

On Optimization of Reliability of Distributed Generation-Enhanced Feeders

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Abstract

Placement of protection devices in a conventional feeder (without distributed generation) is often performed so as to minimize traditional reliability indices (SAIDI, SAIFI, MAIFIE...), assuming the sole source(s) of energy at substation(s). Distributed generation (DG) and storage units located on the feeder may be constrained in terms of power and/or energy capacity, and may include renewable DG units whose output is dependent on the meteorological conditions. Those sources may reduce the number of faults and/or fault durations for customers residing within their protection zones, thus increasing the reliability of service. We propose a procedure for finding optimal recloser positions on the feeder equipped with power constrained distributed generators, using a specially tailored genetic algorithm.

1. Introduction

In a radial feeder, protection devices are only expected to detect the unidirectional flow of current. In a majority of cases, only one device per fault operates. The control logic for protection devices is therefore simple - the nearest recloser upstream from the fault location detects the fault current, trips, and goes into a predefined reclosing sequence in order to restore service, in case the fault was of a temporary nature. If more reclosers are present on the radial feeder, they are coordinated, usually via time lags, such that the recloser closest to the fault operates. Commonly used protection elements include breakers, fuses, reclosers, sectionalizers and switches. Fuses are single-phase devices that interrupt the flow of fault current after a predetermined time delay. Reclosers attempt to re-energize a circuit after a time delay, in case the fault was a self-clearing one. They may be either single-phase or three-phase devices; a three-phase recloser opens all three phases in case of a fault. Breakers may also be single-phase or three-phase devices, commonly with reclosing capability. Switches may be normally open or

closed, and are used to provide a loop feeder structure that may increase reliability, or decrease feeder losses. A normally open switch is often placed on a tie line between two radial feeders. After the fault is cleared, a normally open switch closes to restore service to the customers on a faulted feeder downstream from the fault. Sectionalizers are used to sectionalize the feeder in order to minimize the number of customers affected by the fault, once the flow of the fault current has been interrupted.

In a DG-enhanced feeder, power flow is not unidirectional and conventional protection logic must be altered in order for the fault-detecting devices to successfully perform their function [1]. A faulted branch may be energized from both sides and several protection devices may need to operate in order to completely interrupt the fault current. Several control strategies, using only local or SCADA measurements, may be utilized. Distributed generation and storage units, located on the feeder, may be power and/or energy limited, and may include renewable DG, whose output is dependent on the meteorological conditions. These sources may reduce the number of faults and/or fault durations for customers within their protection zones, thus increasing the reliability of service. We propose a method to include the DG units into the reliability indices calculation. The following related optimization tasks may be investigated:

- Optimize recloser placement for a given DG allocation.
- Optimize DG placement for a given recloser allocation.
- Optimize both recloser and DG placement.

We present a genetic algorithm (GA) designed to solve all three problems. We present the results for the recloser placement problem, assuming the DGs are already deployed on the feeder. However, the algorithm can be readily extended for the remaining two problems by adjusting the optimization function and algorithm properties.

2. Conventional feeder design

Protection devices placement in a conventional (radial) feeder is designed to maximize network reliability, and therefore minimize the traditional reliability indices assuming energy source(s) located only at substation(s). As a brief reminder, we will look at the standard reliability performance indices, such as SAIFI, SAIDI and MAIFIE, and the composite index obtained as a combination of all three. The system average interruption duration index (SAIDI) and the system average interruption frequency index (SAIFI) are typically used to measure average accumulated duration and frequency of sustained interruptions per customer, and are defined as follows:

$$SAIDI = \frac{\sum N_i}{N_T} \quad (1)$$

$$SAIFI = \frac{\sum r_i N_i}{N_T} \quad (2)$$

where N_i is the number of interrupted customers for each interruption event, N_T total number of customers, and r_i is the restoration time for each interruption event. The momentary average interruption event frequency index (MAIFIE) measures the number of momentary interruptions per customer.

