Assessment of Distributed Generation Influences on Fuse-Recloser Protection Systems in Radial Distribution Networks

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Abstract—This paper proposes a technique for assessment of distributed generation (DG) influences on radial distribution network fuse-recloser protection coordination and recloser pick up sensitivity. The assessment methods employ the use of sequential algorithms in conjunction with protection system models to determine synchronous machine based DG penetration levels that yield loss of non-DG system protection infrastructure adequacy. The assessment techniques are demonstrated through time-domain simulations on a test system using the PSCAD/EMTDC program.

Index Terms—Distributed generation, fuse-recloser protection, power system protection

I. INTRODUCTION

Due to increased consumer energy demands, electrical utility grids are experiencing higher levels of distributed generation (DG) penetration. Grid adaptations are beginning to yield significant changes to system short circuit characteristics, introducing substantial challenges in the realm of system planning and expansion studies [1]-[8].

One such challenge associated with increased levels of DG penetration is the influence that short circuit characteristic changes have on existing protection infrastructure adequacy [1]-[8]. DG size, location and interconnection method play a key role in determining the extent of such influences [3]. This has made it prudent that DG integration issues such as loss of coordination are investigated for the determination of feasible solutions, however such research is still in its early stages.

IEEE Std. 1547 [4] was the first standard that dealt with the DG integration problem. It proposed the disconnection of DG sources from a network during fault conditions, preventing DG short circuit current contribution. Inefficiencies associated with this practice include DG resynchronization and power quality degradation for both temporary and permanent faults [1]-[3].

Although research into the mitigation of DG influences is still in its infancy, solutions have been offered. The use of microprocessor based reclosers for the prevention of protection coordination degradation is proposed in [5]-[6]. This involves the selection of multiple operation-based recloser curves determined during prior system operation analysis. Although feasible, this solution would require substantial investment in upgrading recloser infrastructure.

Another solution that has attracted attention is the use of fault current limiters (FCLs). One such solution using FCLs has been presented in [7]. Reference [7] demonstrates the restoration capability of FCLs in the context of relay coordination in looped distribution networks.

The redesign and reevaluation of existing protection infrastructure based on new system short circuit characteristics is proposed as a solution in reference [3]. Like many other solutions, this would require substantial engineering time investment yielding a high capital cost.

Despite substantial time and cost investment in determining the effects and DG integration and mitigation methods associated to prevention of its detrimental effects, scarce research has been reported on evaluation of DG penetration levels required for these effects to degrade existing protection infrastructure. References [1] and [3] present methods for the determination of DG penetration limits resulting in existing protection infrastructure inadequacy. Although methods are offered, results are not presented in time-domain, meaning that DG effects on system time-domain current characteristics are not adequately evaluated and documented, causing difficulty in replication of results and failure to capture DG source dynamic effects on system faults.

This paper proposes an assessment technique for the determination of synchronous machine based DG penetration levels that yield loss of distribution network fuse-recloser coordination, and recloser pick up sensitivity. The approach demonstrates the effective use of sequential algorithms in conjunction with existing protection system models for the determination of DG penetration limits resulting in protection infrastructure inadequacy. The approach is validated through...
A. System Under Study

![Diagram of the suburban distribution system under study.](image)

Fig. 1. Single line diagram of the suburban distribution system under study.

A modified version of the suburban distribution network presented in [3] and shown in Fig. 1 is used in the investigations in this paper. The system consists of a connection to the utility (modeled as a source behind impedance) connected to a double ended substation with a transformer on each side with a rating of 100 MVA. A tie breaker allows twelve feeders to be supplied by a single transformer. A 2 Ω series reactor (to reduce the highest fault current to approximately 6 kA) is placed on the head end. The two suburban loads of 5 MVA each connected at bus 1 are considered lateral feeders and their protective elements are not investigated in this paper. Buses 2 and 3 have 2.1 MVA residential loads. Bus 4 has a 1 MVA industrial load connected, modeled by a 1 MVA induction motor. Bus 5 has a 1 MVA commercial load connected through a delta/wye transformer. More details on the loads, components and cables are presented in [3]. Buses 2 to 5 are fuse protected at the connections to the feeder backbone, which has a recloser and relay present on the head end. Four coordination paths are therefore present, each with a fuse-recloser-relay scheme (fuse is most downstream device). These paths are feeders to buses 2, 3, 4, and 5. Device ratings in the Appendix are sized in accordance with the following sub-section.

