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Optimal Feeder Reconfiguration Optimization problem in Power Distribution Networks

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Abstract

Optimal feeder reconfiguration is a method used to determine optimal on/off statuses of tie and sectionalizing switches in order to reconfigure the network and improve certain objective goals. Mathematically, OFR is a mixed-integer nonlinear programsubjected to system constraints consisting of power flow equations, voltage limits, feeder capability limits and requirements for maintaining radial configuration of the network.In this paper, network reconfiguration problem is solved using branch exchange method. Solution involves a search for optimal on/off switch positionby transferring loads from one feeder to another, until no load transfer can further reduce the power losses, violations of voltage limits, and violations of branch capacity limits.Branch exchange method is applied on two feeder network, and results show that this method can be successfully used to decrease losses, improve voltage profile and resolve the overloading problem.

NOMNECLATURE

V_i	Voltage magnitude at bus i.
δ_i	Voltage angle at bus i.
γ_n	Set of all nodes in the system.
$\gamma_{n(i)}$	Set of nodes connected to node i.
γ_s	Set of all switches in loop.
s_{ij}	Switch state at branch ij, binary value 0 or 1
I_{ij}	Magnitude of the current at branch ij.
$I_{ij_{re}}$	Real component of current at branch ij
$I_{ij_{im}}$	Imaginarycomponent of current at branch ij
$I_{Ci_{re}}$	Real component of current from capacitor connected to node$i$.
$I_{Ci_{im}}$	Imaginary component of current from capacitor connected to node$i$.
$I_{Li_{re}}$	Real component of current from load connected to node$i$.
$I_{Li_{im}}$	Imaginarycomponent of current from load connected to node$i$.
Y_{ij}	Amplitude of the admittance corresponding to the i^{th}row and j^{th} column of admittance matrix.
θ_{ij}	Angle of the admittance corresponding to the i^{th} row and j^{th} column of admittance matrix.
$P_{LOSS_{ij}}$	Power loss at branch ij.
c_{P_L}	Weighting factor for power losses.
$V_{i,min}$	Minimum voltage magnitude at bus i.
$V_{i,max}$	Maximum voltage magnitude at bus i.
$I_{ij,max}$	Maximum allowable line current magnitude.
$c_{V_{i,min}}$	Weighting factor for minimum voltage violation.
$c_{V_{i,max}}$	Weighting factor for maximum voltage violation.
$c_{I_{ij,max}}$	Weighting factor for maximum current limit violation.

1. INTRODUCTION

Increased demand for electricity in distribution systems may cause overloading of feeder capacity. To relieve the overloading of the network feeder, Optimal Feeder Reconfiguration (OFR) can be used as a method which transfers partial loads from heavily loaded feeders to less loaded feeders and reduces total system losses, voltage and branch violations.The most critical usage situations for OFR, in operational mode, are during and after Fault Isolation and Service Restoration [1]-[10] while attempting to energize parts of the network which were deenergized but not faulty. Based on Distribution System State Estimation results [11]-[25] OFR changes the topology of distribution systems by altering the status of sectionalizing (normally close) and tie (normally open) switches. If a single feeder is overloaded, OFR closes currently open tie switch, and open one of currently closed sectionalizing switches to transfer the load to another substation while maintaining a radial topology. Founding the best open/close switch combination, feeder reconfiguration can achieve loss minimization, service restoration or load balancing. Due to the enormous number of switch combinations, feeder reconfiguration is a complicated combinatorial and constrained optimization problem. It can be formulated as a mixed-integer nonlinear programming (MINLP) problem where the goal is to select the pair of switches for opening/closing in order to optimize objective function.

Many algorithms have been proposed to solve the feeder reconfiguration problem. A great amount of research has been conducted regarding minimization of the losses through the network reconfiguration. Optimal feeder reconfiguration for loss reduction is presented in [26]-[36]. An early work that involves loss minimization is presented by Baran and Wu [26]. The solution involves a search over relevant radial configurationsby using branch exchange type switchings. Work in [28] presents a simple and fast heuristic approach for solving the distribution feeder reconfiguration problem with an objective of loss reduction and voltage profile improvement. The optimal feeder reconfiguration for loss reduction is also solved in [29] using ant colony search algorithm (ACSA). A great deal of research has been conducted in the area of network reconfiguration of distribution systems in the presence of distributed generators (DG)[37]-[41]. Methodology based on fuzzy multiobjective and Tabu search is used in [30] to determine the optimal on/off patterns of tie and sectionalizing switches for feeder reconfiguration in a distribution system with distributed generators. Paper [35] proposes a reconfiguration methodology based on an Ant Colony Algorithm (ACA) that aims at achieving the minimum power loss and increment load balance factor of radial distribution networks with distributed generators. The obtainedresults have shown that lower system loss and better load balancing will be attained at a distribution system with distributed generation (DG) compared to a system without DG.In the past years, many artificial intelligent methods were proposed to solve the feeder reconfiguration problems: Particle Swarm Optimization methods[42]-[44], ant colony optimization methods (ACO) [29], [45], genetic algorithms (GA) [46]-[47], evolutionary algorithms (EA) [48]- [49], fuzzy algorithms [50] and so on.

