ADVERSE IMPACT OF DISTRIBUTED GENERATION ON PROTECTION OF THE HELLENIC MV NETWORK – RECOMMENDATIONS FOR PROTECTION SCHEME UPGRADE

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ABSTRACT

The presence of distributed generation (DG) in modern distribution networks has caused a paradigm shift to their operation and protection philosophy. In this paper, the adequacy of existing protection schemes in the Hellenic distribution system is assessed, examining a representative MV network with particularly high DG penetration. The deficiency of the applied protection practices so far is thoroughly discussed and justified by the obtained simulation results. Generally applicable solutions are proposed, which can lead to significant upgrade of distribution protection.

INTRODUCTION

Nowadays, distribution network operators (DNOs) adopt new operational frameworks owing to the electricity market liberalization and the global demand for more "green" power plants. The presence of distributed generation (DG) close to consumption points leads to better efficiency, lower emissions and power losses, as well as economic gain for end-customers. Nevertheless, the large integration of distributed energy resources into modern distribution grids has introduced sophisticated configurations and additional fault current sources, posing thus new threats to the existing protection schemes [1]. Addressing such protection issues becomes even more challenging when DG units operate with conventional machines.

The impact of DG advent on traditional protection schemes is investigated for a representative portion of the Hellenic distribution system, namely the MV network of "Sperchiada". The operation, maintenance, and development of this network are under the responsibility of the Hellenic Electricity Distribution Network Operator (HEDNO). The MV network of Sperchiada is characterized by extremely high penetration of photovoltaic (PV) parks and hydro stations. Distribution feeders are protected by non-directional overcurrent relays with reclosing element, whereas sectionalisers and fuses are used for the protection of laterals and sub-laterals. Protection relays at DG interconnection point operate with under- and overfrequency (81U/O), under- and overvoltage (27/59), neutral voltage displacement (59N), and overcurrent (50/51) elements enabled.

The contribution of this research is manifold and organized as follows. A comprehensive literature review for the protection issues in DG-penetrated distribution networks is presented in the following section. Then, the potential existence of these protection problems, mainly due to hydro units, is exhaustively investigated for the MV network of Sperchiada, taking into consideration various loading and generating conditions. Finally, a gap analysis is carried out for the existing protection scheme of Sperchiada, aiming at the improvement of protection practices applied to the Hellenic distribution system, as well as the revision of the distribution protection code.

OVERVIEW OF PROTECTION ISSUES IN DISTRIBUTION NETWORKS WITH DG PRESENCE

The most common protection problems in modern distribution networks owing to DG presence are thoroughly discussed below.

DG Fault Current Contribution

The penetration of distributed energy resources in distribution grids has significantly changed the magnitude and the flow direction of fault currents [2], [3]. The variation of fault level mainly depends on the technology of DG units (i.e. synchronous or converter-interfaced units), the DG capacity, as well as the location of the point of common coupling (PCC).

Increase of fault current level

The size of power equipment and circuit breakers, as well as the setting values of protection relays, may no longer be adequate. Specifically, the maximum fault level may exceed the short circuit withstand of buses and switchgears in the main substation, and the breaking capacity of circuit breakers (CBs) may be lower than the expected peak fault currents. In addition, coordination of all primary-backup protection pairs in the distribution network may not be ensured due to the increase of minimum and maximum fault currents. Therefore, the adequacy of the existing equipment should be verified and the protection setting values should be revised, after each major change in the network.

Bi-directional fault current flow

In DG-penetrated distribution grids, the power flow direction is inverted when local generation exceeds the local consumption. Moreover, the single direction of short-circuit currents, that is from the main substation to the fault point, does not characterise the modern distribution networks, where fault currents can flow in both upstream and downstream directions.

Impact of Interconnection Transformer

The winding connection of DG interconnection transformers has a major impact on the protection of distribution networks, particularly on the ground fault protection elements. There is no globally accepted best solution [4], and thus DNOs impose the suitable vector group according to their operation practices and interconnection requirements. All candidate vector groups have advantages and disadvantages.

Interconnection transformers with ungrounded high side (e.g. Dd, Dyn, Yd) do not provide zero-sequence current source, therefore they do not affect the sensitivity and coordination of ground fault protection elements in the network. However, overvoltage problems can occur in case of feeder CB tripping, since the islanded part of the network is supplied by an ungrounded source.