The candidate DG connection points of the system used in this paper are bus 1 to 5 [3]. The coordination paths for buses 2 and 3 are similar so bus 3 is not investigated as a DG connection point in this study. These DG connection locations are based on system studies or client requirements.

B. Protection Coordination

In a typical radial type distribution network, feeders have fuses, reclosers and circuit breakers. The recloser operates quickly at first to allow for temporary fault self-clearing. The fuse is left to clear the fault through a fuse-saving scheme if the fault is still present after the recloser has operated [9].

Traditional protection coordination in radial distribution networks require the determination of minimum and maximum fault currents that may be experienced by the feeder in order to ascertain and set the clearing time for the recloser below or above the fast or slow characteristic curve of the recloser respectively, operating the recloser before the fuse melts and facilitating the self-clearing of temporary faults. For permanent faults the fuse will operate before the recloser utilizes the slow characteristic curve. For coordination to be maintained it is imperative that the fault current levels experienced by the feeder remain in the predetermined minimum and maximum range [9].

C. DG Impact Assessment Methods for Radial Distribution Networks

The proposed impact assessment approach considers the effects associated with increasing levels of DG penetration on previously installed protection infrastructure. These effects can be classed as [3]:

1) Loss of Fuse-Recloser Coordination: DG penetration level that renders Fuse-Recloser protection coordination inadequate in the context of fuse saving schemes.
2) Recloser Sensitivity: the level of DG penetration that yields inabilities in recloser pick-up sensitivity.

In order to determine the effect of DG integration on the above points the following simple algorithms may be used:

Increasing DG source penetration can result in downstream protective devices experiencing greater fault levels than those that are upstream [3]. These devices have been set using short circuit analysis results for a system that excludes DG penetration consideration. For adequate DG penetration levels, inadequacy in the original coordination (current protection settings) and alteration of system short circuit
The case study involves a synchronous machine based DG source connected at bus 1 in Fig. 1. Preliminary studies of the system highlight that the highest fault current occurs for a DG source at bus 1 during a three-phase fault at bus 4. To determine the penetration level that yields loss of fuse-

![Diagram of DG penetration assessment algorithm](image)

**Fig. 2. Proposed DG penetration assessment algorithm.**

1) A DG source is connected to a previously determined candidate connection point.
2) Select the load bus that yields the highest/lowest short circuit current. Apply the fault at the determined load bus.
3) The algorithm allows the engineer to determine if loss of fuse-recloser coordination/recloser sensitivity has occurred, through analysis of the time overcurrent characteristics of the equipment for the given coordination path.
4) If loss of fuse-recloser coordination/recloser sensitivity has occurred then it is necessary to look at the previous iteration of the algorithm. If this is the first iteration or the previous iteration caused loss of coordination/sensitivity then decrease the DG penetration level. Otherwise the DG penetration level is noted.

5) If loss of fuse-recloser coordination/recloser sensitivity has not occurred, previous iteration data must be observed. If this is the first iteration or the previous iteration did not cause loss of coordination/sensitivity then increase the DG penetration level. Otherwise the DG penetration level is noted.
6) Repeat the algorithm and record the DG penetration level for each coordination path.

After each coordination path has a DG penetration size recorded the algorithm ends. The result is the lowest DG penetration level recorded. This is the largest DG penetration level for the selected candidate point before a severe fault will cause fuse-recloser miss-operation. The algorithm is applied to all DG candidate connection points.

III. ASSESSMENT OF SYNCHRONOUS MACHINE BASED DISTRIBUTED GENERATION INFLUENCES ON FUSE-RELOSER COORDINATION

The case study was aimed at investigating the impact of increasing synchronous machine based DG penetration levels in radial distribution networks. Additionally, the feasibility of use of algorithms presented in Fig. 2 in determination of DG penetration levels yielding loss of fuse-recloser coordination is investigated. In order to determine the effectiveness of the algorithm presented in Fig. 2, the network presented in Fig. 1 is used in a case study.