This paper presents an algorithm for solving distribution system reconfiguration problem with an objective to reduce power losses, voltage and branch current violations. The algorithm uses branch exchange method which transfers the loads between feeders by closing initially open tie switch (IOS) and opening its adjacent initially closed sectionalizing switch (ICS). For new reconfigured network power flow studies are performed to specify all bus voltages and branch currents needed for calculating objective function. Solution is found by successively repeating branch exchange procedure until load transfer between two feeders cannot further decrease the objective function. In case of multiple initially open switches, the search space is reduced by giving priority to the IOS which communicate with SCADA systems. The effectiveness of the methodology is demonstrated on a distribution system consisting of 33 buses and 22 load points.

The remainder of this paper is structured as follows. Section 2gives the formulation of feeder reconfiguration as MINLP problem. In Section 3, the proposed algorithm for optimal feeder reconfiguration problem is described. In Section 4, OFR method is applied on a two feeder test system and the results are presented. Finally, in Section 5, the relevant conclusions are given.

2. PROBLEM FORMULATION

The main aim of optimal feeder reconfiguration is to remove, or at least decrease, overloading of feeder capacity and violations of voltage limitations. Reconfiguration can be defined as a process of changing structure of the network byopening or closing sectionalizing and tie switches. The position of sectionalizing or tie switches can be treated as binary variable, assuming that ‘1’ represents closed switch and ‘0’ represents open switch. In this case, OFR is formulated as a mixed-integer nonlinear programming (MINLP) problem which optimizes certain objective subject to the several constraints: topological constraints, power flow equations, and operational constraints for node voltage and branch capacity. Some of the most important objectives for optimization include reducing total losses, improving reliability of system and maintaining system balance.In this paper, objective function aims to achieve three different goals: reducing the real power losses, minimization of deviation of node voltages and minimization of the branch current constraint violations. By weighting addition between mentioned factors, the objective function is described as follows:

$$f=\sum_i c_{V_{min}}\left(V_i-V_{min}\right)^2+c_{V_{max}}\left(V_{max}-V_i\right)^2 + \sum_{ij} c_{I_{max}}\left(I_{ij,max}-I_{ij}\right)^2+c_{P_L}P_{LOSS_{ij}} \quad (1)$$

The objective function given in (1) is subject to the following constraints:

Kirchhoff's Current Law
The equality constraints correspond to the KCL at each node:

$$\sum_{j\in\gamma_{n(i)}} s_{ij} I_{ij_{re}} + I_{Li_{re}} - I_{Ci_{re}} = 0,\ \forall i\in\gamma_n \quad (2)$$

$$\sum_{j\in\gamma_{n(i)}} s_{ij} I_{im} + I_{Li_{im}} - I_{Ci_{im}} = 0,\ \forall i\in\gamma_n \quad (3)$$

where

$$I_{ij_{re}} = V_i Y_{ii} \cos(\theta_{ii}+\delta_i) + V_j Y_{ij} \cos(\theta_{ij}+\delta_j) \quad (4)$$

$$I_{ij_{im}} = V_i Y_{ii} \sin(\theta_{ii}+\delta_i) + V_j Y_{ij} \sin(\theta_{ij}+\delta_j) \quad (5)$$

Node voltage limits
Voltage at all buses in the distribution system must be maintained within the specified limits. It is necessary that voltage is inside voltage margin with upper and lower limits defined as:

$$V_{i,min} \le V_i \le V_{i,max} \quad (6)$$

Usually, violations of limits are considered in cases where voltage is lower than0.95 (p.u) or higher than 1.05 (p.u.)Voltage constraint equation (6) is included in MINLP as non-linear inequality constraint.