$$MAIFIE = \frac{\sum ID_i N_i}{N_T} \quad (3)$$

where ID_i is the number of interrupting device operations. One can optimize the recloser placement with respect to any of these three, or some other, indices. In order to include the effects of both sustained and momentary interruptions, a composite index may be used, as defined below:

$$C = W_{SAIFI} \frac{SAIFI - SAIFI_T}{SAIFI_T} + W_{SAIDI} \frac{SAIDI - SAIDI_T}{SAIDI_T} + W_{MAIFIE} \frac{MAIFIE - MAIFIE_T}{MAIFIE_T} \quad (4)$$

where W_x indicates appropriate reliability index weights, and the subscript T indicates the target value. In the numerical example provided later in the text, we will use the default weights W (0.2, 0.4, 0.4) and targets (1, 2.2, 7) for SAIFI, SAIDI and MAIFIE respectively. Note that these target values indicate satisfactory level of reliability

for a conventional feeder, and may be exceeded in a DG-enhanced feeder yielding negative values for the composite index c .

The conventional logic suggests placing a recloser at the half of the radial feeder with uniformly distributed load, which, in theory, would yield a 25% feeder-wide reliability improvement, assuming uniform load distribution. Similarly, locations at 1/3 and 2/3 of feeder length should be considered if two reclosers are to be placed. In real life situations, in the presence of critical loads and non-uniform load distributions, utilities often resort to engineering judgment to place reclosers according to the reliability guidelines. As an example, Figure 1 shows a typical rural feeder, with substation breaker and two reclosers. Assuming there is no DG at the end of the feeder, a fault anywhere on the line will lead to the opening of the first recloser upstream from the fault. For example, after a fault between reclosers 1 and 2, recloser 1 operates, leaving all customers downstream without service. If DG is present, recloser 2 would also operate, allowing the portion of the feeder downstream from it to operate as an island.

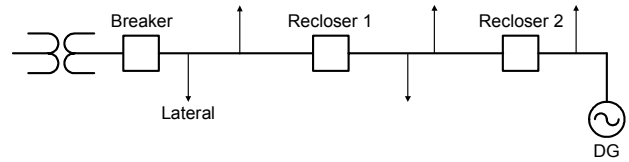


Figure 1. Strategically placed reclosers increase reliability of the system by reducing the number of customers affected by the fault.

3. DG-enhanced feeder design

After the fault is isolated, distributed generators in the part of the feeder not affected by the fault may be allowed to reconnect and operate in stand-alone, or islanded mode, reducing the number and duration of outages to the customers in their respective zones. In order to operate in island mode, DG(s) have to be able to satisfy the islanded load, and therefore keep both the voltage and frequency within acceptable ranges. Islanded operation requires significant coordination of distributed generators with feeder protection devices. The sequence of events after the fault should be as follows:

- DG is tripped, and fault detected and isolated by one or more protection devices.
- DG reconnects if not within the faulted zone.
- After the fault is cleared, recloser synchronizes its reclosing operation with DG.

The positions of protection devices and distributed generators are therefore strongly dependent. Incorrect recloser placement may lead to islands with not enough generation and would not yield additional reliability benefits. On the other side, by strategically placing reclosers, one may be able to significantly increase the reliability of service to customers in such islands.

The distributed generation and storage systems deployed on the feeder are limited in power and energy capacity, which limits their reliability contributions. Power limited generator is able to supply the load up to its rated power, as long as the fuel is supplied. If the power output of the generator is sufficient to supply the local feeder load, it will continue to feed the islanded load, which will decrease the number of sustained interruptions, lowering both the SAIFI and SAIDI indices. If the load becomes higher than the generator power output, there will be an interruption, however the duration time, and incidentally SAIDI, will decrease. Energy limited generators (and storage systems) are able to sustain the load for a finite known period. If the fault is cleared before the energy runs out, they will also reduce both SAIDI and SAIFI; in other case, only the SAIDI will be reduced.

