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Optimal Allocation of DG along with Network Reconfiguration considering Protection Constraints

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Abstract
Power losses and voltage deviations in the distribution network are a frequent issue for electrical distributors. Network reconfiguration is a typical method of reducing power losses and improve the voltage profile of a distribution system. At the same time, integration of DGs in the form of renewable energy are increasing which can change the direction of power flow that may lead to blinding of protection and miscoordination of protective devices. It is uneconomical and technically demanding to redesign or replace the original protective devices on distribution network. So, study on network reconfiguration (NR) incorporating distributed generations (DGs), it is usual to have concern on power loss, voltage deviation, DG sizing, and placement and operating conditions of protective devices as these are crucial and necessary during the design stage of distribution system. The objective of this paper is to find the optimal size and location of distributed generation along with network reconfiguration to simultaneously minimize active power losses, improve voltage profile while ensuring existing protection devices remain coordinated under normal and overload condition of the network. Constraints on network reconfiguration, DGs size and protection coordination are explicitly formulated in the proposed method. Genetic Algorithm is used as optimization technique to meet the objective of this study. The validity of the proposed method is analyzed on IEEE 33-bus radial distribution network.

Keywords
Protection Constraints, Genetic algorithm, Relay

1. Introduction

Power losses from different networks are a typical problem for electrical distributors. These losses raised their overhead costs, which in turn reduced their profit. Long-term power generation at the grid location to make up for the aforementioned power losses will also cause environmental issues. Network reconfiguration (NR), is a proven method for reducing power losses or for load balancing in the distribution system. Network reconfiguration is the act of changing/altering the state of switches (the switch might be either normally closed known as sectionalizing switches or normally open, referred as tie-switches) of the distribution network. By changing the state of switches, if the optimum reconfiguration could be found, [1, 2], this would reduce power losses and enhance the overall voltage profile of the DN as the load will be moved to feeders that are generally lightly loaded. In this respect, network reconfiguration (NR) could be used as a reasonably simple and affordable method to reduce power loss and enhance the overall voltage profile of the network.

But, the reconfiguration technique was only able to reduce power losses to a certain extent on its own. Further Installing local generating, also known as distributed generation, could also reduce power losses. Distributed generation, which typically uses renewable energy sources like solar, wind, mini-hydro, and biofuels, is the term for a small generating unit deployed at main points in the distribution system [3]. The integration of distributed generation (DG), notably in the form of renewable energy, has grown significantly over the past few decades as sustainability and environmental concerns have drawn attention. From one aspect, the incorporation of distributed generation allows network reconfiguration further minimize power loss and enhance the voltage profile, deferring network expansion, and enhance reliability and stability of distribution system.

However, the distribution network operators face additional issues as a result of high distributed generation penetration, particularly with regard to the reliability of the protection systems[4]. To ensure the correct and timely functioning of protection devices in times of need, the effects that the distributed generations have on the distribution network protection system must be carefully studied. Integration of distributed generations on distribution system, alters the direction and magnitude of current flowing in the feeder and hence leads to the miscoordination and protection blinding of protective devices installed on distribution network[5]. According to the researchers, no research has been done on the impacts of protection coordination on network reconfiguration while distributed generation is connected to reduce power loss and enhance voltage profiles. Instead, studies on network reconfiguration focus solely on issues related to power loss, voltage profile, distributed generation sizing, and location during the design stages [6]-[7], while the impact of protective systems is disregarded during the operational stage. The objective of the paper is to find the optimal size of distributed generations along with Network Reconfiguration considering over load factor.

2. Methodology

2.1 Flowchart

The flowchart for conducting optimal reconfiguration with protection constraints is shown in figure No 1.

