DISTRIBUTION NETWORK INTERCONNECTION FOR FACILITATING THE DIFFUSION OF DISTRIBUTED GENERATION

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SUMMARY

The foreseen increasing diffusion of Distributed Generation (DG) in the distribution networks is giving the impetus to the study of active distribution networks. The recent EU directive 54/2003 may help to accomplish these objectives by defining DG as a planning alternative for distribution expansion problems.

In the paper, considering the importance of interconnection in active networks, meshed schemes have been deeply studied both in steady state and transient condition in order to point out the effect on the integration of DG. In particular, different types of meshed distribution networks have been examined and compared to the radial scheme. Steady state simulations have been performed in order to assess the impact on the voltage profile, on the short circuit level, on the power losses, on the continuity of service, and on the exploitation of lines and transformers. Finally, the greater attention has been paid to analyse the dynamic behaviour of meshed distribution networks. In order to complete the study a mix of different DG sources - directly connected generators or with static converters - have been considered.

RADIAL AND MESHED NETWORK

Traditionally, utility electric power systems were not designed to accommodate active generation and storage at the distribution level. Thus, MV Distribution Networks (DNs) are currently operated according to the radial scheme. The low degree of reliability obtainable with radial network is generally improved by adding emergency ties, that provide alternative routes for power supply in case of outages or scheduled interruptions: such emergency ties end with an open switch so that radial structure is maintained during normal conditions. Therefore, it is reasonable considering the actual MV DNs already partially meshed and they will likely become more meshed in the future due to reliability reasons.

Furthermore, if the DG penetration reaches an high level, as predicted by many authors, Distribution System Operators (DSOs) will be certainly called to properly integrate such amount of DG into the existing electric power systems, fully realizing benefits and avoiding negative impacts on system reliability and safety. DSOs may consider the flexible meshed structure as potentially able to reduce the negative effects of the presence of DG. Reduction of power losses, improvement of voltage profile, and deferment of investment resulting from reduced equipment exploitation are the main advantages expected by the adoption of DG and meshed arrangements.

But, it is prominent to observe that only accurate planning studies can maximise the benefits achievable with either DG and meshed schemes [1]. Indeed, without careful planning strategies, the adoption of a meshed scheme can also worsen some technical aspect of the network operation, especially if the DG penetration level becomes significantly high. In this case, the power losses resume to rise, the voltage profile worsens and the equipment could be again heavily overworked. Obviously, compared to radial, meshed networks present also some drawbacks: a more complex planning and operation, that consequently involves higher costs, and a rising of short circuit current in each node, that may require the substitution of the existing circuit breakers, due to the exceeding of their interrupting capacity. Above all, the whole DNs practice and operation have to be adapted to meshed systems by implementing new control and protection systems and by training personnel to manage the networks in normal and emergency conditions. Nevertheless, meshed distribution networks may allow postponing investments and integrating a massive penetration of DG with few adjunctive costs. These features may in some cases justify the huge amount of money necessary for the changing [2-3].

CASE STUDY

In order to analyse the meshed distribution networks, a test system, a clustered model of a real small part of Italian distribution network, has been considered [4]. The schematic representation of the five different networks investigated, obtained by interconnecting the 8 existing feeders, is shown in Fig. 1. The following classification for the different case studies has been adopted:

- C0: radial configuration (open loop network);
- C1: closed loop network, obtained by closing only the existing open rings;
- C2: 1st meshed level, obtained by connecting two “adjacent” closed loops at about half of their length (adjacent means that they share the same HV/MV substations);
- C3: 2nd meshed level, obtained by using an additional edge to connect two not-adjacent closed loops;
- C4: 3rd meshed level, obtained by adding new edges; which connect the adjacent closed loops at one quarter and three quarter of their length.