The renewable distributed generators, such as photovoltaic and wind systems, create additional difficulties in quantifying their reliability benefits, due to the probabilistic nature of their input (sunshine, wind) and their power output. If an energy storage system is used in addition to renewable DG, duration of time and the load that it can support in an island will increase due to renewable DG generation. However, if only renewable DG with random energy input is placed in an island, it could not be relied upon to support its local load.

Typically, there will be a momentary interruption to the customers in the island, due to the need for the DG to disconnect after the fault in order not to interfere with protection devices' operation. If however, reclosers are able to disconnect immediately, there may not be even a momentary interruption, and thus MAIFIe index may also be reduced.

4. Genetic algorithm for recloser placement

In a DG-enhanced feeder, the optimization is not as straightforward as in the case of a conventional feeder, due to the presence of additional generators, which may be able to satisfy portions of the feeder load after fault has been isolated, as shown in the simple example presented above in Figure 1. In a large, meshed network, the task of locating optimal recloser positions that would create possible self-supporting islands is not trivial. The optimal recloser position(s) depend on the types, locations and

sizes of distributed generators deployed at the feeder. Conversely, if the reclosers are already placed on the feeder, optimal DG positions and sizes can also be determined. Finally, both the placement of reclosers and DG can be optimized concurrently during the planning stage of the feeder design.

We propose a simple genetic algorithm (GA), based on the algorithm presented in [2], to solve for optimal recloser positions, by minimizing the composite reliability index, described in (4). Genetic algorithms are suitable candidates for such optimization problems, due to the nature of the optimization function. The search space is spanned by mimicking the natural principles of reproductive evolution. Starting from an initial population of individuals, GAs effectively implement the 'survival of the fittest' strategy – fitter individuals (those with higher values of the optimization function) are more likely to reproduce and/or survive to the next generation, thus improving the overall population. The population evolves using two genetic operators, mutation and crossover. Various techniques exist for selecting the individuals that will continue on to the next generation, and/or be chosen for mutation and crossover, which can all be fine-tuned depending on the application. The GA terminates either after a pre-specified number of generations or after population converges to a single solution.

In our application, the elements of the parameter vector X are positions of individual reclosers to be placed on the feeder, i.e. the dimensions of X are $N \times m$ - N being the number of possible branches in the system where reclosers may be placed, and m being the number of reclosers considered. The composite reliability index is chosen as an optimization function. Since reclosers can only be placed on feeder branches, the optimization is a discrete optimization problem; throughout the optimization procedure, all operators were adjusted to produce only discrete numbers.

For selecting the individuals chosen to continue into the next generation, we use a normalized geometric ranking selection procedure, where a probability of selecting each individual is given by

$$p(x_i) = \frac{q(1-q)^{r-1}}{1-(1-q)^P} \quad (5)$$

where q is the probability of selecting the best individual (given in advance), r is the rank of the individual after sorting (1 being the best), and P is the population size. Additionally, the elitist model is implemented, with the best individual always included in the next generation.

In the crossover step, we employ a combination of arithmetic and heuristic operators. Arithmetic crossover provides random mixture of individuals, while heuristic

operator also incorporates fitness information, resulting in individuals more likely to have higher values of the objective function. Arithmetic crossover produces offsprings c_1 and c_2 from parents p_1 and p_2 , by calculating linear combination of parents, i.e.:

$$\begin{aligned} c_1 &= \alpha p_1 + (1-\alpha)p_2 \\ c_2 &= (1-\alpha)p_1 + \alpha p_2 \end{aligned} \quad (6)$$

where α is $U(0,1)$, uniformly distributed random number between 0 and 1. Heuristic crossover produces offsprings by linear extrapolation along the line formed by two parents, outward in the direction of the parent with higher value of the objective function:

$$\begin{aligned} c_1 &= p_2 + \alpha(p_2 - p_1) \\ c_2 &= p_2 \end{aligned} \quad (7)$$

assuming parent p_2 is fitter than parent p_1 , and α is again $U(0,1)$. If c_1 is outside the feasible range for the individual, the step is repeated five times with different random number α . If no feasible value is obtained after five tries, c_1 is set to parent p_1 . Both crossover operators are applied to 10% of individuals randomly chosen from the population in each generation.

