EFFECTIVE IMPACT OF DER ON DISTRIBUTION SYSTEM PROTECTION

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ABSTRACT

Distributed Energy Resources (DER) operating in radial parts of the distribution network, at low and medium voltage levels, are often considered as a cause of fail-to-trip as well as incorrect trip of over-current protection.
The EU-DEEP project has developed the "hosting capacity" concept, a general methodology that determines the amount of DER which can be operated in a sub-network with an acceptable level of inconvenience. Initially introduced for quantifying the impact on voltage quality, this concept has been extended to the protection scheme performances.
Qualitative and quantitative studies have been performed. Simple closed form approaches have been completed using detailed dynamic simulations to assess more precisely the risks of degraded performances of classic protection systems in presence of significant penetration of DER in distribution.

INTRODUCTION

The presence of significant amounts of DER may negatively impact the protection of distribution feeders in a number of ways. An often-discussed issue is the risk of unintentional islanding. Anti-islanding protection is often in place to prevent this. This protection will however also disconnect the DER units for many disturbances that do not result in islanding. With larger penetration levels, such protection would too much endanger the quality and reliability for other customers. In this paper it has therefore been assumed that the DER units will remain connected during the fault and thus contribute to the fault current. This fault contribution will in turn impact the existing overcurrent protection. In this paper synchronous-machine interfaces have been assumed. Other types of interface contribute less to the fault current, with the possible exception of double-fed induction generators; but their over excitation capacity is fairly limited (further the power electronic must be transiently safe guarded by crow-bar protection).

PROTECTION FAILURE AND HOSTING CAPACITY

Protection systems may fail in two different ways: to unnecessarily remove a non-faulted component (mal-trip); or to not remove a faulted component (fail-to-trip).

The two cases are shown in Figure 1. A mal-trip can occur when the DER unit feeds an upstream fault. This current may overstep the limit of the overcurrent protection at the actual feeder, which will therefore be unnecessarily disconnected. Fail-to-trip occurs for downstream faults. In this case the fault current is mainly composed of the current originated from the DER unit. Therefore, the fault current through the overcurrent protection can be below the setting and the protection remains passive: the faulty feeder will not be disconnected.

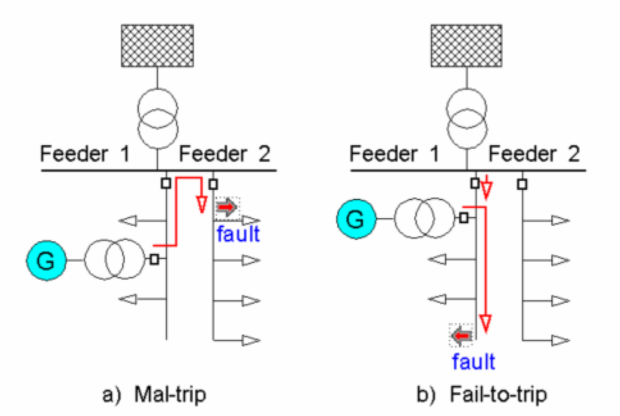

Figure 1 - Mal-trip of feeder 1 during upstream fault (left) and fail-to-trip during downstream fault (right).

In an existing network designed without considering the presence of any DER, some modifications may be necessary with DER present. In order to determine the maximum allowed penetration of DER into an existing network, different indices can be formulated, corresponding to varying degrees of modification, for which varying amount of DER can be accepted. These indices are the base for determination of the so-called 'hosting capacity' [1].
Concerning power-system protection in distribution networks a number of different hosting-capacity levels may be distinguished:

- The penetration level at which it becomes necessary to change the current setting of one of the overcurrent relays. This may be a decrease of the current setting to prevent fail-to-trip (Figure 2) or an increase to prevent mal-trip (Figure 3).
- The penetration level at which it becomes necessary to introduce an additional time delay for one of the overcurrent relays. This occurs when the minimum current for a downstream fault becomes less than the maximum current for an upstream fault (Figure 4).
- The penetration level at which it becomes necessary to add additional circuit breakers or fuses. This occurs when the minimum current for a downstream fault becomes less than the maximum load current (Figure 5).
- The penetration level at which it becomes necessary to replace overcurrent relays by relays with a directional element. This occurs when the hosting capacity in Figure 4 is exceeded for two or more feeders from the same bus.