The network is constituted by 27 MV/LV nodes and 38 edges, divided in 8 feeders, and supplied by three 132/20kV Primary Substations (PS), identified with PS1, PS2 and PS3 in Fig. 1 (where the PSi has two HV/MV transformers). Synchronous Generators (SGs) have been considered for the steady state analyses. The DG Penetration Level (PL), calculated as the ratio of the DG power capacity and total load demand, has been varied from 10% to 120% [4].
For the dynamic simulations, two scenarios with eight allocation sites have been implemented. The first scenario includes 1MW-SGs in all the eight sites chosen for DG. In the second scenario the three following different types of DG technologies have been considered:
- SGs directly connected to the grid;
- Inductions Generators (IG) directly connected to the grid;
- DC-source interfaced with a static converter to the grid.
In particular, three 1MW-SGs, three 2x0.63MW-IGs, and two 2MW-PWM-Converters (PWM-C) interfaced DC generating units, have been implemented. Thus, the DG PL is 35% and 48% in the first and in the second scenario respectively. Different inertia constants have been considered for their impact on the Critical Clearing Time (CCT) of the SGs ($H_1=2s$ and $H_2=4s$) and the IGs ($H_1=0.3s$ and $H_2=0.6s$).

STEADY STATE BEHAVIOUR

Steady state analyses aim at assessing whether weakly meshed networks have the potentialities to accommodate more generation than radial ones. The expected advantages of weakly meshed networks consist in a more uniform power flow, that allows improving voltage profile, reducing power losses, limiting and balancing the exploitation of lines and transformers.

The studies have been carried out on a portion of Italian distribution network, the same that has generated the clustered network in Fig. 1 [4]. The steady state behaviours have been compared by varying the network configuration (from C0 to C4), the load demand (from 10% to 50% of the equipment loading), and the DG PL (from 10% to 120% of the total load demand). The power losses, the voltage profile, the equipment exploitation and the short circuit level have been deeply analysed in [4]. The followings are the main results:
- The changing from open loop to closed loop networks is generally positive for the DG integration.
- More thicken meshes have to be carefully planned on the basis of the load and generation location [1].
- Short circuit level can increase to intolerable values and this fact can lead to change many switchgears in the network (it should be noticed that even of less gravity, this problem may arise also in radial system with much DG). A solution may be resorting to short circuit current limiters [5].
- The tap-changer use should be revised, because generators modify power flows leading to errors. Meshed networks try to equalize voltage along feeders and this may be useful to achieve an acceptable voltage regulation. In order to have a better voltage regulation DG should contribute to regulation.
- The DG and the meshed network, thanks to the alternative supply paths it provides, allow reducing the equipment exploitation deferring costs for the system upgrading [2].
- Particularly important is the capability of meshed network to withstand severe contingencies; the more thicken the meshed network the more it can withstand to faults in the network.
- Protection coordination is the main issue for the transition from radial to meshed operation. Many authors deal with protection coordination in weakly meshed networks without presence of DG, or, alternatively, in radial networks with DG. In [7] an adaptive protection that can work on weakly meshed distribution networks with DG is presented.

DYNAMIC BEHAVIOUR

With the aim of evaluating the possibility of keeping in service the generators during a network disturbance, three-phase, two-phase, single and two-phase-to-ground short circuits have been simulated, located in many points of the power system (i.e. along the lines or in the MV busbar where the generators are connected, near to the interconnection edges, in the MV busbars of the primary stations, etc.).

The protection logic. In radial network, the protection devices operations have been timed in agreement to the normal protection system practice of Italian distribution networks. The first open of the protection devices has been supposed 300ms after the fault occurrence. Furthermore, to increase the network reliability in case of transient faults (duration $<0.6s$) a high-speed reclosure (300ms after the trip out of circuit breaker) has been planned. In case of an unsuccessfully reclosure due to a permanent fault, another breaker operation has been considered (after further 150ms). In meshed networks, it has been assumed that the protection system is able to automatically localize the fault and isolate the faulty portion of the network to the remaining healthy part [7]. The network, at the event of a fault, is divided into zones by means of automatic circuit breakers remote controlled by a main breaker sited in the PS. The main breaker, equipped with a microprocessor, is able to communicate with the others zone-breakers, and to identify and isolate the faulty zone, independently by the DG size, number, and position. Therefore, when a fault occurs anywhere along the meshed network, the circuit breakers that protect the faulty zone...
firstly trip out after 300ms, then try to reclose after further 300ms, and finally keep close or reopen, depending on the fault is cleared or not.