We employ three mutation operators: single uniform, single non-uniform and multi non-uniform mutation. Single uniform mutation changes only one of the parameters (in our case position of one of the reclosers), by replacing it by a uniformly generated number within the allowed parameter space. In other words, a recloser is placed randomly on the feeder. Single non-uniform mutation replaces one of the parameters x_i according to the following formula:

$$x_i = (1 - f(g))x_i + bf(g) \quad (8)$$

where b is either the lower or upper bound of the parameter space, with probability of 0.5 of choosing each value, and the non-uniform operator $f(g)$ is defined as:

$$f(g) = \left(r \left(1 - \frac{g}{G} \right) \right)^t \quad (9)$$

where r is $U(0,1)$, g current generation number, G maximum number of iterations, and t is the tuning parameter. The amount of mutation per generation decreases as g increases, allowing the algorithm to search more of the parameter space early on and fine-tune the solution as it approaches the maximum number of generations. The multi non-uniform mutation applies the

single non-uniform mutation to all parameters of the individual. We applied all three mutation operators to 5% of the population per generation.

In the example presented, the number of generations is 50, while the population size is obtained by multiplying the number of reclosers to be considered by 40, acknowledging the increased complexity of the problem as the number of reclosers increases. Algorithm is initialized with randomly generated starting population.

As a test system, we consider the 69-segment, 8-lateral distribution feeder, based on [4], with a few modifications in the placement of loads. Total nominal feeder load is 3.8MW, and distributed generators are placed at the end of each lateral, at buses 26, 34, 38, 54, 58 and 90. The feeder layout is shown in Figure 2.

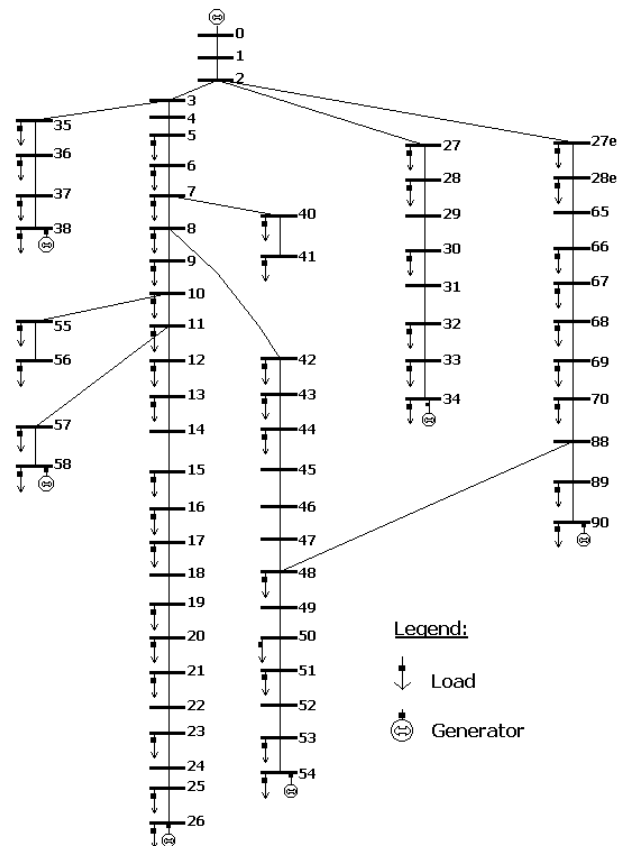


Figure 2. The test system with six distributed generators located at lateral ends.

We assume that the fault incidence rate and the duration of faults (damage restoration time, DRT) are uniform over all feeder branches. We also assume that in the case of the fault, only the minimum number of reclosers closest to the fault should operate, and isolate the fault. The actual implementation of the control algorithm required for such operation is not the subject of

this paper. For each recloser configuration, a composite index is calculated by determining the reliability zones (zones bounded by the reclosers), simulating the faults in those zones, determining the online and offline loads, and finally calculating the composite index.