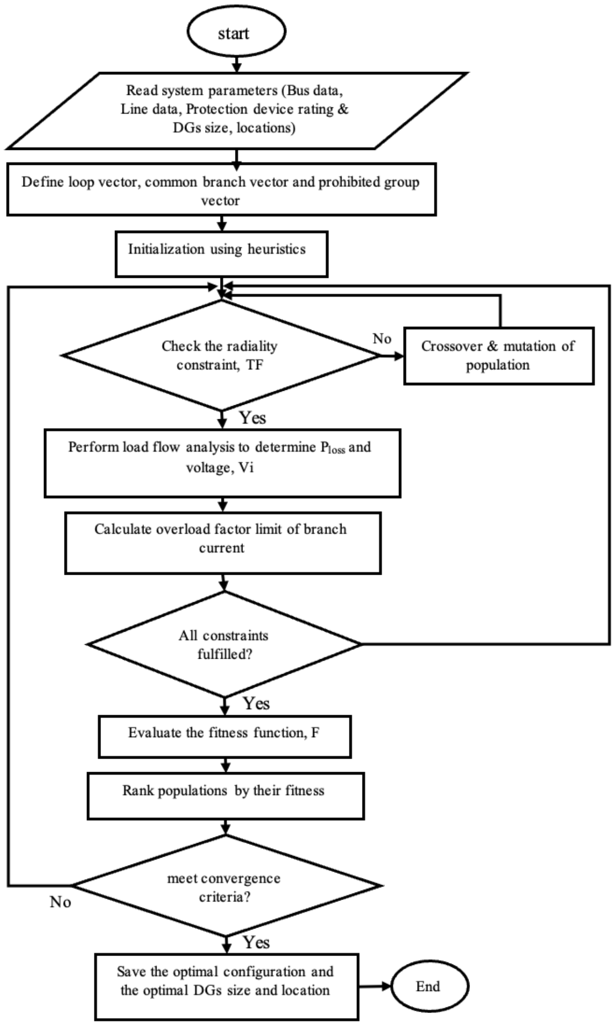

Figure 1: Flowchart of the proposed strategy to determine optimal NR with optimal DG size and location considering protection constraints

2.2 Mathematical formulation and constraints

This study aims is to find the optimal allocation of DG along with NR to simultaneously minimize active power losses, improve voltage profile while ensuring existing protection devices remain coordinated under normal and fault condition.

2.2.1 Objective function

The objective function, F of the optimization process can be represented as:

$$F = min(P^R_{loss} + VDI) \tag{1}$$

The net active power(P^R_{loss}) is the ratio of total active power loss after distributed network reconfiguration(P^{rec}_{loss}) to total active power loss before reconfiguration (P^0_{loss}) as indicated by 2. Network total active power loss is determined by the summation of losses in all lines.

$$P^R_{loss} = \frac{P^{rec}_{loss}}{P^0_{loss}} \tag{2}$$

Voltage deviation index (VDI) is defined as follows:

$$VDI = Max^n_{i=2} \frac{|V_1 - V_i|}{|V_1|} \tag{3}$$

where V_i is the measured voltage at bus i; and n is the number of buses of the network and V_1 is the nominal voltage.

2.2.2 Constraints

There are three types of constraints that the optimization is subjected to NR along with distributed generations considering protection constraints are:

1. Network reconfiguration constraints
2. Distributed generations sizing constraints and
3. Protection constraints

Network Reconfiguration Constraints

1. Bus Voltage Constraints
   Voltages at all buses in the network should not exceed the minimum and maximum allowable limits. In this study, allowable voltage limit is set at ±10% of the rated voltage.

   $$V_{min} \leq V_{bus} \leq V_{max} \quad (4)$$

   Where V_{min} and V_{max} are the lower and upper limits of voltages at all buses.

