Reliability Constrained Distribution Feeder Reconfiguration for Power Loss Minimization

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***Abstract*—This paper presents a path-based mixed integer quadratic programming (MIQP) formulation of distribution feeder reconfiguration (DFR) for loss minimization and reliability enhancement. Analytical expressions for standard reliability indices like SAIFI and EDNS are obtained by adopting standard assumptions regarding component failures. A path-based modeling framework is adopted to allow for easy evaluation of the reliability indices. The proposed path-to-branch incidence matrix results in linear expressions for the reliability indices and power flow equations. These linear models are suitably deployed in a flexible DFR optimization framework wherein reliability can feature in either via objectives or constraints. The proposed MIQP formulations are applied to different test systems to optimize network losses or reliability or both. Numerical results showcase the wide range of capabilities of the proposed formulations.**

I. Introduction

Distribution feeder reconfiguration (DFR) is an important tool in distribution management systems. It allows for changing the network topology by appropriately switching the statuses of the normally closed sectionalizing switches and normally open tie switches. The flexibility offered by such switching actions has been traditionally used for minimizing network losses, load balancing and service restoration [1], [2], [3]. DFR has been shown to improve system reliability as well [4]. While reduction in active power losses is attractive to the utilities as it directly translates to profits, they are also required to adhere to reliability standards set by regulatory councils. Furthermore, the move towards smarter systems and the opportunity for customers to choose between service providers also necessitate that the utilities endeavor to improve service reliability: DFR offers one way to achieve this goal [5]. Finally, smart grid technologies are expected to herald an era where line switching in real time will be feasible. To fully realize the potential of line switching for improving system performance, a rigorous decision making framework is needed. This paper proposes an MIQP approach to determine optimal system configuration with respect to loss minimization and reliability enhancement.

The DFR problem has been traditionally studied in the context of power loss minimization [1], [6], [7]. The algorithms in these references can be generally classified as *branch-exchange* algorithms, wherein an appropriate pair of sectionalizing switch and tie switch are opened and closed simultaneously to attain a new radial network topology that lowers network losses. Reference [1] lays down the foundation for identifying the optimal choice of tie-sectionalizer pair for switching. A greedy search algorithm for achieving this is proposed in [2]. Such methods have the disadvantage that the resultant topology is dependent on initial configuration. Combinatorial methods using non-linear power flow equations and integer variables representing switch statuses render DFR as a mixed integer non-linear programming problem. Using *DistFlow* equations [2], Taylor and Hover [8] present mixed-integer quadratic, quadratic constrained and second-order cone programming formulations for the DFR problem. A linear power flow based MIQP formulation presented in [9] is able to find optimal configurations in a short time even though it uses a ZI load model for the distribution system.

Inherent complexity of mixed integer programming has paved the way for heuristic approaches to be applied to the DFR problem [10]. Fuzzy logic [11], genetic algorithms [12], [13] and evolutionary programming [14] are some of the common choices. The application of heuristics is even more common when multiple objectives such as loss minimization and reliability enhancement come into play [15], [16], [17]. Attempting multi-objective DFR optimization as a mixed integer program is a very hard problem and to the best of authors' knowledge has not been attempted. This paper outlines preliminary steps towards such optimization.

Appending reliability oriented objectives in the DFR problem is complicated by the modeling considerations that come into play. Rigorous modeling of reliability indices in the DFR problem requires probabilistic methods and state sampling. Due to the difficulty in optimizing reliability indices directly, some papers propose load balancing as the method to improve reliability by relieving component stress [3], [18]. Heuristic methods have been applied for solving the DFR problem where reliability is included as an objective or constraint [6], [19]. Heuristic methods have the disadvantage that the solutions obtained may not be globally optimal. It is also difficult to ascertain the nature of the optimum to which the algorithm converges. In this paper, suitable yet reasonable assumptions are adopted to derive analytical expressions for standard reliability indices which are then incorporated as constraints or objectives in the DFR optimization problem. The

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reliability indices for the optimized configurations are verified using Monte Carlo simulations.