![Case study network diagram](image)

**Fig. 3. Three-phase fault at bus 4 with a 5.2 MVA synchronous machine based DG connected at bus 1.**

The case study involves a synchronous machine based DG source connected at bus 1 in Fig. 1. Preliminary studies of the system highlight that the highest fault current occurs for a DG source at bus 1 during a three-phase fault at bus 4. To determine the penetration level that yields loss of fuse-

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characteristics can result in fuse-saving scheme miss-coordination.

Contextually, adequate DG source size can also yield short circuit current contribution excessive of the utility resulting in possible recloser fault detection inadequacy.

In order to determine DG penetration levels yielding fuse-recloser coordination and recloser sensitivity inadequacy, the following method adapted from the ideas in [3] and presented in Fig. 2 is used (due to space constraints both are presented. In Fig. 2 red signifies it only applies to loss of coordination, blue signifies it only applies to loss of sensitivity). The loss of fuse-recloser coordination (similar for sensitivity) can be explained by:

Select candidate DG connection point

Place DG source at selected connection point

Select a load bus that yields the highest/lowest fault current

Decrease DG size

Increase DG size

Did previous DG size cause loss of coordination/sensitivity?

Yes

No

Has loss of coordination/sensitivity occurred?

Yes

No

Record DG size for fault at specified bus

Yes

Have all load buses been faulted?

No

DG penetration level that first causes loss of coordination/sensitivity for specified connection point is the lowest of the DG sizes recorded

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The proposed DG penetration assessment algorithm is as follows:

1. **Select candidate DG connection point.**
2. **Place DG source at the selected connection point.**
3. **Select a load bus that yields the highest/lowest fault current.**
4. **Decrease or increase DG size.**
5. **Did previous DG size cause loss of coordination/sensitivity?**
   - If yes, proceed with the next step.
   - If no, continue with the same DG size.
6. **Has loss of coordination/sensitivity occurred?**
   - If yes, proceed with the next step.
   - If no, continue with the same DG size.
7. **Record DG size for fault at the specified bus.**
8. **Have all load buses been faulted?**
   - If yes, proceed with the next step.
   - If no, continue with the same DG size.
9. **DG penetration level that first causes loss of coordination/sensitivity for the specified connection point is the lowest of the DG sizes recorded.**
recloser coordination for this case, the setup shown in Fig. 3 is used.

Following the procedure in Fig. 2, the lowest penetration level of synchronous machine based DG connected at bus 1 for the system in Fig. 1 that yields loss of fuse-recloser coordination is 5.2 MVA.

Figs. 4 to 6 present sample time domain simulation results for the case study. They show the loss of fuse-recloser coordination when a 5.2 MVA synchronous machine based DG source is placed at bus 1 with a three-phase fault at bus 4.

![Fig. 4. Recloser/fuse time-domain current and status during a three-phase fault at bus 4 with no DG presence 9 seconds into the simulation.](image)

Analysis of the results (current values are presented in RMS) presented in Figs. 4 to 6 yield the following:

- The short circuit current experienced by the bus 4 fuse increases from 3869 A for the suburban distribution system without DG presence to 4319 A (11.7% increase) and 4064 A (5% increase) for synchronous machine based penetration levels, a bus 1 of 8.4 MVA and 5.2 MVA respectively.

- The short circuit current experienced by the head end recloser decreases from 3917 A for the suburban distribution system without DG presence to 3750 A (4.3% decrease) and 3844 A (1.9% decrease) for synchronous machine based penetration levels a bus 1 of 8.4 MVA and 5.2 MVA respectively.

- The bus 4 fuse will clear the fault in 0.0316 seconds for the suburban distribution system without DG presence. It will clear the fault at bus 1 in 0.0274 and 0.0291 seconds for synchronous machine based penetration levels a bus 1 of 8.4 MVA and 5.2 MVA respectively.

- The head end recloser will clear the fault in 0.029 seconds for the suburban distribution system without DG presence. It will clear the fault in 0.0294 and 0.0291 seconds for synchronous machine based penetration levels a bus 1 of 8.4 MVA and 5.2 MVA respectively.

- For the 5.2 MVA penetrated system, the recloser and bus 4 fuse will clear the fault simultaneously: this is the synchronous machine based DG penetration level that first will yield loss of fuse-recloser coordination.