2. Radial Configuration
   After the reconfiguration process the network configuration/topology should be radial where the main substation must be connected to all the buses and there is no loop in the network. The function of graph theory in MATLAB is utilized to determine this radiality [8].

   $$TF = graphisspa\_ntree(G)$$
   $$if,$$
   TF=1 then Radial
   TF=0 then Non-Radial (5)

Distributed generation sizing constraints

1. Distributed Generation Capacity
   Distributed generation size at bus i, PDG_i, is limited by the maximum and minimum capacity of the distributed generation, P_{max} and P_{min}, respectively.

   $$P_{min} \leq P_{DG,i} \leq P_{max} \quad (6)$$

2. Power injection

   $$\sum_{i=1}^{k} P_{DG,i} < \sum_{n}^{n_{bus}} P_{load,n} + P_{loss} \quad (7)$$

   where k is the distributed generation number; P_{load} is the load at bus n; n_{bus} is the bus number; and P_{loss} is the overall active power losses in the network. This constraint is to prevent power from distributed generations to flow to the grid and potentially disturb the grid protection system[9] is described by Eq. 8

3. Power balance
   The total power consumed by the load and power losses of the network must be equal to the total power capacity generated from distributed generations and substation [10]. This is in line with the equilibrium principle which stated supply and demand of power must be equal.

   $$\sum_{i=1}^{k} P_{DG,i} + P_{substation} < \sum_{i=1}^{n_k} P_{load,n} + P_{loss} \quad (8)$$

Protection constraints

1. Over load factor limit
   During network reconfiguration, due to change in topology of distribution network, if current flowing through any branch if greater than the operating current of the fuse or pick-up current of the relay under normal operating condition of distribution network, the protective devices must immediately isolate the coverage area to minimize damage to the distribution equipment. The overload factor (OLF) limit is formulated in Eq. 9.

   $$OLF \times I_N < I_p \quad (9)$$

   Here, OLF is the overload factor(1.25), I_N is the branch current flow through the protective device after the reconfiguration; and I_p is the operating current of the protective device.

2.3 Test System

The test system is IEEE 33-bus distribution network. The single line diagram of 12.66 kV, 33-bus system is shown in figure 2. the apparent power is assumed to be 100 MVA. The dotted lines in figure 2 represents open switches(tie-switches). Different data for initial state of this network is shown in Table 1.

3. Results

The following five case has been studied.
Case 1 Optimal Network Reconfiguration(NR) without DG
Case 2 Optimal NR with optimum DG sizing (Simultaneously)
Case 3 Optimal NR with optimum DG sizing and location
Case 4 Optimal NR considering PC

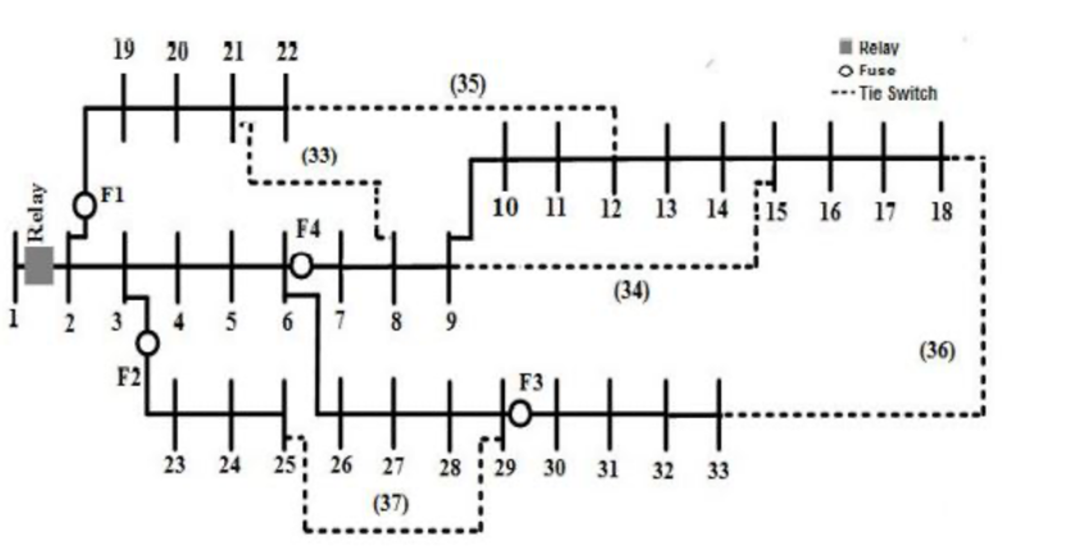

Figure 2: IEEE 33-bus DN with five tie-switches and protective devices before NR

Table 1: IEEE 33-Bus system data in initial configuration

Parameter	Power loss (kW)	Minimum voltage (p.u.)	Tie-switches	Objective Function (p.u.)
Value	202.6744	0.913092 at 18-Bus	33-34-35-36-37	1.086908

