

A Novel Method to Reduce Direct-Coupled Distributed Generation Impact on Electric Distribution System Protection

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Abstract— This paper presents a method to place, size, coordinate and adequate protection systems in electric distribution networks with directly-coupled distributed generation (DG). DG penetration brings several benefits to the grid. However, adding DG to the grid may cause serious problems. This paper introduces a method to determine the allocation of protective devices, as well as their coordination and sizing. Firstly, recloser allocation problem is treated in a multiobjective approach, solved using particle swarm optimization. Fuse cutouts allocation is determined by a set of rules, developed considering feeders particularities. DG is then considered, and its effects on the protection coordination are evaluated. In order to adapt the grid to receive DG, fault current limiters (FCL) are placed to avoid fuse cutouts miscoordination, as well as recloser - fuse miscoordination. Recloser operation is analyzed to avoid misoperation in the presence of DG. Results are presented for the considered test systems to show the functionality and performance of the proposed method.

Keywords— Distributed generation; Distribution Systems; Fault current limiters; Protection Systems.

I. INTRODUCTION

The operation of traditional electric distribution systems (EDS) are changing due to the development of new technologies that aim to improve energy supply. With smart grids in evidence, also grows distributed generation (DG) penetration in EDS. This distribution sources can reduce power

losses in distribution systems, improve energy quality and voltage profile, among others [1]. However, the increase in DG penetration in traditional EDS causes problems that must be addressed, such as voltage control difficulties, reactive energy management problems, unintentional islanding, protective devices miscoordination, among others [2]. Distribution systems have its protective devices allocated before considering DG penetration, having their coordination already established. DG contribution for fault current alters the protective devices sensitivity, causing several miscoordination problems, demanding new protection studies [3]. In order to solve miscoordination problems, several authors developed methods to reduce the influence of DG on protective devices coordination. In ref. [4] it is presented an adaptive overcurrent protection of DN with DG. The method considers islanding detection, grid re-synchronization and characteristics of downstream relays as an input, measuring voltage, current and frequency. However, the method must calculate the time taken to eliminate the fault to change relays' settings, so, it will permit the fault to last. Moreover, fuse cutouts and reclosers are not contemplated by the method, which makes the method impossible to apply in a real DN. Authors in ref. [5] claim to have developed an adaptive relay mechanism for the complete protection of DN with DG penetration. Although the Fourier algorithm for tracking power system signals was proved efficient, the method is not applicable to the complete protection of DN, since the authors only considered the protection system composed only by overcurrent relays. The authors in [4] developed a multiagent system-based protection and control scheme to deal with several operational conditions

in DN with DG. The method is based on the cooperation between DG controller and relays, being developed and adaptive protection and control algorithm designed on a converter-based wind turbine DG to limit the influence of infeed fault current. With this method the relays have their settings adapted, considering DG control modes. The method considers only relay settings, disregarding recloser settings, which are essential in DN to avoid unnecessary interruptions. In [6] the authors claim to have solved recloser - fuse miscoordination in DN with DG. The method consists in place FCL to reduce fault current to the coordination zone determined by recloser and fuse time - current characteristics. However, this method does not take into account the possibility of DG feeding the fault after recloser fast operation, which makes their practical use unfeasible.

II. PROBLEM STATEMENT

A. DG influence in electric distribution system protection

A traditional radial distribution feeder consists in main feeder and branches that supply loads radially. The protection system is composed by a substation overcurrent relay, recloser, and fuse cutouts protecting lateral branches that feed distribution transformers.

With the insertion of DG sources (synchronous generators directly coupled), the fault current will be the sum of substation contribution and DG contribution for the fault, as shown in Fig. 1.

Current methodologies state that allocating a FCL to limit DG contribution will solve recloser – fuse miscoordination [7] [8] [9]. Considering a coordinated protection system, when a temporary fault occurs, recloser will operate in its fast characteristic. However, depending on DG location, there still will be contribution from DG sources downstream of the fault, and it may cause fuse cutout to blow or the recloser fast curve operation will not clear the fault since the dielectric characteristic of the air will not recover, regardless of nature of the fault (temporary or permanent), as shown in Fig. 2. Therefore, depending on DG short circuit power, it will be impossible to eliminate the electric arc during recloser fast operation, which invalidates these methodologies.