According with this protection logic, the faults have been distinguished by their duration as follows:

- **Self-extinguishing faults**: extinguished within the operation time of the protection system ($T_{clear}=0.3$ s),
- **Transient faults**: for this kind of faults the high-speed reclosure will be successful ($0.3 \leq T_{clear} <0.6$ s), and
- **Permanent faults**: followed by an unsuccessful reclosure ($T_{clear}=0.6$ s).

**The CCT concept.** The CCT is the most used parameter to evaluate the possibility of keeping in service the generators during a network disturbance [8-9]. Whether the CCT gives enough time to detect and isolated the faulted area, the majority of generators may remain in service during the disturbance (i.e. transient due to self-extinguishing short circuits). It is well known that the dynamic behaviour of each previous mentioned type of technologies differs to each other. Moreover, while the CCT concept is well defined for the rotating generating units (SGs and IGs), its definition appears difficult for PWM-Converter interfaced DG units.

**Synchronous Generators.** SGs, during normal operating conditions, run at synchronous speed. When in the network occurs anything that alters the balance between mechanical and electrical powers the rotor angle changes and starts to oscillate. If the amplitude of rotor angle oscillations increases indefinitely till loss of synchronism, the generator must be disconnected immediately, to avoid re-energization out of synchronism. Alternatively, if a new equilibrium condition between the mechanical and electrical powers has been reached, the generator angle can return to its original value and the speed come back to the synchronism condition. The maximum rotor angle within SGs could remain stable determines the clearing time of protection devices. For SGs, the CCT is defined as the maximum time interval, from the fault instant, within SGs can retain a stable operation and return at synchronism condition.

**Induction Generators.** Also for the IGs, the CCT concept is correlated to the balance between the electromagnetic torque $T_e$, developed during normal conditions, and the mechanical torque $T_m$, applied on the rotor of the associated prime mover. $T_e$ decreases if anywhere in the network a fault happens that reduces the IG terminal voltage. Assuming that $T_m$ is kept constant, the rotor acceleration increases in accordance with the swing equation [10].

If the reduced $T_e$ is sufficiently great to compensate the kinetic energy cumulated by rotating masses during the fault conditions, the IG, following a few oscillations, reaches a new equilibrium operation point. Otherwise the rotor speed continues to increase and the IG loses his stability. Therefore, the CCT is specified as the maximum time within a fault must be eliminated to avoid that IGs exceed their stability limits.

**PWM-Converters.** Many typologies of DG units need DC/AC (i.e. fuel cells) or AC/DC/AC (i.e. microturbines) static converters as interface to the distribution network. By assuming the load power demand always within the power capability of the DG unit and a primary control system keeping constant the DC terminal voltage at the nominal value, the dynamic analysis can be reduced only to the inverter control system, disregarding the behaviour of upstream generation unit [11-12]. In fact, unlike SGs and IGs directly connected to the network, the static converters do not suffer heavily the effects of network disturbances because they do not have the typical inertia of SG and IG rotating masses and they are characterized by a faster response to sudden perturbations than IGs and SGs. The rapidity and the kind of the response depend only and essentially on the control system adopted, which is normally able to keep constants the electrical variables at the interface point [11].

In the paper the scheme adopted for this kind of DG units includes one generic DC source interfaced by a PWM-static converter controlled by a P-Q regulator, that maintains the requested values of active and reactive power by acting on the amplitude and phase of the fundamental voltage [12].