Case 5 Simultaneously NR and DG sizing and siting along with considering PC

Network reconfiguration without DG and protection constraints is performed in case 1. The open switches for optimal NR are 7-9-14-28-32.The power loss, minimum voltage, tie-switches are tabulated in table 2. It can be seen that power loss is reduced by 30.93%, minimum voltage is improved by 3.07%, percentage improvement in objective function by 31.06%. The improvement in voltage profile of the network from initial condition to case 1 is shown in figure 3. We can observe from the graph that, voltage at each node in improved than that of initial condition.

Under case 2, simultaneous network reconfiguration and optimal DG output is considered. Three DGs are connected at bus 31,32 and 33. To further reduce the power loss and improve voltage profile, DGs outputs are optimized. Due to the practical constraint, the maximum DGs output is set to 3.5MW. In this case, DGs are injecting only active power to the network. The minimum and maximum value of DG is set to be 0.5MW and 1.5MW respectively. The results from simultaneously NR and optimal DG outputs is tabulated in table 3 and in figure No 4. It shows that by adopting DG into network, power loss is further reduced to 77.0098 kW, minimum voltage is improved to 0.976419 and objective value in

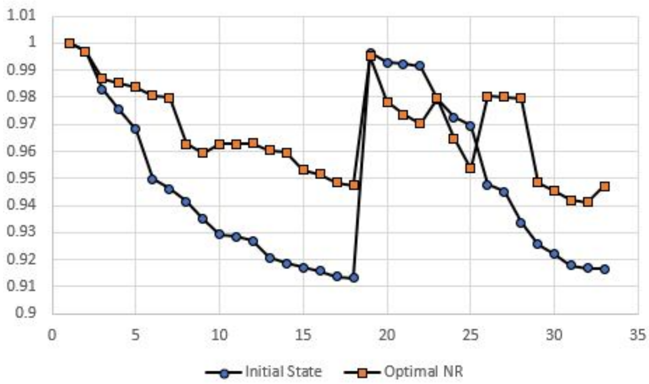

Figure 3: Comparison of improvement in voltage profile by optimal NR

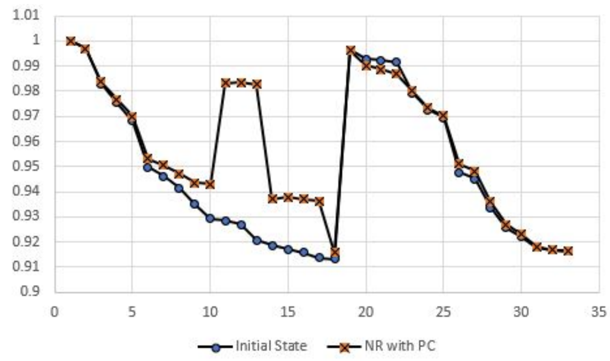

Figure 4: Voltage profile of IEEE 33-bus for initial case, Optimal NR and simultaneously NR and optimal DG outputs

Table 2: Showing system loss reduction, voltage profile improvement and improvement in objective function by performing optimal NR without DG

Parameter	power loss (kW)	Losses Reduction %	Minimum voltage (p.u.)	Tie-switches	Objective Function (p.u.)
Value	139.9781	30.93	0.941287 at 32-Bus	7-9-14-28-32	0.749368

Table 3: Different parameters obtained by simultaneously NR and optimal DG output

Parameter	power loss (kW)	Minimum voltage (p.u.)	Tie-switches	DG output (MW)	Objective Function (p.u.)
Value	77.0098	0.976419 at 27-Bus	7-9-12-26-32	DG1=0.630836 DG2=0.824302 DG3=0.736220	0.403549