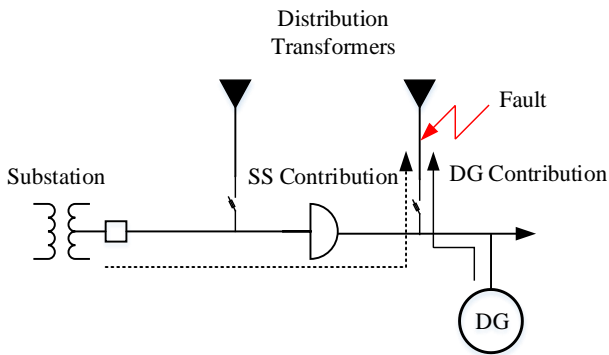


Fig. 1: Substation and DG contribution for fault current

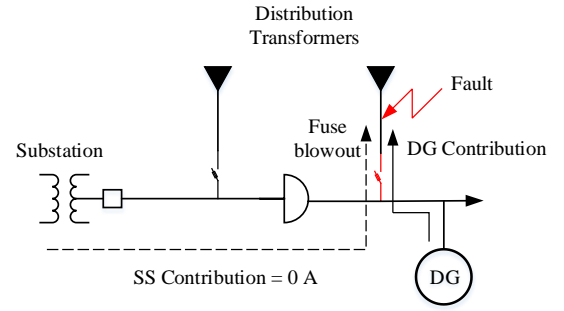


Fig. 2: Fuse blowout due to DG contribution for the fault current

In order to avoid recloser fast operation and fuse blowout due to DG contribution, it is imperative that recloser operational philosophy is changed from coordinated to selective, and that this extra contribution for fault current by DG does not affect fuse cutout selectivity. Therefore, to solve this problem, this paper will present a methodology to allocate FCL to reduce the influence of DG on recloser – fuse miscoordination as well as establish recloser operation philosophy (coordinated or selective) in order to maintain an acceptable reliability level.

B. Objective Functions

Firstly a short circuit calculation is performed in all system nodes. This preliminary calculation is a reference to be used in the optimization process. So, the number, placement and specification of DG that can be connected to any system node is made, allowing any combination of DG. Considering all DG connected, a new short circuit calculation is made and thus the new fault currents are determined.

The objective functions modeled for FCL allocation problem aim to minimize the difference between fault currents that the protective devices are subject to without considering the installation of DG sources and after the connection of DG. Also, the size of the FCL must be minimized, thus restricting the associated cost.

The objective functions are shown in (1) and (2).

$$f_1 = \sum_{n=1}^{n_{pfuses}} |I_{PDG_n} - I_{PNoDG_n}| + \quad (1)$$

$$+ \sum_{p=1}^{n_{ped_fuses}} |I_{PedDG_p} - I_{PedNoDG_p}|$$

$$f_2 = \sum_{k=1}^{n_{FCL}} (R_k + X_k) \quad (2)$$

Where:

n_{pfuses} : Number of protecting fuse cutouts;

I_{PDG_n} : Fault current on the n^{th} protecting fuse cutout, considering DG penetration;

I_{PNoDG_n} : Fault current on the n^{th} protecting fuse cutout, without DG penetration;

n_{ped_fuses} : Number of protected fuse cutouts;

I_{PedDG_p} : Fault current on the p^{th} protected fuse, considering DG penetration;

$I_{PedNoDG_p}$: Fault current on the p^{th} protected fuse, without DG penetration;

n_{FCL} : Number of fault current limiters;

R_k : Resistance of the k^{th} fault current limiter;

X_k : Inductance of the k^{th} fault current limiter.

These objective functions aim to determine FCL placement in order to reduce fault current difference between protecting and protected fuse cutouts with and without DG, in order to maintain selectivity. Also, FCL size must be minimized, to reduce costs, since these devices costs depend on their impedances.

C. Restrictions

Restrictions must reflect technical and economical boundaries, in order to adequate the solution to a feasible region on the search space.

$$I_{i,DG} - I_{i,NoDG} < Tol \quad (3)$$

$$X_{min} \leq X_{FCL} \leq X_{max} \quad (4)$$

$$X_{min} \leq X_{FCL} \leq X_{max} \quad (5)$$

$$(I_{protecting_k}, I_{protected_k}) \leq I_{selectivity_k} \quad (6)$$

Where:

$I_{i,DG}$: Current on the i^{th} feeder section, considering DG;

I_{i,No_DG} : Current on the i^{th} feeder section, before DG connection;

Tol : Tolerance for the difference between currents before and after DG connection;

X_{min} and X_{max} : FCL reactance limits (X_{FCL});

R_{min} and R_{max} : FCL resistance limits (R_{FCL});

$I_{protecting_k}$: Selective fault current in protecting fuse cutout k ;

$I_{protected_k}$: Selective fault current in protected fuse cutout k ;

$I_{selectivity_k}$: Selectivity current limit between $I_{protecting_k}$ and

$I_{protected_k}$.