Branch current limits
The amount of current flow on the line is limited by maximum allowed current limits specified by the conductor manufacturers. The line current limits are described as:

$$I_{ij} \le I_{ij,max} \quad (7)$$

In order to prevent overloading of distribution lines, current must be less than this limit. The line current bound from equation (7)isincluded in MINLP formulation as inequality constraints.

Radial structure of the network
Radial structure of distribution network is preserved if the following constraints are satisfied:

$$\sum_{ij\in\gamma_b} s_{ij} = \gamma_s - 1 \quad (8)$$

$$s_{ij} = \{0,1\} \quad (9)$$

Equations (8) and (9) guarantee that in each loop always one switch is open to ensurethat network has radial structure.

In general, MINLP problems are very difficult to solve since they combine complexcombinatorialnature of mixed integer programming (MIP) and difficulties of non-linear programming (NLP). For solving general MINLP problems, several optimization solvers have been developed: BARON, BONMIN,GUROBI, MOSEK, KNITRO, CPLEX, DICOPT, MINLP_BB [51].The most common solution approaches for MINLP available in the literature are Branch and Bound, Outer Approximation, Branch and cut, Generalized Benders Decomposition, Extended Cutting Plane, Extended Ant Colony method, etc. [51].

3.OFR ALGORITHM

Distribution feeder reconfiguration can be defined as combinatorial, nonlinear optimization problem which involves search for optimal combination of switch statuses that satisfies the network constraints and minimizes the objective function. This paper describes algorithm for solving optimal feeder reconfiguration problem based on branch exchange method. Branch exchange is a popular method usually used for solving the problems of fault contingency and feeder overload.

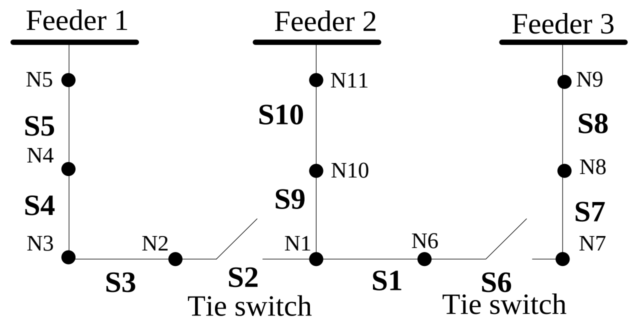

Figure 1. Three Feeder network

For the case shown in Figure 1, there are 8 ICS and two IOS (S2,S6). The first decision to be made is related to the choice of IOS as starting point for the optimization. Method takes one of the IOS and closes it (say switch S2). This creates loop in system where one load is supplied from two different feeders (Feeder1 and Feeder2). To ensure radial topology in which every load is connected to a single substation, one of the neighboring currently closed sectionalizing switches needs to open (say S3), and loads on bus N2 will be transferred from Feeder1 to Feeder2. This two-step operation is known as branch exchange method [27]. New status of switch pair S2-S3 changes the network topology and new power flow calculations are needed to calculate objective function for changed network configuration.In case of more than one tie switch, same procedure needs to be repeated forall other initially open switches to ensure that the optimal solution is found. For example used here, it is necessary to check objective in the case that IOS S6 is closedand one of its neighboring switchesS1 or S7 is opened. From all possible switching combinations (S2-S3, S2-S1, S2-S9, S6-S1,S6-S7), method selects the one which improves the objective function the most (say S2-S3). For that combination, method continues to search switching operations successively.Branch exchange continues by closing switch S3 and opening S4, closing S4 and opening S5, and so on until network reconfiguration cannot bring any further improvements in objective function.
However, examining all possible combinations to find the best solution is computationally very demanding, especially for large scale networkswhereit isveryimpractical to calculate power flowfor eachpossiblecombination ofswitches. Therefore, certain search procedures needs to be defined to cut the search space and reduce the total number of possible switching

candidates for optimization process.One of the strategies is selection of the IOS as the starting point for OFR. To avoid checking every IOS in the network, some of the IOS should have priority, and considered as the first option for closing. One of the strategiesis to give priority to the switches that communicate with SCADA. This strategy is justified by the fact that SCADA connected switches can be controlled much faster than others, what can be huge advantage, especially in emergency cases where time is the crucial factor for proper network control.

In summary, the OFR algorithmcanbe described with several steps (Figure 2):

Step1 Trace the topology to identify all possible loops in the system. For each loop, detect one switch in a loop as initially open switch (IOS), and create a list of all related sectionalizing switches (ICS).