![Fig. 5. Recloser/fuse time-domain current and status during a bus 4 three-phase fault 9 seconds into the simulation with a bus 1 connected 5.2 MVA synchronous machine based DG source.](image)

Fig. 6. Summary of short circuit currents for an 8.4 MVA and 5.2 MVA synchronous machine based DG source integrated at bus 1 with a three-phase fault applied at bus 4.

- For the 8.4 MVA penetrated system, the bus 4 fuse will clear the fault before the head end recloser.

Similar results were obtained for alternate DG connection points. Synchronous machine based DG penetration levels of 5.5, 3.8 and 3.8 MVA for bus 2, 4 and 5 interconnection points respectively were found to cause loss of coordination.

Comparison of results in Fig. 6 demonstrate that synchronous machine based DG penetration levels beyond 5.2 MVA in the context of the case study will yield loss of coordination. This validates the methodology in Fig. 2.

IV. ASSESSMENT OF SYNCHRONOUS MACHINE BASED DISTRIBUTED GENERATION INFLUENCES ON RECLOSER PICK UP SENSITIVITY

This case study was aimed at investigating the feasibility of use of algorithms presented in Fig. 2 in determination of DG penetration levels yielding loss of recloser pick up sensitivity. To determine the effectiveness of the algorithm in Fig. 2, the network in Fig. 1 is used.

The case study involves a synchronous machine based DG source connected at bus 1 in Fig. 1. Preliminary studies of the system highlight that the lowest recloser current occurs for a DG source at bus 1 during a line-to-line fault at bus 5. To determine the penetration level that yields loss of recloser
pick up sensitivity, the setup shown in Fig. 3 is used however, the line to line fault is placed at bus 5.

Fig. 7. Recloser time-domain current and status during a line-to-line fault placed at bus 5 with no DG presence 9 seconds into the simulation.

Fig. 8. Recloser time-domain current during a bus 5 line-to-line fault 9 seconds into the simulation with a bus 1 connected 55.6 MVA synchronous machine based DG source.

Following the procedure set out in Fig. 2, the lowest penetration level of synchronous machine based DG connected at bus 1 for the system in Fig. 1 that yields loss of recloser pick up sensitivity is 55.6 MVA.

Figs. 7 to 9 present a sample time domain simulation for the case study and show the loss of recloser pick up sensitivity when a 55.6 MVA synchronous machine based DG source is placed at bus 1 with a line-to-line fault at bus 5.

Analysis of the results (values are presented in RMS) presented in Figs. 7 to 9 yield the following:

- The short circuit current experienced by the head end recloser decreases from 851 A without DG presence to 665 A (21.9% decrease) and 556 A (34.7% decrease) for synchronous machine based penetration levels a bus 1 of 8.4 MVA and 55.6 MVA respectively.
- For increasing levels of synchronous machine based DG penetration (in the context of the case study) the recloser current will decrease. This is only evident for faults downstream of the DG source and utility.

Similar results were obtained for alternate DG connection points. Synchronous machine based DG penetration levels of 55.5, 50.5 and 48.8 MVA for bus 2, 4 and 5 interconnection points respectively were found to cause loss of sensitivity.

Comparison of results in Fig. 9 demonstrate that synchronous machine based DG penetration levels beyond 55.6 MVA in the context of the case study will yield loss of recloser pick up sensitivity. This validates the methods presented in Fig. 2.

V. CONCLUSION

This paper proposes a technique for assessment of distributed generation influences on radial distribution network fuse-recloser protection coordination and recloser pick up sensitivity. Results obtained reveal that DG penetration levels of 24% of the load demand supplement power delivered by utility sources. This yields an increase in short circuit current experienced by lateral fuses when fault conditions occur and can result in nullification of fuse-saving schemes employed in radial distribution networks.

Additionally, results demonstrate that loss of recloser pick up sensitivity for the case study presented occurs at synchronous machine based DG penetration levels in excess of 300% load demand. At such high penetration levels, the recloser pick up sensitivity is greatly affected, reducing the reach capability, and leaving sections of radial networks unprotected by head protection infrastructure. This sensitivity loss increases susceptibility of utilities feeding faulted lines if fuse protection fails to operate for permanent faults.

Lastly, the proposed DG integration assessment method offers significant practical value in the domain of network expansion planning. The algorithms presented serve as a method of assessing the adequacy of existing fuse-recloser protection systems in response to DG penetration levels.

APPENDIX


REFERENCES