The contributions in this paper are twofold. First, a path-based modeling framework for the distribution network is presented that allows easy mapping of network topology into reliability indices. Second, simplified *DistFlow* equations are exploited to construct two MIQP formulations for DFR optimization: a reliability constrained loss minimization problem, where reliability considerations are modeled as linear constraints; and a multi-objective optimization problem for loss minimization and reliability enhancement. The performance of the algorithms is tested on standard distribution test systems.

The rest of the paper is organized as follows. In Section II standard assumptions related to reliability modeling are discussed. Section III introduces the proposed path based formulation and the "path-to-branch" incidence matrix. Complete problem formulation and the reliability optimization framework are explained in Section IV. The results obtained on widely used test systems are discussed in Section V. Concluding remarks are included at the end.

II. Reliability Modeling

Level of reliability of a system is associated with the following quantities: (1) frequency of failures (2) duration of failures (3) amount of power (or energy) not served. System performance indices give an indication of reliability by capturing the effect of one or more of these factors. For example, system average interruption frequency index (SAIFI) is defined as the ratio of total number of customer interruptions in a given period to the total number of customers [20] and expected demand not served (EDNS) as the total power demand not supplied in a given period. In this study, SAIFI and EDNS are chosen as constraints for the reconfiguration problem as they characterize two important reliability measures, namely the frequency of failures and power not supplied.

In general, the probabilistic nature of component failures demands sampling based methods like Monte Carlo simulations for reliability assessment. In sampling based methods, an accurate estimate of system reliability will require large number of samples across long durations of time. For a decision making problem like DFR, sampling based evaluation of reliability indices does not provide adequate flexibility. However by making suitable assumptions about the behaviour of component failures, it is possible to obtain analytical expressions for reliability indices. The following assumptions are made in this study:

1) Component failure events are independent
2) Individual component failure rates are exponentially distributed and can be approximated by Poisson distribution

Various studies have indicated that load point failure rates are approximately Poisson distributed when the component failure rates themselves are exponentially distributed. The validity of this claim has been demonstrated by comparing the analytical results with Monte Carlo simulations [21].

Under the above assumptions, the average load point failure rate at load point n (denoted λ^n) can be expressed as $\lambda^n = \sum \lambda_i$, where the sum is over all components upstream from the load point n till the source node of the system and λ_i is the failure rate of component i. In addition to lines, components like circuit breakers, switches and transformers will also have failure rates which contribute to λ^n. Analytical expressions for SAIFI and EDNS can now be obtained as:

$$SAIFI = \sum_n \lambda^n C^n \Big/ \sum_n C^n \tag{1}$$

where the sums are over all load points and C^n is the number of customers connected to load point n. Similarly,

$$EDNS = \sum_n \lambda^n P^n \tag{2}$$

where P^n is the real power demand at load point n.

For a given topology, information about the components along the path taken from each load point to the source node will simplify the evaluation of λ^n. The analytical expressions for SAIFI and EDNS thus obtained can be easily incorporated into the problem formulation. This motivated a path based formulation for the DFR problem with reliability constraints.

III. Path Based Modeling of Distribution Network

Distribution systems are usually operated with a radial structure. One of the simplest ways to represent the topology of the system is by a branch-to-node incidence matrix. But the incidence matrix model does not facilitate easy evaluation of reliability constraints for which the notion of "path to source" is important. A path-to-branch incidence matrix is introduced in this paper which will simplify the evaluation of reliability as well as branch flow constraints.

A. Building the Path-to-Branch Incidence Matrix

The radial distribution system can be represented as a graph $\mathcal{G} = (\mathcal{N}, \mathcal{L})$, where $\mathcal{N}$ is the set of nodes in the system and $\mathcal{L}$ is the set of branches. A branch between node i and node j is represented as (i, j). In a typical distribution network, there are sectionalizing switches which are normally closed and tie switches which are normally open. It is assumed that every branch in the system considered is available for switching. The status of each branch is represented using the variable u_{ij} where its values are $0/1$ based on whether the switch between nodes i and j is open/closed respectively.