On the contrary, interconnection transformers with grounded high side (YNd) eliminate overvoltage problems during ground faults. However, they establish a zero-sequence current source perturbing the sensitivity and coordination of ground overcurrent relays.

Overvoltages that evolve during ground faults can also be eliminated utilising the “YNyn” connection. In this case, zero-sequence current source is added in the distribution network only if the neutral node of the DG unit is grounded. The main disadvantage of this transformer type is that allows the ground overcurrent element of the feeder protection to pick up and respond to ground faults inside the DG station.

Feeder Protection Blinding

Distribution networks were radial and single-fed so far, and protective relays were set to “see” a certain distance down the feeder. This distance is commonly known as the reach of the protective device. When the DG station is located between the utility substation and the fault point, the total fault current is increased due to the partial contribution from DG, as illustrated in Fig. 1. On the other hand, the fault current seen by feeder relay R1 is actually decreased for the same fault, due to the fault current division, and may lead to insensitivity of R1.

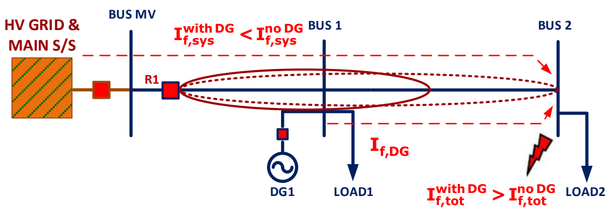

Figure 1 – Change in fault currents due to DG presence (protection blinding).

This unwanted protection performance is widely known as protection blinding [5], [6]. The term of protection under-reach is also used, since the actual reach of the feeder relay is decreased due to DG fault current contribution, as shown in Fig.1. The blinding effect results in delayed protection operation, or even total desensitisation in case of weak upstream system and large DG presence. Detailed investigation can be found in [7].

Sympathetic Tripping

Sympathetic tripping is the undesirable response of feeder relays to out-of-zone faults. It is also called false tripping, and belongs to the wide class of nuisance tripping problems caused by various root causes. In distribution networks, sympathetic tripping is mainly caused by delayed voltage recovery conditions, or DG backfeed to adjacent feeder faults.

DG units can cause false tripping and undesirable disconnection of healthy feeders. This can be made clear in Fig. 2, where a fault occurs at Feeder 2 and the DG unit connected to Feeder 1 feeds the short circuit through the substation MV bus. In case of large DG contribution, R1 may operate before R2 takes action and clears the fault. Sympathetic tripping is very likely to happen when non-directional overcurrent relays are used for feeder protection, which cannot detect the change of fault current direction and discern if faults are forward or reverse. The utilisation of non-directional overcurrent relays was a long-established protection practice of DNOs worldwide, due to the single-fed radial topology of traditional distribution networks. Detailed analysis of sympathetic tripping in DG-penetrated distribution networks is given in [7].

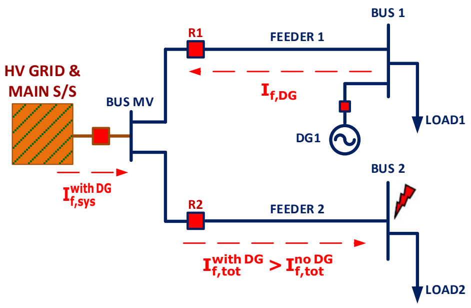

Figure 2 – DG contribution to adjacent feeder fault (sympathetic tripping).

Failed Reclosing

Reclosing attempt with connected DG

A reclosing attempt is deemed to be successful when the time period between consecutive shots is sufficient for the fault arc to dissipate and clear. Therefore, DG protection should be able to detect the faults and disconnect in-service units early in the reclose interval. Otherwise, DG station will continue supplying the fault, hindering the arc extinction, and the fault that would be temporary becomes permanent.

In this case, some customers will experience a sustained service interruption, whereas they should have been subjected to only a momentary one. Furthermore, the active power unbalance during the dead time of the reclosing sequence can lead to frequency fluctuation in the islanded part of the distribution grid, and generators may drift away from the synchronism with respect to the main system [3]. Should the DG units remain in service, a reclosing attempt would couple two asynchronously operating networks which might be destructive for the power equipment.