For each reliability zone that has a DG, after a fault in other zones, the maximum output of all zone generators is compared with the load duration curve for zone loads, and the number of faults is reduced by the percentage of time that the zone generation exceeds zone load. The load duration curve is obtained from the actual utility data for a Central-US small city. Figure 3 represents the load duration curve of a reliability zone, and the maximum active power generation of its distributed generators. In this example, the zone generation is higher than its load for slightly more than 50% of the time, indicating that for more than the half of the failures outside this zone, its customers would not be disconnected.

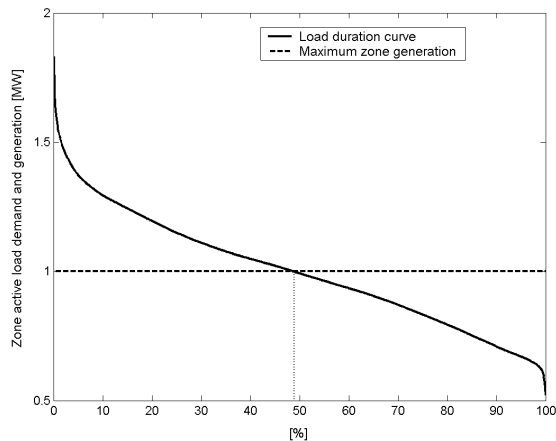


Figure 3. The load duration curve and maximum generation of distributed generators.

In the case that all generators in the zone are energy limited, we would check if they can maintain the production during the duration of the fault, by comparing their energy capacity with the duration curve of the running sum of the power (from the load profile data) for the duration of the fault.

5. Results

The results of the algorithm are presented in Table 1, which shows the top three values for the composite index, and corresponding branches at which reclosers are placed, when up to five reclosers are strategically placed on the feeder. The branch numbering corresponds with numbering shown in Figure 1. Four different cases are

considered: a radial feeder without DG, and a DG-equipped feeder with six generators at lateral ends. The maximum active power is limited to 0.3 MW, 0.5 MW and 1 MW for each of the generators.

In the one-recloser case, recloser placement is dominated by the “conventional” benefits obtained by placing the recloser towards the middle part of the feeder. Additional benefits are realized only from distributed generators located at buses 26 and 58. Generators limited to 0.3 MW may supply the island downstream from branch 8-9 only for limited portions of time (nominal island load is 0.7 MW), yielding only a marginally better composite index. Generators limited to 0.5 MW will support the island much better, resulting in significant index improvement. Finally, 1 MW generators are likely to support the island regardless of the time of the fault, yielding the maximum obtainable improvement.

In the case with two reclosers, we have the similar situation. Generators limited to 0.3 MW and 0.5 MW improve the reliability index, but do not significantly change the optimal recloser positions, compared to the non-DG case. However, in the 1 MW case, the best result is obtained when the second recloser is placed on a 48-49 branch. Note that this configuration in the non-DG feeder would yield the unsatisfactory composite index value of 2.7179. Similar trend continues for the cases with more than two reclosers. Note that in some cases, the composite index becomes negative, indicating that the target values for reliability indices have been exceeded. This is because target values for reliability indices used in the definition of the composite index in (4) represent sufficient level of reliability for a conventional distribution network.

6. Conclusions

Distributed generators may improve distribution system reliability, by providing energy to some of the customers, even after the fault in the distribution system. The level of improvement depends on the number and size of the distributed generators, number of reclosers placed on the feeder, and positions of both generators and reclosers on the feeder. The improvement in overall reliability is demonstrated by finding optimal recloser positions in a feeder equipped with several power-constrained distributed generators, using a specially tailored genetic algorithm. Future work focuses on determining the benefits of energy constrained sources and storage systems, and renewable distributed generators.

Table 1. The composite index for various DG sizes and recloser placement strategies.