**RESULTS**

Several simulations have been performed in order to obtain some general results about the effect of network meshing on dynamic stability. Directly rotating machines and PWM interfaced DC and AC sources have examined. Preliminary, it should be noticed that PWM interfaced sources have less problems than the SGs or the IGs directly connected to the network. Indeed, the increase of fault level or swing instability is generally not a serious problem. Even in the worst case of long duration faults at the DG bus, the effect is a negligible increase of current at the common bus, generally not exceeding the value of maximum current allowed by the network (the PQ control of the PWM inverter limits the current to a prefixed threshold).

For SGs and IGs directly connected to the network the situation is much more complicated because the effects of faults are related to the mutual position of generators and faults, determining which generators may or may not be kept in service. To better clarify the impact of several factors on generators stability, a small subset of the simulations results has been classified in Table I (the fault points are depicted in Fig. 1). As it can be easily seen the most important factors are the type of generators, the distance from the fault, the inertia constant and, of course, the kind of network. In the following sections the behaviour of radial and meshed networks is compared.

**Radial network.** In order to evaluate the minimum CCT

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**Table I: CCT [ms] of rotating DG units during a three-phase short circuit**

<table>
<thead>
<tr>
<th>DG Units</th>
<th>Distance DG/ fault</th>
<th>Radial</th>
<th>Meshed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C0</td>
<td>C1</td>
</tr>
<tr>
<td>SC</td>
<td>F1 (0.0km)</td>
<td>195</td>
<td>270</td>
</tr>
<tr>
<td></td>
<td>F3 (2.0km)</td>
<td>200</td>
<td>275</td>
</tr>
<tr>
<td>IG</td>
<td>F2 (0.0km)</td>
<td>225</td>
<td>460</td>
</tr>
<tr>
<td></td>
<td>F4 (2.0km)</td>
<td>225</td>
<td>465</td>
</tr>
</tbody>
</table>
The dynamic behaviour of generators connected to meshed networks has the following characteristics:

- All generators connected to faulty lines must be disconnected to allow safe maintenance practices for permanent faults.

Radial and meshed networks compared. In Fig. 2 the rotor angle and the terminal voltage of the SG_02 in Fig. 1 are drawn for a three-phase short circuit in the F3 point lasting 300ms. The effect of meshing is clearly evident, but the increase of CCT can be sufficient to maintain in service only the slowest SG (H_1=4s). The rotor speed and the terminal voltage have been developed for the IG_01 in Fig. 1, in case of a three-phase short circuit followed by a high-speed successful reclosure in both radial and meshed networks (C0 and C2). The plots in Fig. 3 show that the slow IG connected to the C2 configuration may remain in service also after the operation of the protection system and the terminal voltage reasummes the nominal value only when the rotor speed reaches the equilibrium condition. In Fig. 4 the current magnitude and the voltage at the AC terminal of the PWM_03 (bus 6 in Fig. 1) following a self-extinguishing three-phase short circuit (duration 300ms) have been reported. The radial network (C0) has been compared to the C3 case: the terminal voltage reduction is deeper in the meshed configuration, and consequently the current increase is greater. However, the transient behaviour of the current is not characterized by sustained oscillations, as it happens in case of a fault at the traditional rotating unit terminal (Fig. 2-b). The absence of oscillations avoids the risk of nuisance tripping of DG protections. It should be noticed that the fault current increase due to DG connected with static converters is limited to 2.5 p.u. (Fig. 4-a) whereas the presence of SGs raises the current magnitude even to six times the nominal value (Fig. 2-b).