Loss of fuse-saving scheme

Furthermore, the DG presence in distribution networks challenges the coordination between feeder reclosers and downstream lateral fuses. Fuses are the most common overcurrent protective means in distribution networks, characterised by low cost and high reliability, while automatic circuit reclosers are employed to “give every fault a chance to be temporary” [8]. The majority of DNOs worldwide has successfully applied fuse-saving schemes so far, aiming at the highest level of service availability for their customers.

In a fuse-saving scheme, the recloser operates with its fast curve when a fault occurs, and trips before the downstream fuse starts melting. Then, it recloses its poles after a sufficient time delay, to allow transient faults to extinguish and re-establish cold, non-ionised air at the fault point. In case of a permanent fault, the recloser operates with its slow curve, allowing the load-side fuse to clear the fault.

Fuse-saving schemes are based on the premise that both the recloser and the downstream fuse sense the same current. However, the total fault current is increased due to the DG presence in distribution networks, and thus the branch fuse may see more current than upstream recloser. As a result, the fuse might blow before the recloser’s fast operation, as shown in the coordination diagram of Fig. 3.

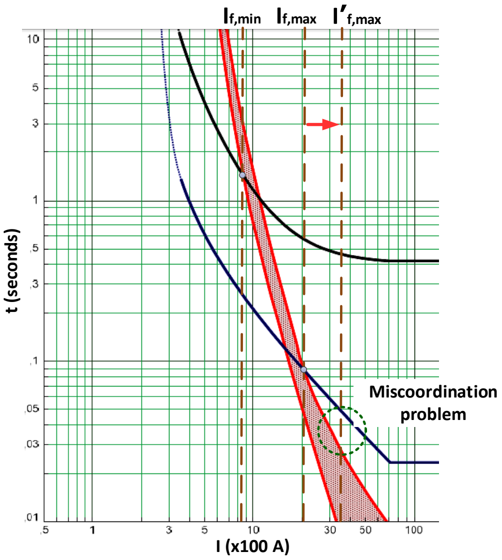

Figure 3 – Loss of fuse-saving scheme due to increased fault current.

Fuse-Fuse Miscoordination

A widely adopted rule of thumb for the coordination between fuses in distribution networks imposes that the total clearing time of the primary fuse must be lower than 75% of the minimum melting time of the backup fuse [8]. However, this safety margin cannot be always maintained when DG units are present, as a result of the increased faults currents. Therefore, backup and primary fuses may blow simultaneously, as illustrated in Fig. 4.

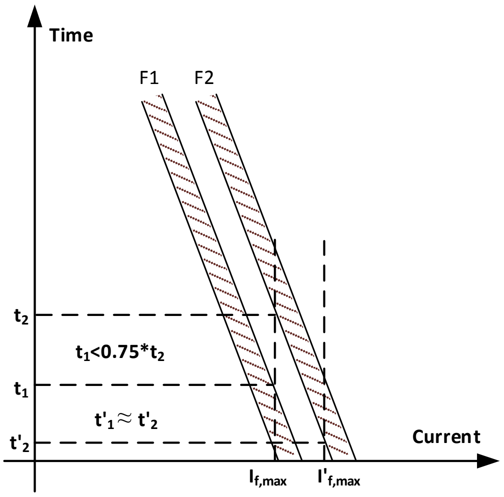

Figure 4 – Fuse-fuse miscoordination due to increased fault current.

PROTECTION PROBLEMS IN THE HELLENIC MV SYSTEM DUE TO DG PRESENCE – THE CASE OF SPERCHIADA

The representative case of Sperchiada MV network was selected by HEDNO to investigate the potential protection threats due to DG presence, and assess the sufficiency of the applied protection practices. This part of the entire Hellenic distribution system is characterised by large penetration of distributed PVs and hydro stations, which leads to power injection into the transmission system under light load conditions.