Table 4: Simultaneously NR and Optimal DG sizing and siting

Parameter	power loss (kW)	Minimum voltage (p.u.)	Tie-switches	DG output (MW)	Objective Function (p.u.)
Value	58.8948	0.972102 at 32-Bus	7-10-13-32-37	DG14=0.703847 DG24=0.924318 DG30=0.907066	0.318484

minimized to 0.403549. Open switches are transferred to switches 7-9-12-26-32. We can see that the power loss is reduced by 62% than power loss in initial condition and by 45% than power loss in case 1. Similarly, objective function is improved by 62.87% than in initial condition value.

Under the case 3, simultaneously NR and Optimal DG allocation (sizing and siting) is considered. Results for this case is tabulated in table 4 and shown in figure 5. It shows that by Simultaneously NR and optimal DG allocation adopting into network power loss is reduced to 58.8948 kW, minimum voltage is 0.972102 and objective function is improved to 0.318484. When we compare the results of case 2 and three, we can see that there is better improvement in the objective function (by 70.7%) when DGs location are optimized (i.e. locations of DGs are diversified) than concentrated at bus 31,32 and 33.

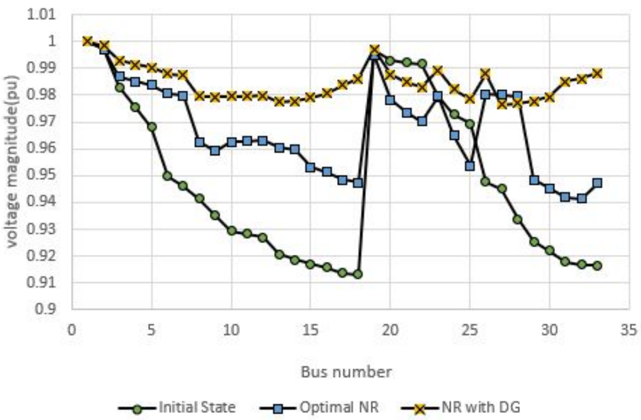

Figure 5: Voltage profile of IEEE 33-bus system for initial case, optimal NR, simultaneously NR and optimal DG sizing and simultaneously NR and optimal DG sizing and siting

We can see that optimal size and location of DGs shows better results than in case-2. Power loss is by reduced 70.94 % than power loss in initial condition and by 23.5% than in case 2.

Table 5 shows the mis-operation of protection devices despite being optimal re-configurations.

Table 5: Condition of protective devices in optimal network configuration with DGs sizing without protection constraints

Protective device	Load Current (A)	Load current with 25% overload (A)	Protective device condition with 25% overload
Relay, 500	225.28	281.60	Close
F1,60	67.55	84.43	Open
F2, 125	111.63	139.53	Open
F3, 125	95.16	118.95	Close
F4, 150	17.88	22.35	Close

Under the case 4, extension of case 3 is performed where constraints on protection devices are considered. In this case too, three DGs are connected at bus 31,32 and 33. The results obtained from optimal network reconfiguration with optimum DG sizing considering protection constraints is tabulated in table 6. It shows that by adopting DG into network, power loss is significantly reduced to 92.4591 kW, minimum voltage is improved to 0.9801 and objective value in minimized to 0.476096 value. Open switches are transferred to switches 11-28-31-33-35. We can see that the power loss is reduced by 54.38% than power loss in initial condition. Similarly, objective function is improved by 56.20% than in initial condition value. Table 7 shows that protection constraints of protection devices are fulfilled under normal load condition and 25% overloading condition of the distribution system. Improvement in voltage profile of distribution system under this case is shown in figure 6. It can be seen that best voltage profile of distribution system is obtained by optimal integration of DGs along with consideration of protection constraints.