Since it is possible to switch any branch of the network, a node may have multiple paths to the source. We represent any one such path (π_k^n) as an ordered set of branches which connect a node to the source. For the k^{th} path from node n,

$$\pi_k^n = \{(i, j) \mid (i, j) \in \mathcal{L} \text{ is in the path}\}. \tag{3}$$

Let Π^n be the collection of all paths from node n to source,

$$\Pi^n = \{\pi_1^n, \pi_2^n, \dots, \pi_{K_n}^n\},$$

where K_n is the total number of such paths from node n. Let u_k^n represent the status of path π_k^n, which takes the value 0 if the path k is not active and 1 if it is active.

By arbitrarily assigning power flow directions to the branches, we can define the elements of the k^{th} row of "path-to-branch" incidence matrix ($\mathbf{M}$) as,

$$m_{ij}^k = \begin{cases} 0 & \text{if branch } (i,j) \text{ is not in path } k \\ 1 & \text{if branch } (i,j) \text{ is in path } k \text{ and in the assigned direction} \\ -1 & \text{if branch } (i,j) \text{ is in path } k \text{ and opposite to the assigned direction.} \end{cases}$$

B. Formulation of Constraints

In reliability constrained optimization of power losses by feeder reconfiguration, there are three classes of constraints to be considered:

- Topology related constraints which ensure connectivity and radiality of the resultant network
- Line flow related constraints to take care of capacity limits of lines
- Reliability constraints on selected performance indices

We show how the path-based formulation outlined in the previous sections simplifies these constraints.

Each node in the system is to be supplied by one and only one substation. This necessitates that the number of active paths from each load point to the source node should be at least and at most one. It will also ensure connectivity and radiality of the resultant topology. This constraint can be written as,

$$\sum_{k:\pi_k^n \in \Pi^n} u_k^n = 1 \qquad \forall n. \tag{4}$$

A path will be active if and only if all the branches constituting the path are active. Let $\#\pi_k^n$ be the cardinality of the path π_k^n. Then,

$$\sum_{(i,j)\in\mathcal{L}} |m_{ij}^k| u_{ij} \geq \#\pi_k^n u_k \qquad \forall k,\ \forall n. \tag{5}$$

where u_{ij} is 1 or 0 depending on whether (i,j) is active or not.

We use simplified *DistFlow* equations [2] for writing the power flow constraints. Power loss on each line is neglected as their magnitudes are small in comparison with the power demands.

Let p_{ij} and q_{ij} be the flows corresponding to branch $(i,j) \in \mathcal{L}$, P_L^n and Q_L^n be the real and reactive power demands at node n. If branch (i,j) is in the path π_k^n, P_L^n and Q_L^n will contribute to the flow in that branch. Then,

$$p_{ij} = \sum_{n,k} m_{ij}^k P_L^n u_k^n \tag{6}$$

$$q_{ij} = \sum_{n,k} m_{ij}^k Q_L^n u_k^n. \tag{7}$$

The advantage of the above formulation is that we do not have to perform power flow in each iteration of the optimization process to determine branch flows.

The average load point failure rates at the terminal node of each path can now be expressed as,

$$\lambda_k^n = \sum_{(i,j)\in\mathcal{L}} |m_{ij}^k| \lambda_{ij} \qquad \forall k,\ \forall n \tag{8}$$

where λ_{ij} corresponds to the effective failure rate of the line (i,j). The assumption of Poisson distribution of component failure rates enables us to add the failure rates of all components like switches, circuit breakers and transformers between the nodes i and j to obtain λ_{ij}. Due to the property of Poisson distribution, λ_{ij} are also Poisson distributed.

We can write the linear expression for SAIFI from (1) as,

$$SAIFI = \sum_{n,k} \lambda_k^n u_k^n C^n \Big/ \sum_n C^n. \tag{9}$$

Similarly from (2),

$$EDNS = \sum_{n,k} \lambda_k^n u_k^n P_L^n. \tag{10}$$

A path-based formulation for DFR problem has been reported recently in [22]. We arrived on our formulation independently, motivated by path-based solution approaches in transportation and network optimization [23].