Operation of Sperchiada MV Network

Network Topology

Sperchiada is a rural area at the centre of the Greek mainland. It comprises a radial distribution network with six feeders, namely P-21, P-22, P-23, P24, P-25 and P-26, supplied by the 150/20 kV substation of Sperchiada. The operating voltage of the MV bus at the substation ranges from 20.3 to 21 kV depending on the loading conditions. The six distribution feeders serve rural loads, and accommodate the DG stations. The length and installed nominal load of each feeder are given in Table 1.

Table 1 – Data of Sperchiada distribution feeders

Feeder	Length (km)	Nominal Load (kVA)
P-21	9.885	200
P-22	17.883	12290
P-23	5.387	13290
P-24	28.079	14135
P-25	7.775	16635
P-26	28.270	6750
Total installed load (MW):		63.3

Distributed Generation

There are 109 PVs and 6 hydros installed in Sperchiada MV network. DG units are connected to the network through step-up transformers with Dyn11 winding connection. The number and installed capacity of DG stations at each feeder are given in Table 2.

Table 2 – Data of Sperchiada DG stations

Feeder	PVs		Hydros	
	Number	Capacity (kW)	Number	Capacity (kW)
P-21	–	–	1	4500
P-22	20	3300	–	–
P-23	11	940	1	3500
P-24	49	3240	2	2935
P-25	24	6929	–	–
P-26	5	500	2	2100
Subtotals	**109**	**14909**	**6**	**13035**
Totals	**Number of DG stations: 115**		**DG Capacity (MW): 27.944**	

MV Network Protection

In the 150/20 kV substation of Sperchiada, the MV incomer (P215) and the CB of each outgoing feeder (P210–P260) are controlled by non-directional overcurrent relays (50P/G, 51P/G). Feeder CBs have also reclosing capability. The reclosing elements are set to execute one fast and three slow operations to prevent extended outages in case of temporary faults. The neutral of the substation transformer at the MV side is grounded through a 12-ohm resistance to limit ground fault currents below 1 kA. A separate neutral overcurrent relay (50N) is used to detect high-impedance ground faults or abnormal unbalances and issue alarm signals.

Concerning the distribution network of Sperchiada, the existing protection scheme was designed considering single-fed radial topology. Laterals and sublaterals are protected by fuse cut-outs or sectionalisers, depending on the maximum served load. There are no reclosers installed in the network, therefore the main trunks are exclusively protected by the associated CB in the substation. Moreover, the 20/0.4 kV distribution transformers are protected by K-type (fast) fuses.

DG stations are connected to the MV network through an interconnection CB, which is equipped with appropriate multifunction protection relay according to the interconnection requirements of HEDNO. The phase overcurrent element (50/51) is activated to protect both the DG station against faults within the facility and the MV network against faults fed by the generating units. In addition, under-/overvoltage (27/59) and under-/overfrequency (81U/O) elements are utilised to detect islanding conditions and disconnect promptly the DG station. The neutral voltage displacement (59N) element is also employed to detect ground faults fed by ungrounded source and broken conductor instances.

Investigation Results

The entire MV network of Sperchiada down to distribution transformers was simulated using PSS/ADEPT 5.3 software of Siemens PTI Inc. Various loading and generating conditions were considered, and the accuracy of the network model was verified by the available power and current measurements of the last five years. To assess the increase of fault level, maximum (close-in three-phase) and minimum (line-end two-phase) short-circuit currents were calculated at each feeder, with DGs in offline and online status, respectively. The obtained results are displayed in the comparison chart of Fig. 5. Ground fault currents are not affected and thus not presented, since DGs are ungrounded at the network side.

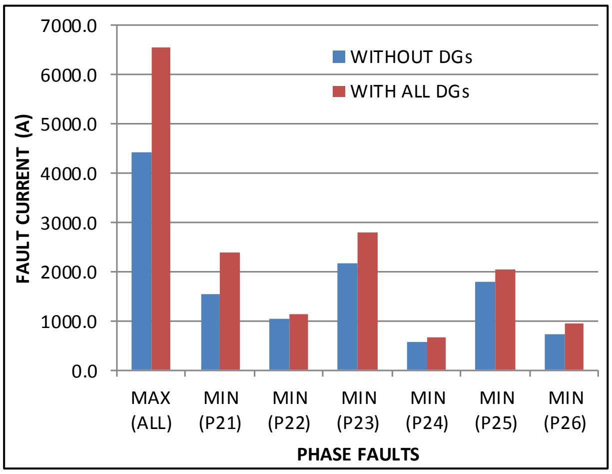

Figure 5 – DG influence on maximum and minimum fault currents in Sperchiada MV network.