Restriction (3) states that the fault current difference in feeder section i with and without DG contribution must be lower than a pre-established tolerance. Restrictions (4) and (5) limits FCL size between a minimum and maximum value of reactance and resistance, respectively. Restriction (6) relates to current selectivity limits between fuse cutouts, which must be met.

D. Solution method: Multiobjective particle swarm optimization

To solve multi-objective problems, the Pareto solutions (non-dominated) must be maximized. In multiobjective particle swarm optimization, it is necessary to decide how to select the particles to give preference to those non-dominated and how to maintain the diversity of the swarm. The implementation of multiobjective particle swarm optimization algorithm is shown in the flowchart of Fig. 3. Firstly, the system data is read and short circuit calculations are performed not considering DG connected. The algorithm then considers DG and FCL connections and performs new short circuit calculations, which are considered in the particle swarm optimization technique.

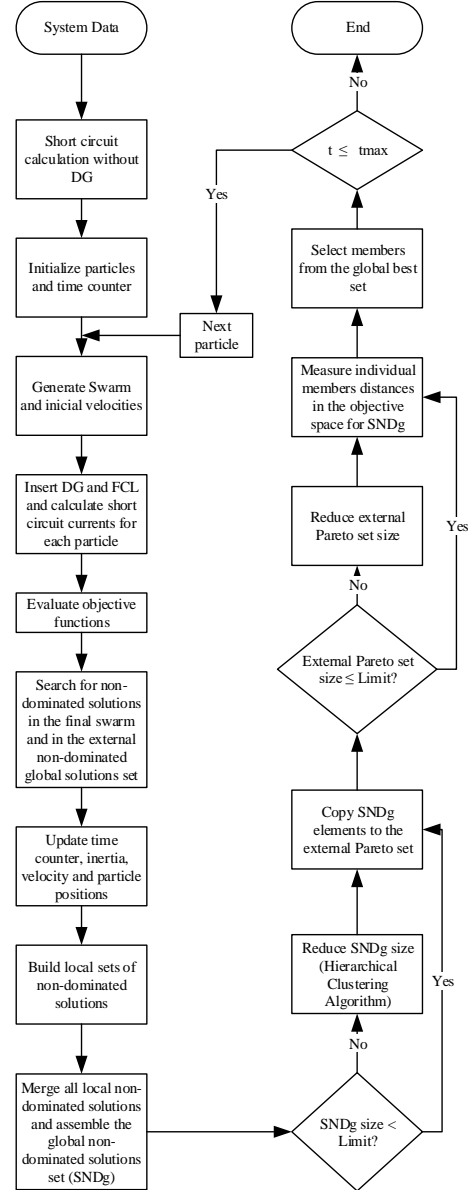


Fig. 3: Multiobjective particle swarm optimization

E. Recloser operational philosophy

To determine if recloser fast characteristic should be on (coordinated) or off (selective), DG position must be investigated. Previously research found in the literature do not consider DG position, and that is proven to be a mistake because of DG contribution to temporary faults when reclosers opens the circuit in its fast characteristic. When DG is located downstream of the recloser, and a fault occurs between these two, there will be a fuse blowout due to DG contribution, making fuse saving scheme not suitable, because there will not be enough time to eliminate the electric arc. To solve this problem, recloser operation philosophy should be switched from coordinated to selective, disabling recloser fast characteristic and allowing the fuse cutout to blow, disconnecting the minimum number of consumers. When DG is located upstream the recloser, it will significantly increase fault current for faults downstream of the recloser and cause recloser – fuse miscoordination, although it will not require recloser philosophy alteration. This paper solved this situation through the FCL allocation.