Step2 Define strategy which will determine order for each IOS. Create a priority list for all initially open switches, and perform optimization by that order.

Step3 Perform Branch-exchange method, i.e. close a normally-open switch and open one of the neighboring closed sectionalizing switches and transfer the loads from one feeder to other.

Step4 Perform power flow calculation [52]-[71].Power flow calculations provide information about voltages and currents needed for calculation of objective function. If Y is matrix of branch admittances calculated using equivalent π model for given branch parameters and$I$ is the vector of injected currents, current iteration method can be expressed as:

$$[V]^{n}=[Y]^{-1}[I]^{n-1} \quad (9)$$

In each iteration method calcaultes new voltages using parameters of the branch and injected current at one end of the branch. Injected current is a function of voltage from previous iteration. Convergence requires that voltage values of the previous iteration are close to voltage values of the current iteration (within some specified tolerance). During the optimal feeder reconfiguration, banch exchange method affects vector of injected currents, since overall load loactions are changed due to their transfer from one feeder to other.

Step5 Calculate objective function as a weighted sum of power losses, bus voltage violations and capacity line violations.

Step6 If objective function is improved, repeat the procedures from Step3 to Step5 for all other sectionalizing switches in that loop; if objective function is not improved repeat Step3 to Step5 for next IOS in priority list; if all IOS are examined, finish the OFR algorithm.

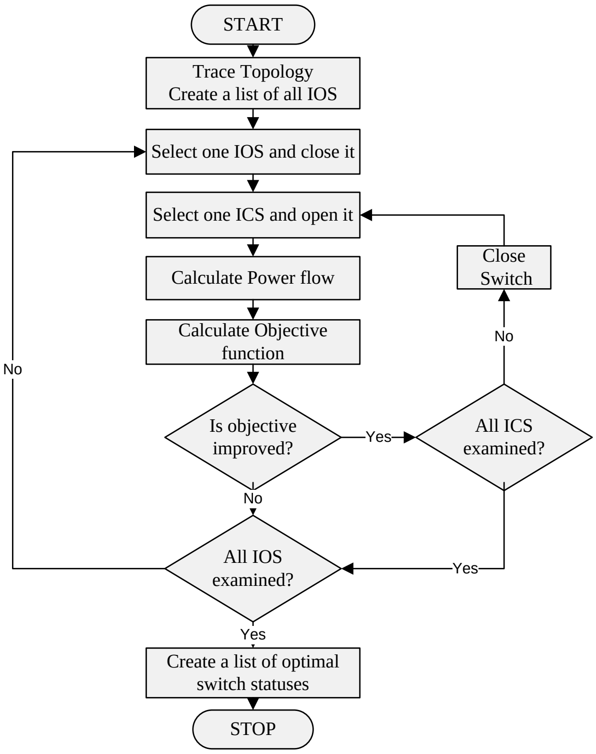

Figure 2. OFR Algorithm

4. RESULTS

The optimal feeder reconfiguration algorithm has been tested on a distribution system with 33 buses. The single-line diagram of the system is depicted in Figure 3. As shown in figure, the initial configuration has two feeders, one normally open switch (tie-line), 5 sectionalizing switches and 22 loads.

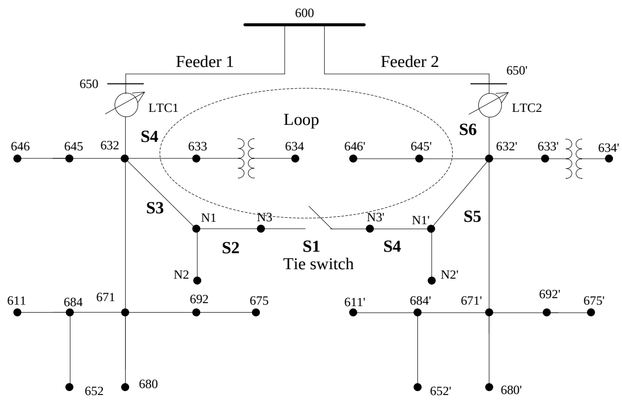

Figure 3. 33 bus network, initial configuration

For the initial configuration, substation transformer 1 is overloaded and the voltage magnitudes at all buses downstream are below its limits. For this case, the total real power lossesobtained by power flowcalculations are found to be 148.143 KW. To demonstrate the effectiveness of the described algorithm in reducing total system losses and solving overloading problemsOFR mechanism is applied on overloaded system from Figure 3.