Our model has the advantage that the directions of branch flows are also captured along with their magnitudes. This will enable to extend the feeder reconfiguration problem to systems with distributed generation where the flow in different directions can be constrained individually. Also, our strategy of determining the status of paths based on constituent branch status is more intuitive and simple than the approach in [22], which requires identification of sub-paths contained in other paths.

The path-based formulation can be applied to systems with multiple substations by treating the substation nodes as a single source node. All the constraints outlined above apply to this modified network and the solution obtained is optimal.

IV. DFR for Power Loss and Reliability Optimization

In this section, the formulation of feeder reconfiguration as an MIQP problem is explained. Reliability indices are added to the DFR problem in two different ways: (1) as linear objective terms along with loss minimization (2) as constraints to the loss minimization objective. Both formulations are outlined in the following subsections.

A. Combined Optimization of Power Losses and Reliability

Simplified *DistFlow* equations can be used to obtain a quadratic expression for total active power losses in the system. Voltage magnitudes are assumed to be equal to 1.0 pu. Based on the above assumption, the loss minimization objective can be written as

$$min \sum_{(i,j)\in\mathcal{L}} r_{ij} \left(p_{ij}^2 + q_{ij}^2\right) \tag{11}$$

where r_{ij} is the total resistance of the section between nodes i and j.

By introducing linear terms for SAIFI and EDNS in the objective, we will be able to perform minimization of power loss and the reliability constraints simultaneously. The objective function can be written as,

$$F(x) = w_1 f_1(x) + w_2 f_2(x) + w_3 f_3(x) \tag{12}$$

where $f_1(x)$, $f_2(x)$ and $f_3(x)$ are the normalized total active power losses, SAIFI, and EDNS respectively. The objectives are normalized so that their magnitudes become comparable. Power loss objective is normalized with respect to its base-case value. SAIFI and EDNS are normalized with respect to their maximum values obtained by maximizing the respective objectives. By varying the weights $w_1,\ w_2$ and w_3, we can optimize the objective with different priorities for $f_1(x)$, $f_2(x)$ and $f_3(x)$. The weights are chosen such that $w_1+w_2+w_3 = 1$.

The minimization is subject to topology constraints (4), (5) and line flow constraints (6), (7).

Constraints on line flows are added so that,

$$p_{ij,min} \leq p_{ij} \leq p_{ij,max} \tag{13}$$

$$q_{ij,min} \leq q_{ij} \leq q_{ij,max}. \tag{14}$$

B. Reliability Constrained Loss Minimization

Target values for reliability indices can be chosen according to the requirements set by regulatory authorities. These constraints can be incorporated into the formulation as,

$$SAIFI \leq SAIFI^t \tag{15}$$

$$EDNS \leq EDNS^t \tag{16}$$

where $SAIFI^t$ and $EDNS^t$ are the target values.

As mentioned earlier, a node can possibly have multiple paths to the source. As the system size grows, the number of paths to be considered will become quite large. It can be shown that the inclusion of tight bounds on SAIFI and EDNS constraints can improve the performance of the computation by eliminating paths which violate the reliability constraints. Suitable bounds for SAIFI and EDNS can be chosen from historical data of the system.

Path-based formulation in [22] outlines a heuristic based on electrical distance to reduce the number of paths explored by the optimization problem – paths with electrical distance less than or equal to three times that of the shortest path to source from each node are the only ones considered. A similar reduction in search space is achieved in our approach by the reliability constraints without resorting to heuristics.

The quadratic objective and presence of binary variables u_{ij} and u_k^n makes the formulation an MIQP problem. Out of the decision variables p_{ij}, q_{ij}, u_{ij} and u_k^n, the explicit variables are only u_{ij}. The system topology is completely defined once we have the u_{ij} values.

V. Numerical Results

The proposed algorithms are tested on three commonly used test systems in literature for DFR. This section presents the results obtained on these systems and discusses important observations.