III. TEST RESULTS

In order to evaluate the method’s efficiency, it is considered a test system widely used in the literature to evaluate recloser – fuse miscoordination

The considered radial test system is shown in Fig. 4, and it was chosen because of the available data [13], being modelled in Matlab® for mathematical purposes and Digsilent® to evaluate technical characteristics. Protective devices placement is shown in Table I. Three DG sources are considered separately and combined, connected to the network directly through a transformer and all combination of DG connections are addressed. DG data is found in Table II. Recloser and fuse cutouts are previously sized and coordinated, using a traditional method [12]. Table III shows FCL allocation and sizing and the adequate recloser operational philosophy for the considered test systems.

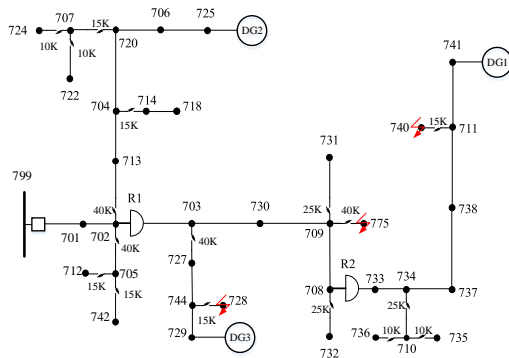


Fig.4: Test System – IEEE 37 Nodes

Faults were simulated in nodes 728, 740 and 775, which represent three different fault directions regarding recloser’s positions. In Table IV, the results are presented for the worst case scenario, depending on which DG is connected.

In Table IV, recloser philosophy is shown for different faulted nodes, where *S* means Selective and *C*, Coordinated philosophy. It is noticeable that, depending on the fault,

recloser must have its fast characteristic disabled to avoid DG contribution for the fault during recloser fast operation.

TABLE I. PROTECTIVE DEVICES PLACEMENT SECTIONS

System	OC Relay	Reclosers	Fuse cutouts
IEEE 37 Nodes	799-701	702-703 (Pos. 1); 708-733 (Pos. 2)	702-705; 702-713; 704-720; 703-727; 709-731; 709-775; 708-732; 734-710; 711-740

TABLE II. DG SOURCES DATA

Parameter	Data
Power	2 MVA
Synchronous reactance (Xs)	2.95%
Transient reactance (X’d)	0.25%
Sub-transient reactance (X’’d)	0.17%
Direct-axis transient short-circuit time constant (T’d)	0.47
Direct-axis sub-transient short-circuit time constant (T’’d)	0.054
DG reactance	9.67%
DG transformer	5%, 12.47kV /480 V
Base voltage	12.47 kV
Base MVA	100 MVA

TABLE III. FCL PLACEMENT, SIZING AND RECLOSER PHILOSOPHY FOR IEEE 37 NODES

DG Combination	FCL Locations	FCL Sizes
DG1	DG1; 730-709	j0.48; 0.48+j0.32
DG2	DG2; 730-709	0.1+j0.28; 0.48+j0.32
DG3	DG3; 730-709	0.3+j0.36; 0.48+j0.32
DG1 + DG2	DG1; DG2; 730-709; 704-713	j0.48; 0.1+j0.28; 0.48+j0.32 0.15+j0.22
DG2 + DG3	DG2; DG3; 730-709; 704-713; 727-744	0.1+j0.28; 0.3+j0.36; 0.48+j0.32; 0.15+j0.22
DG1 + DG3	DG1; DG3; 727-744; 730-709;	j0.48; 0.3+j0.36; 0.48+j0.32; 0.15+j0.22
DG1 + DG2 + DG3	DG1; DG2; DG3; 704-713; 730-709; 727-744	j0.48; 0.1+j0.28; 0.3+j0.36; 0.48+j0.32; 0.15+j0.22

TABLE IV. RECLOSER PHILOSOPHY FOR DIFFERENT FAULTS

#	DG Combination	Faulted node (728)	Faulted node (740)	Faulted node (775)
1	DG1	R1: S R2: C	R1: C R2: S	R1: C R2: S
2	DG2	R1: C R2: C	R1: C R2: C	R1: C R2: C
3	DG3	R1: S R2: C	R1: S R2: C	R1: C R2: C
4	DG1 + DG2	R1: S R2: C	R1: C R2: S	R1: S R2: C
5	DG2 + DG3	R1: S R2: C	R1: C R2: C	R1: S R2: C
6	DG1 + DG3	R1: S R2: C	R1: C R2: S	R1: S R2: C
7	DG1 + DG2 + DG3	R1: S R2: S	R1: C R2: S	R1: S R2: S

It is possible to see that, in case 1, there will be the fast operation of the recloser for a fault in 728. However, DG will continue to contribute for the fault, preventing reclosing and even causing fuse cutout to blow. Recloser philosophy in this case must be selective in order to disconnect only consumers downstream of 728.