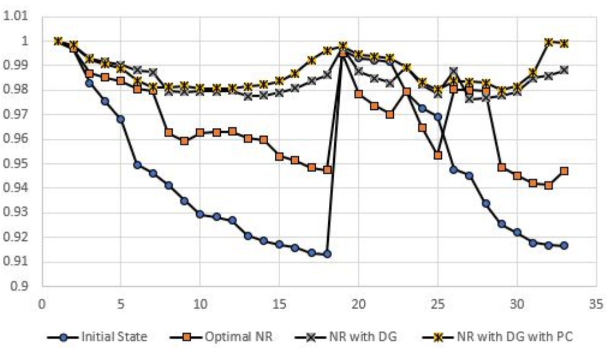

Figure 6: Comparison of voltage profile for initial case, optimal NR , optimal NR with DGs sizing and optimal NR with DGs sizing considering protection constraints

Under case 5, simultaneously network reconfiguration and DG sizing and siting without considering protection constraints is considered. Simulation results obtained under this case is shown in figure 7. It shows that by Simultaneously NR and optimal DG allocation adopting into network, power loss is reduced to 58.8948 kW(which is lowest value than all other cases), minimum voltage is 0.972102 and objective function is improved to 0.318484. Compared to earlier all four cases, we can see that there is better improvement in the objective function (by 70.7%) when DGs location are optimized (i.e. locations of DGs are diversified) than concentrated at bus 31,32 and 33.

Table 7: Protective devices condition in optimal network reconfiguration with optimum DG sizing considering protection constraints

Protective device	Load Current (A)	Load current with 25% overload(A)	Protective device condition with 25% overload
Relay, 500	213.56	266.95	Close
F1,60	31.27	39.09	Close
F2, 125	99.28	124.1	Close
F3, 125	83.74	104.67	Close
F4, 150	54.75	68.43	Close

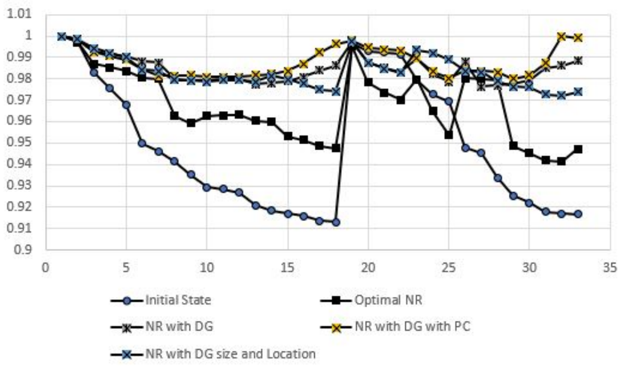

Figure 7: Voltage profile system for initial case, optimal NR, optimal NR and DG sizing, optimal NR with DGs and PC and NR and optimal DG sizing and siting

4. Conclusion

This paper has proposed a new way to determine the optimal network reconfiguration problem with distributed generations considering protection constraints using genetic algorithm as optimization tool. The feasibility of the proposed approach has been validated on the IEEE 33-bus. Network reconfiguration of distribution system without considering protection constraints has reduced the power loss and improved the voltage profile of distribution system but it will have unavoidable impact on the operating conditions of protective devices which is not practically feasible to be implemented in distribution network. Despite the power loss is increased and voltage profile of distribution network is degraded when network reconfiguration with protection constraints is

Table 6: Different parameters obtained by optimal network reconfiguration with optimum DG sizing considering protection constraints

Parameter	Power Loss (kW)	Minimum voltage (p.u.)	Open switches	DG output (MW)	Objective Function (p.u.)
Value	92.4591	0.9801 at 29-Bus	11-28-31-33-35	DG31=1.147194 DG32=0.674460 DG33=0.691377	0.476096

considered, this method proves to be practically implementable as protective devices are working properly even the feeder or distribution system is under overloading condition.

Similarly, when reconfiguration of distribution network is done with integration of distributed generations considering protection constraints, power loss is drastically reduced and voltage profile is better than original cases, and protective devices are functioning properly for both normal as well as overloading condition of distribution system. As the integration of distributed generations in distribution system is growing continuously, while replacement of original protective devices are expensive and technologically difficult task, this thesis work helps in improving the integration of distributed generations in distribution network while existing protective devices remains coordinated.

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