Table 1summarizes voltage and current violations before and after feeder reconfiguration.

TABLE 1.VOLTAGE AND CURRENT VIOLATIONS FOR 33 BUS SYSTEM

Results	Case1 S1 open	Case2 S2 open	Case3 S3 open
No: Voltage violations	63	63	63
No: Current violations	4	4	0
Obj:Voltage violation	0.282958	0.260608	0.225302
Obj: Current violation	11.6117	5.69562	0
Total objective	13.3761	7.39667	1.61609

Case1 presents initial configuration where feeder overload and voltage violationsare maximum (column 2). To solve the overload problem by OFR mechanism, optimizationstarts by closing switch S1 and opening switch S2 (Case 2). This transfers the loads at node N3 from Feeder1 to Feeder2. The used branch exchange procedure improves results, what can be seen from Table 1 (column 3), where both violation indices (voltage violation and current violation) become smaller. The reason for this is that loads between switches S1 and S2 are now supplied from Feeder2, and Feeder1 is relieved from these loads.But, even if Case 2 improves the results, there is still a small overload at transformer1, indicated by calculated objective for line capacity violations.To relieve this overload,feeder reconfiguration continues by closing switch S2,and opening switch S3(Case 3) which transfers the loading of N1 to Feeder2. This operation brings improvement in total objective function and removes the feeder overload as shown in Table 1 (column 4, current violations are 0). Figure 4 shows feeder configuration after overall switching operations.

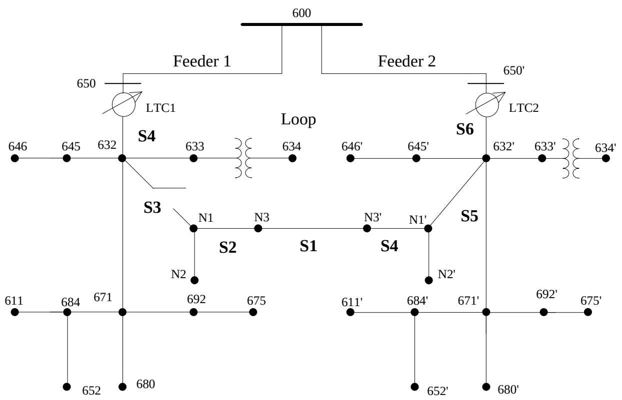

Figure 4. 33 bus network, final configuration

For the final configuration, total losses of the network are reduced, and voltage profiles are improved. This is shown in Table 2.

TABLE 2. REAL POWER LOSSES AND BUS VOLTAGES

Reconfiguration	Power Losses (kW)	Minimum Bus Voltage (p.u)	Correspond. bus No.
Initial	148.143	0.826	611
Final	139.078	0.853	611

The voltage profile of the 33 bus system before and after reconfiguration is shown in Figure 5. As can be seen from figure, the voltage profile of the 33 bus system has been improved due to the relieving of the capacity of certain network branches.

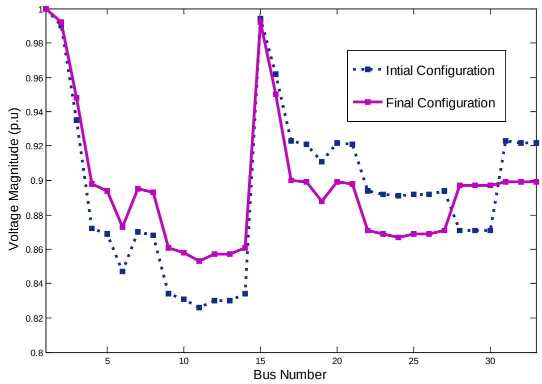

Figure 5.Voltage profile comparison for 33 buses (phase c)

The numerical results indicate that the optimal solution obtained using OFR method explained in Section 3, significantly decreases the objective function and it can be successfully applied for solving the problems of feeder overload.

5. CONCLUSIONS

This paper describes an algorithm for optimal reconfiguration of radial distribution networks. The algorithm employs branch exchange mechanism to find the switching combinationof sectionalizing and tie-switches that satisfies the best minimization of real power losses, minimization of the deviations of bus voltages and minimization of the branch current constraint violation. Algorithm is tested on 33-bus network with two feeders, and results show that algorithm finds combination of the switches which transfers the loads from one feeder to other in such way thatfor new network topology feeder overload is relieved, voltage profiles improved and total losses reduced.

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