CONCLUSIONS

The DG effect on a distribution network strictly depends on the generators allocation, the network configuration, and the nature of loads. However, it is possible to outline some guidelines useful to understand macroscopically the effects of DG. The paper aims principally at finding these general guidelines with reference to the dynamic behaviour of DG connected to radial and meshed distribution. Indeed, it is a well-known fact that network meshing generally helps to improve stability but the scope of the paper is to analyse this effect in distribution networks with a mix of the most common DG sources. The first general conclusion is that SGs are the most sensitive to faults and this fact remains valid in radial and meshed networks. IGs are generally less sensitive to faults and they can remain in service during faults lasting longer than for the SGs. This phenomenon is clearly exalted in meshed networks and it can be concluded that the thicker the meshes the longer the CCTs are. This means that some generators may remain in service during faults (i.e. transients caused by short circuits) occurred in interconnected networks. The CCT of the generators supplying the meshed network, depending of their inertia constant, gives enough time to detect and isolate the faulted area, allowing the majority of generators being in service. PWM interfaced DG sources do not have any problem to keep in service during the clearing of (CCT_{max}) in radial schemes, the worst fault positions have been selected at the DG terminals (e.g. F1 and F2 in Fig. 1). In addition, with the aim to establish whether the DG connected to the healthy feeder may keep in stable conditions also the branches closest to the sending end (i.e. first lines from the PSs, the closest to the healthy feeder), have been chosen as further fault positions.

The main findings can be summarized as follows:

- All SGs fast (H_1=2s) or slow (H_2=4s) connected to the healthy line may remain in service following a self-extinguishing three-phase short circuit in lines or busbars cleared in standard time (300ms). The fastest SGs connected to the faulty line must be disconnected in a shorter time (CCT_{min}=195ms, Tab. I), whereas the slowest ones may remain in service if the fault has duration less than 270ms.
- The CCT_{min} for IGs in case of a fault at the generator bus is 225ms or 460ms, if the inertia constant is H_1=0.3s or H_1=0.6s respectively (see Tab. I). Thus, for three-phase self-extinguishing short circuits only the slowest IGs may remain in service.
- All the SGs and the IGs connected to the healthy lines remain stables for temporary faults longer than 0.3s (time taken by the protective devices to operate).
- For three-phase short circuit followed by a high-speed successful reclosure (transient faults), while all the SGs connected to faulty lines must be tempestively disconnected to avoid re-energization of SGs out of synchronism, the slowest IGs connected far enough from the fault may remain in service. In any case all DGs must be disconnected within their CCT.
- All generators connected to faulty lines must be disconnected for three-phase short circuits followed by a high-speed unsuccessful reclosure (permanent faults).

Meshed networks. In a meshed network the distinction between healthy and faulty portion of the network is not straightforward. In order to identify the healthy and faulty portions new protections are necessary. In the meshed schemes investigated in this paper protection devices are placed in all the nodes with more than two edges converging. The faulty zone is the one isolated by the protection system within the conventional operating times. The dynamic behaviour of generators connected to meshed networks has the following characteristics:

- After self-extinguishing short circuits slow SGs connected far enough from the faulted point may remain in service. Fast SGs must be disconnected.
- Slow IGs (H_2) may remain in service after three-phase short circuits cleared in standard time (300ms). The fastest IGs may stay connected during the faults only for the weakly meshed configurations (Tab. 1).
- For transient three-phase short circuits followed by a high-speed successful reclosure all slow SGs connected to healthy zones and the fast ones connected far enough from the fault point may remain in service. SGs connected to the faulty zone have to be disconnected.
- IGs may have a CCT that exceeds even the time of the first reclosure (CCT>600ms). Thus, the majority of IGs keeps in service during a transient fault as shown in Tab. I for the weakly meshed configurations.
process. Finally, one of the most important remarks is that a revision of technical standards may be necessary even if the network remains radially operated and, above all, if it will become meshed. Indeed, the requirement of disconnecting all generators connected to the faulty line when the main line breaker trips seems to be excessively precautionary, considering that some generators on faulty line, IGs and PWM, can generally remain in service during the clearing of faults without loosing the synchronism.

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