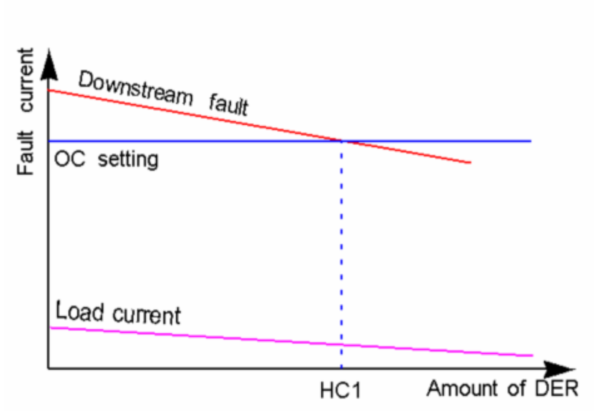

Figure 2 - Need to change current setting to prevent fail-to-trip.

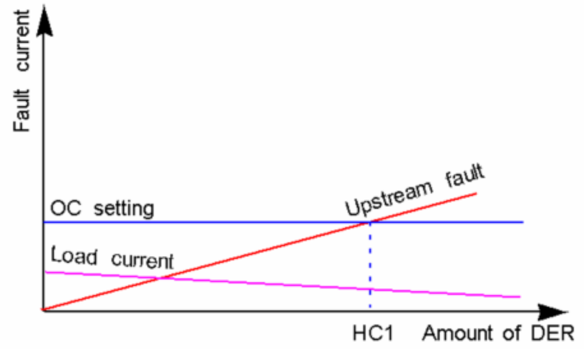

Figure 3 –Need to change current setting to prevent mal-trip.

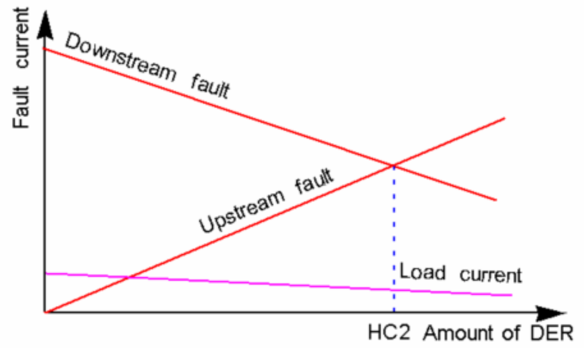

Figure 4 - Need to introduce additional time delay.

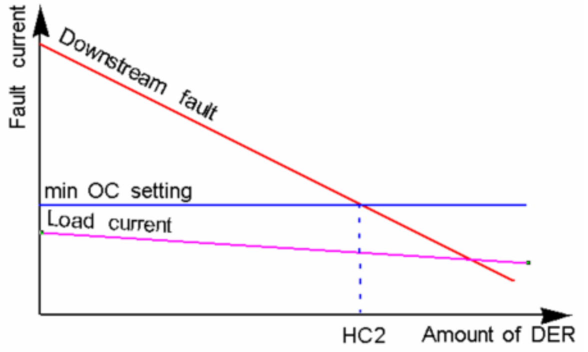

Figure 5 - Need to add a circuit breaker or fuse.

Detailed simulations are necessary to check the importance of these facts in realistic contexts.

DETAILED SIMULATION

The behavior of protection schemes in presence of an increasing proportion of DER is checked using a full dynamic simulation. A test system has been set up using best practice design principles. The single line diagram of this test system is given on Figure 6.
This MV system is supplied by a two HV–MV transformers substation feeding eight 15 kV feeders (4 open loops, in normal operation). One of these loops is explicitly represented. The system is designed for being “N-1” robust. This means that the voltage drop, including the low voltage part of the system, remains acceptable, in peak conditions, when the loop is closed and is fed from one of it extremities, the first section of the other feeder being open.
The protection scheme is set up, the feeder being broken down into three parts, with relays R_1, R_2 and R_3 for feeder 1, and relays R_4 to R_6 for feeder 2. The parameters of inverse-time over-current relays are tuned following state of the art techniques, in the absence of DER, for three phase faults and single phase to earth faults. Single earthing at MV substation through impedance is used.

The response of these schemes is first checked for system without DER. Then it is checked considering synchronous generators installed in different locations in the MV system, along feeder 1.