Number of reclosers placed on a feeder	No DG		$P_{max} = 0.3 \text{ MW}$		$P_{max} = 0.5 \text{ MW}$		$P_{max} = 1 \text{ MW}$	
	Index value	Recloser positions	Index value	Recloser positions	Index value	Recloser positions	Index value	Recloser positions
1	3.2454	8-9	3.1508	8-9	2.7802	8-9	2.7326	8-9
	3.4029	10-11	3.2089	10-11	2.9422	9-10	2.9122	9-10
	3.4160	9-10	3.3038	9-10	3.1026	10-11	3.1023	10-11
2	2.0847	8-9, 30-31	1.9982	8-9, 30-31	1.5624	8-9, 28-29	1.3569	8-9, 48-49
	2.1288	8-9, 27-28	2.0614	8-9, 27-28	1.5904	8-9, 27-28	1.3829	8-9, 49-50
	2.1434	8-9, 28-29	2.0649	8-9, 28-29	1.6258	8-9, 2-27	1.3979	8-9, 27-28
3	1.1937	3-4, 30-31, 47-48	1.1816	3-4, 30-31, 47-48	0.9550	8-9, 28-29, 50-51	0.7745	3-4, 47-48, 27e-28e
	1.1993	4-5, 30-31, 47-48	1.1871	4-5, 30-31, 47-48	0.9733	8-9, 28-29, 51-52	0.7764	4-5, 47-48, 27e-28e
	1.2485	3-4, 2-27, 47-48	1.2345	3-4, 27-28, 47-48	0.9773	8-9, 27-28, 50-51	0.7765	3-4, 47-48, 28e-65
4	0.3981	3-4, 30-31, 47-48, 27e-28e	0.3954	3-4, 30-31, 47-48, 27e-28e	0.3178	4-5, 30-31, 47-48, 67-68	0.2252	8-9, 27-28, 36-37, 49-50
	0.4037	4-5, 30-31, 47-48, 27e-28e	0.4038	3-4, 30-31, 47-48, 28e-65	0.3199	3-4, 30-31, 47-48, 66-67	0.2272	8-9, 28-29, 36-37, 49-50
	0.4068	3-4, 30-31, 47-48, 65-28e	0.4061	3-4, 2-27e, 30-31, 47-48	0.3234	4-5, 30-31, 47-48, 66-67	0.2308	8-9, 27-28, 36-37, 48-49
5	0.1490	3-4, 11-12, 30-31, 47-48, 28e-65	0.0898	3-4, 10-11, 30-31, 47-48, 27e-28e	-0.0305	3-4, 10-11, 30-31, 47-48, 67-68	-0.1484	3-4, 10-11, 30-31, 49-50, 67-68
	0.1546	4-5, 11-12, 30-31, 47-48, 28e-65	0.0982	3-4, 10-11, 30-31, 47-48, 28e-65	-0.0265	4-5, 10-11, 30-31, 47-48, 67-68	-0.1476	3-4, 9-10, 30-31, 49-50, 67-68
	0.1630	4-5, 11-12, 30-31, 47-48, 67-68	0.1041	4-5, 10-11, 30-31, 47-48, 28e-65	-0.0250	3-4, 10-11, 30-31, 47-48, 66-67	-0.1463	4-5, 10-11, 30-31, 49-50, 67-68

7. References

- [1] Lj. A. Kojovic, R. D. Willoughby, "Integration of Distributed Generation in a Typical USA Distribution System", Proceedings of the 16th CIRED, pp. 5, Vol. 4, 2001.
- [2] C. R. Houck, J. A. Joines, and M. G. Kay, "A Genetic Algorithm for Function Optimization: A MATLAB Implementation", NCSU-IE Technical Report, 1995.
- [3] D. E. Goldberg, Genetic Algorithms in Search, Optimization, and Machine Learning, Addison-Wesley, 1989.
- [4] M. E. Baran and F. F. Wu, "Optimal Capacitor Placement on Radial Distribution Systems", *IEEE Transactions on Power Delivery*, Vol. 4, No. 1, January 1989, pp. 725-732.
- [5] IEEE Trial-Use Guide for Electric Power Distribution Reliability Indices, IEEE 1366-1998 Standard, 1998.