downstream breaker D for loop network (b).

Curve 2 represents the contribution to the fault current incoming from the generator, this could cause untimely trip of the typical non-directional protections used in radial networks. Finally, curve 3 indicates the value of the current in the faulted point, that represents the short circuit current that breaker C must interrupt.

Also in the case of meshed network various faults downstream the breaker C have been simulated. In this case the critical factor is the maximum value of the fault current, instead of the DG contribution, since the directional protections maintain a correct selectivity in presence of generators as well. Moreover it can be observed in Figure 6 (c) that also in the absence of DG the total fault current (curve 3) consists of two contributions incoming from the two HV/MV substations (curves 1 and 2). The considered constraint for the loop network is that the fault current incoming from the DG must be less than 500 A (curve 6 in Figure 6 (b)), that is the trip threshold of the protection placed in the ring center. Finally in table 2 are reported the maximum injectable powers by the DG for various network constraints.

Tab. 2 Maximum DG injectable power for various network schemes.

Radial Network					
Max. load		**DG1 [MW]**	**DG2 [MW]**	**DG3 [MW]**	**DGu [MW_{tot}]**
Voltage profile constraint	VP	20	12	9	13
Load factor of line constraint	LF	17	15.5	14	18
Selectivity protection constraint	SP	$6^{(1400)}$	$7^{(1400)}$	$9^{(1400)}$	$7^{(1400)}$
Maximum injectable power		6	7	9	7
Tightest constraint		**SP**	**SP**	**SP**	**SP**
Min. load					
Voltage profile constraint	VP	14.5	8	5	8
Load factor of line constraint	LF	13	13	12,5	13
Selectivity protection constraint	SP	$6^{(1400)}$	$7^{(1400)}$	$9^{(1400)}$	$7^{(1400)}$
Maximum injectable power		6	7	5	7
Tightest constraint		**SP**	**SP**	**VP**	**SP**

Loop Network					
Max. load		**DG1 [MW]**	**DG2 [MW]**	**DG3 [MW]**	**DGu [MW_{tot}]**
Voltage profile constraint	VP	20	16	14	20
Load factor of line constraint	LF	20	20	20	20
Selectivity protection constraint	SP	$7^{(1400)}$	$9^{(1400)}$	$7^{(500)}$	$9^{(1400, 500)}$
Maximum injectable power		7	9	7	9
Tightest constraint		**SP**	**SP**	**SP**	**SP**
Min. load					
Voltage profile constraint	VP	17	11	9	13
Load factor of line constraint	LF	14	16	20	17
Selectivity protection constraint	SP	$7^{(1400)}$	$9^{(1400)}$	$7^{(500)}$	$9^{(1400, 500)}$
Maximum injectable power		7	9	7	9
Tightest constraint		**SP**	**SP**	**SP**	**SP**

Meshed Network					
Max. load		**DG1 [MW]**	**DG2 [MW]**	**DG3 [MW]**	**DGu [MW_{tot}]**
Voltage profile constraint	VP	20	16	14	20
Load factor of line constraint	LF	20	20	20	20
Maximum injectable power		20	16	14	20
Tightest constraint		**-**	**VP**	**VP**	**-**
Min. load					
Voltage profile constraint	VP	17	11	9	13
Load factor of line constraint	LF	14	16	20	17
Maximum injectable power		14	11	9	13
Tightest constraint		**LF**	**VP**	**VP**	**VP**

It can be observed that, in general, the tightest constraint is the protection systems selectivity. However such constraint can be easily eliminated by employing opportune interfaces between DG and public network, as some category of electronic converters for new generators type, or by interposing transformers which have a high leakage reactance in the case of synchronous generators that operate at the network frequency.

Vice versa the voltage profiles and the load factor of the lines are constraints that do not depend from the employed type of DG and they can only be eliminated by means of a grid reinforce. Therefore, in presence of DG high level, it is advisable to adopt loop or meshed network.

VII. CONCLUSIONS

Distribution networks are traditionally constructed to be passive. The introduction of generators alters the normal operation of the electrical system and hence requires a careful evaluation of its effects.

The study carried out has been focused around the DG impact in various network schemes and the determination of maximum injectable power as a consequence of various parameters in order to respect constraints arising from voltage profiles, line currents and short circuit currents. In order to do this, a series of numerical simulations has been carried out on a properly simplified network model. For each generator connection point and for each network structure, Table 2 shows the maximum power which can be injected while meeting all the constraints discussed and the tightest one. It can be noted that for radial and loop networks short circuit currents are in general the tightest constraint and that the maximum injectable power increases with distance from the HV/MV station. However, the situation is different if the generators employed are interfaced by means of electronic converters which contribute much less to the fault current. In this case, the tightest constraints are linked to voltage profiles and line currents and the maximum injectable power increases when the connection point draws closer to the HV/MV station. If meshed networks is adopted, directional relays assure the protection selectivity.

From the comparison between loop and meshed networks results it can be noted that they are the same excepted the short circuit current constraint. So, supposing an extensive penetration of DG and in order to assure its better integration in the system, it would be wise to adopt a meshed network or a loop structure only if the DG is interfaced by means of electronic converters, or high leakage transformers.

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IX. Biographies

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