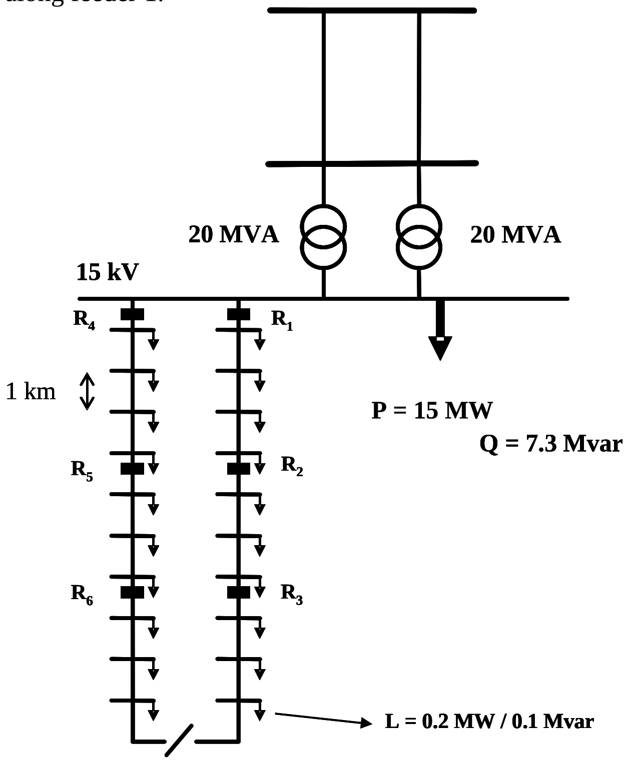

Figure 6 - Test system

Protections selectivity

The fault level at the primary of HV–MV transformers is 525 MVA while the fault level at the MV side is 165 MVA. The peak loading of each of the MV feeders is 2 MVA.
The coordination between relays used for these calculations follows the methodology presented in [2] and [3] using a delay of 300 ms between relays. Setting over-current relays involves selecting the parameters which define the required time – current characteristic of the inverse time relays. This process has been carried out for the phase relays and for the earth-fault relays.
The phase relays characteristics are given in Figure 7.

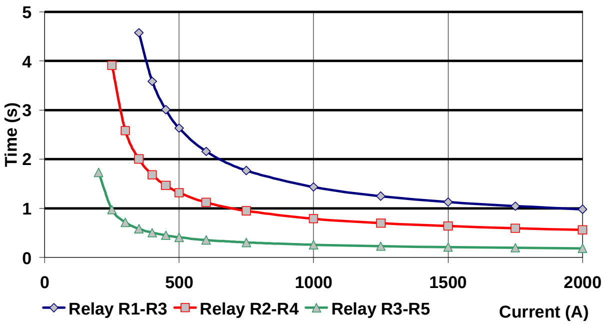

Figure 7 – Relays characteristics

DER selection

In general all forms of DG contribute to some increase to fault levels. The connection of DER to the distribution network could impact the protection scheme, but all DER do not contribute in a similar way.
In order to study the critical impact of DER on the selectivity of protection in the generic network, the worst case scenarios are selected. This means that few, "big" synchronous generators are considered. The performances of their excitation system are supposed independent of the system state as it is the most severe assumption.

Test cases

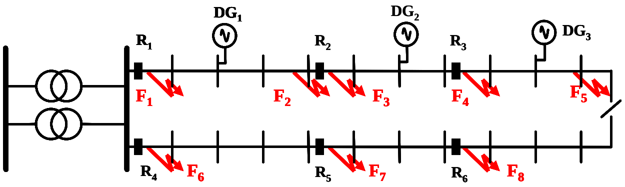

Figure 8 – DER and fault possible locations

The case studies identify problems of relays coordination when synchronous machines DER are present. The work carried out does not consider islanding issues.
Figure 8 presents the possible location of the distributed generators DG_1, DG_2 or DG_3 connected to the MV network and the location of the faults applied (both single and 3-phase faults).

Tests are implemented for normal operation. For abnormal situations, when the open point is placed elsewhere along the second feeder, the protection scheme is no longer selective. This is generally accepted in the common practice because the probability that a fault takes place in such situation is obviously low.
The maximum capacity for a single DER is 7.5 MW, which is more than 3.5 times the After Diversity Maximum Demand (ADMD) which led to the "sizing" of the feeder. Above 7.5 MW voltage issues are encountered, interaction with protection setting can also take place in steady-state.

Results

When a DG of increasing capacity is connected to feeder 1 at DG_1 position, no interferences are noted. But when the power of the DG is sufficiently high, the relay R_1, which is not directional, is finally activated by a too high steady-state current flowing on feeder 1. This is the case when DG_1 produces 7.5 MW. This could be corrected by a slight adjustment of the settings of the relays integrating the higher permanent current.
The grading of the relays makes them more sensitive away from the substation. Hence problems will arise more rapidly when considering DG_2 and will become even more critical when considering DG_3. Results, which are confirming this fact, are only presented for DG_3 with a generation of 2 MW and 4 MW.