In case 2, the coordinated recloser philosophy can be applied due to the fault current sensed by the recloser being composed by the sum of substation and DG. This temporary fault will be removed by recloser's fast operation.

Finally, this novel method cannot be compared to previously developed methods that claim to solve recloser – fuse miscoordination because these do not consider coordination and selectivity aspects and present misconception, being impossible to apply in real systems.

IV. CONCLUSIONS AND RECOMMENDATIONS

The developed methodology was able to efficiently allocate fault current limiters in electric distribution systems in order to reduce selectivity violations between protective devices. Also, unlike several previously developed methods, this technique successfully considered recloser – fuse miscoordination, taking into account recloser operational philosophy selection. FCL placement is responsible for limiting DG contribution to fault current, in order to avoid selectivity violations between fuse cutouts and between fuse links and reclosers, in appropriate situations. The method was applied in a widely used test system for evaluation. The results showed excellent performance, successfully avoiding selectivity violations between fuse cutouts and, consequently, between fuse cutouts and reclosers. Also, reclosers' operational philosophy was changed depending on DG location, avoiding fuse cutouts to

blow or failure of reclosing attempts while DG continues to feed a temporary fault during the reclosing interval after recloser fast operation.

REFERENCES

- [1] Ochoa, L. F., Feltrin, A. P., Harrison, G. P., "Evaluating distributed generation impact with a multiobjective index", IEEE Trans. Power Delivery, v. 21, n. 3, pp. 1452 – 1458, 2006;
- [2] Manditereza, P. T., Bansal, R., "Renewable distributed generation: The hidden challenges – A review from the protection perspective", Renewable and Sustainable Energy Reviews, n. 58, pp. 1457 – 1465, 2016;
- [3] Kennedy, J., Ciuffo, P., Agalgaonkar, A., "A review of protection systems for distribution networks embedded with renewable generation", Renewable and Sustainable Energy Reviews, n. 58, pp. 1308 – 1317, 2016;
- [4] Mahat, P., Chen, Z., Bak-Jensen, B., Bak, C.L., "A simple adaptive overcurrent protection of distribution systems with distributed generation", IEEE Trans. Smart Grid, v.2, n.3, pp. 428 – 437, 2011;
- [5] Kumar, D. S., Srinivasan, D., Reindl, T., "A fast and scalable protection scheme for distribution networks with distributed generation", IEEE Trans. Smart Grids, v. 31, n. 1, pp. 67 – 75, 2016;
- [6] Hussain, B., Sharkh, S. M., Hussain, S., Abusara, M. A., "An adaptive relaying scheme for fuse saving in distribution networks with distributed generation", IEEE Trans. Power Delivery, v. 28, n. 2, pp. 669 – 677, 2013;
- [7] Hussain, B., Sharkh, S.M., Hussain, S., Abusara, M. A., "An adaptive relaying scheme for fuse saving in distribution networks with distributed generation", IEEE Transactions on Power Delivery, Vol. 28, n. 2, April 2013;
- [8] Shah, P. H., Bhalja, B. R., "New adaptive digital relaying scheme to tackle recloser – fuse miscoordination during distributed generation interconnections", IET Generation, Transmission & Distribution, Vol. 8, n. 4, pp. 682 – 688, 2014;
- [9] Chaitusaney, S., Yokoyama, A., "Prevention of Reliability Degradation from Recloser – Fuse Miscoordination Due To Distributed Generation", IEEE Transactions on Power Delivery, Vol. 23, n. 4, pp. 2545 – 2554, 2008;
- [10] Lim Sung-Hun, Kim Jae-Chul, "Analysis on protection coordination of protective devices with a SFCL due to the application location of a dispersed generation in a power distribution system", IEEE Transactions on Applied Superconductivity, vol. 21, n. 3, 2011;
- [13] IEEE Distribution Planning Working Group Report, "Radial distribution test feeders", IEEE Transactions on Power Systems, Volume 6, Number 3, pp 975-985, August 1991.