Increase of fault current level

As can be seen in Fig. 5, the maximum fault current reaches 6.6 kA. This value is well below the rated short-time withstand current of MV busbars and the rated short-circuit breaking current of CBs in Sperchiada substation, which both are 14.5 kA at 20 kV. Therefore, the existing equipment is deemed totally adequate.

Protection blinding of MV incomer

Numerous fault scenarios were examined to reveal potential insensitivity problems of installed overcurrent relays. It was observed that the feeder protection performance is not affected, since DG units connected to neighbouring lines cause increase in the partial fault current that flows through the CB associated with the fault. However, presence of 13.035 MW hydro generation in the MV network reduces the contribution from the HV system, causing thus partial, or even total, blinding to the MV incomer under minimum fault conditions.

Sympathetic operation of phase overcurrent elements

As has been already mentioned, DGs in Sperchiada MV network cannot contribute zero-sequence current. Thus, sympathetic tripping events are not expected during ground faults. However, a close-in phase fault on any feeder causes sympathetic tripping of phase overcurrent elements at feeders with accommodated hydros, due to the high fault current contribution from hydro units.

Loss of fuse-saving scheme

In the general case, feeder CBs which execute reclosing shots cannot save lateral fuses. The increased fault currents result in instantaneous fuse blowing, and thus CB fast operation becomes ineffective. The fuse-saving scheme can be maintained for some far-end faults, only where the feeder overcurrent relay has to coordinate with the 30T fuse type (maximum fuse rating in Sperchiada), as was deduced from the investigation.

Fuse-fuse miscoordination

Coordination between lateral fuses is ensured for fault currents up to a maximum value, satisfying the “75% rule”. The increased fault currents may exceed this upper limit, causing miscoordination problems. 20T and 30T fuse types in Sperchiada MV network cannot coordinate with each other for fault currents higher than 990 A. As an example, the simultaneous blowing of these two fuses for a three-phase fault on a P-23 lateral is shown in the coordination diagram of Fig. 6.

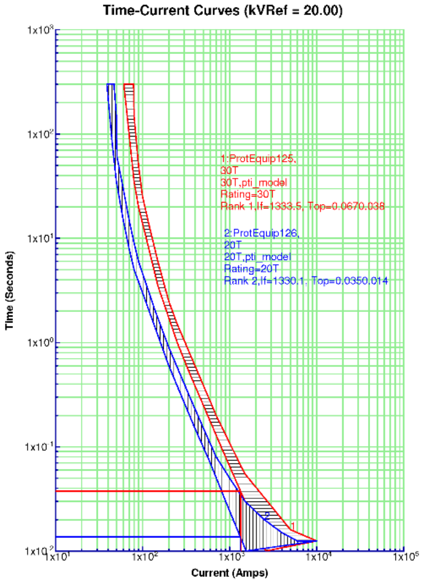

Figure 6 – Miscoordination between 20T & 30T fuses.

RECOMMENDATIONS

The aforementioned protection problems can be eliminated and the overall protection scheme can be considerably upgraded, performing the following actions:

- Revision of short circuit study considering all DG units in service in order to verify the adequacy of the existing primary and protective equipment.
- In addition, revision of relay setting values to prevent blinding incidents, where possible, paying particular attention to minimum faults.
- Feeder protection with directional overcurrent relays or distance relays to prevent sympathetic incidents, even though the installation of voltage transformers augments the upgrade cost.
- Replacement of main lateral fuses with sectionalisers based on the results of cost-benefit analysis, where loss of fuse-saving scheme or fuse-fuse miscoordination is inevitable.
- Utilisation of communication-based transfer trip schemes to provide more reliable anti-islanding protection and prevent failed reclosing incidents.

CONCLUSION

In this paper, the major protection issues arisen in modern distribution networks due to large DG integration were discussed, by examining a representative network of the Hellenic MV system. Thorough analysis of the findings and generally applicable recommendations were given, aiming at the improvement of current protection practices. This work can also serve as reference for distribution utilities with similar network configuration.

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