DG_3: 2 MW	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
R_1	**0.64**	**0.71**						
R_2			**0.42**					
R_3	**0.73**	**0.72**	**0.72**	**0.15**	**0.16**			
R_4						**0.65**		
R_5							**0.42**	
R_6								**0.15**

Table 1 – Relays operation time (s) with DG_3: 2 MW

With a generated power of 2 MW, Table 1 shows that no major interferences exist. Relay R_3 is operating for fault located in F_1 to F_3 because of its setting. This is taking place in a part of the system that becomes islanded. The spurious response (shaded cells) of this relay, which is located downstream of the fault, is not considered as a problem as islanding regime is not allowed.

DG_3: 4 MW	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8
R_1	**0.64**	**0.71**						
R_2			**0.42**					
R_3	**0.41**	**0.40**	**0.40**	**0.13**	**0.14**	**0.40**		
R_4						**0.65**		
R_5							**0.42**	
R_6								**0.15**

Table 2 - Relays operation time (s) with DG_3: 4 MW

If the generated power is increased up to 4 MW (2 times the ADMD of the feeder), spurious operation of relay R_3 is taking place for faults located on another feeder (red shaded cell). Table 2 shows that the spurious response of relay R_3 is taking place previous to operation of F_4 relay.

For single phase to ground fault all of the faults are selectively cleared for DG power lower or equal to 5 MVA. Figure 9 shows the voltage and the frequency of DG_3 in case of fault in F_3 leading to the trip of R_2 and R_3. The last section of feeder 1 becomes islanded. The islanded operation is simulated and the model used for DER represents voltage and power – frequency controllers. The islanded operation is successful because the load in this section is lower than generator initial power. It can be seen that frequency is sufficiently high during the transient to provoke islanding with usual setting of anti-islanding protection.

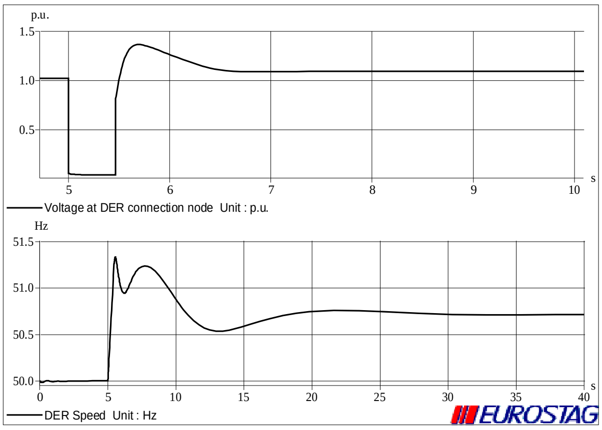

Figure 9 – Response of DG_3 islanded from the system

CONCLUSIONS

The performed calculations show that significant margins exist for the penetration of DER considering present day distribution networks. These calculations took as reference synchronous machines. If power electronic or induction machines are used as interface with the system the conclusions are even more favorable. Further, massive MV connected DER have been simulated, this means that considering LV distributed generation would have permitted still higher percentages of DER integration.

This seems in contradiction with number of results presented so far. This can be explained by the next considerations:

- Significant margins exist because the operation in island is not allowed. In fact in this case the operation of protection schemes based on overcurrent relays cannot be selective, nor distance protections. Also, for DER with low short-circuit contribution, like with power electronic interfaces, even more sophisticated protections can get into trouble.
- These margins are direct consequences of the short-circuit current injected by the transmission network which often largely dominates.
- Comparing different systems, it can be shown that basic implementations of protection scheme are dependent on local specificities. In particular high penetration of air conditioners in the system supposes totally different protections settings, giving significantly more room for DER penetration without interaction with network protection.
- Not all deficiencies of the protective scheme can be considered unacceptable. Indeed in present distribution networks, without any DER, abnormal operation like reconfigured radial network after “N-1” contingency, can lead to non selective relays operation. But this is usually accepted in today distribution networks taking account of the low probability of occurrence of such event.

This paper briefly presents the “hosting capacity” concept that has been set up in the EU-DEEP integrated Project for studying the technical integration of DER in distribution networks. This method is most often based on closed form approaches. More detailed investigations are needed for completing this general purpose methodology.

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ACKNOWLEDGMENTS

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