A. Test System Data and Implementation Details

The system data for 14-bus, 33-bus and 70-bus systems are available in [1], [2] and [24] respectively. The 14-bus and 70-bus systems have multiple source nodes and are modeled by combining the source nodes. Shunt capacitors are ignored. Customer data for the 33-bus system is given in [15]. For the other systems, number of customers at a node is taken to be proportional to the real power demand at that node. Failure rates are obtained by taking λ_{ij} of the line with largest impedance as 0.4 failures/year and that of the section with smallest impedance as 0.1 failures/year. The failure rates of the other sections are interpolated proportionally [15]. The information about paths are required a priori. For this, the paths are enumerated by using a depth-first search based algorithm.

CPLEX solver in the TOMLAB Optimization Environment for MATLAB® is used for solving the MIQP problem detailed in Section IV. Solutions are obtained on an Intel Core i7-5500U CPU at 2.40 GHz and 8 GB RAM laptop.

The performance of each optimal network topology obtained from the MIQP problem is characterized in terms of total active power losses, SAIFI, EDNS and minimum voltage magnitude (V_{min}). Power losses and voltage magnitudes are obtained by running Newton-Raphson power flow using MATPOWER. SAIFI and EDNS are calculated using the analytical expressions given in Section III and their accuracy is verified by performing Monte Carlo simulations.

The basecase configurations of 14-bus system, 33-bus system and 70-bus system given in [1], [2] and [24] respectively are chosen as the benchmark topologies for comparing the optimal configurations. Performance of the benchmark configurations are given in Table I.

TABLE I. Benchmark configurations for test systems

System	Open Lines	Losses (kW)	SAIFI	EDNS (kW/year)	V_{min} (pu)
14-bus	5-11, 10-14, 7-16	657.7	0.6338	18.189	0.952
33-bus	8-21, 9-15, 12-22, 18-33, 25-29	202.7	1.2753	4.5181	0.904
70-bus	22-67, 15-67, 21-27, 9-50, 29-64, 9-38, 45-60, 38-43, 9-15, 39-59, 15-46	227.5	1.2145	80.9	0.905

B. Performance of Optimal Configurations

For minimizing only the total losses, MIQP formulation using objective function (12) is solved by setting $w_1 = 1$, $w_2 = 0$ and $w_3 = 0$. The performances of optimal configurations obtained for the three test systems are listed in Table II. The optimal configurations and magnitudes of loss reduction are in accordance with what is reported in literature [8], [9], [24]. These configurations thus validated serve as an additional benchmark to compare against the topologies obtained for reliability optimization and reliability constrained loss minimization. Lines shown in bold in the

TABLE II. LOSS MINIMIZED CONFIGURATIONS

System	Open Lines	Losses (kW)	SAIFI	EDNS (kW/year)	V_{min} (pu)
14-bus	8-10, 9-11, 7-16	606.6	0.6247	17.929	0.956
33-bus	7-8, 9-10, 14-15, 32-33, 25-29	139.5	1.167	4.1816	0.938
70-bus	14-15, 26-27, 37-38, 44-45, 49-50, 65-66, 9-38, 15-46, 29-64, 39-59, 67-15	205.3	1.1953	79.65	0.927

corresponding tables indicate the changes from the minimum loss configuration.

SAIFI and EDNS can be optimized individually by choosing appropriate weights in the objective function (12). For optimizing only SAIFI, weights are chosen as $w_1 = 0$, $w_2 = 1$ and $w_3 = 0$. Similarly for minimizing the value of EDNS, w_3 is set to 1.0 while weights for power loss and SAIFI are set to 0. Performances of the configurations obtained by minimizing SAIFI are presented in Table III. Minimization of EDNS resulted in the same topology that minimized SAIFI for all three test systems. This observation suggests that optimizing over one reliability index can improve other reliability measures. Further investigations are needed to fully explore the potential of this claim.

TABLE III. SAIFI/EDNS OPTIMIZED CONFIGURATIONS

System	Open Lines	Losses (kW)	SAIFI	EDNS (kW/year)	V_{min} (pu)
14-bus	9-11, **10-14**, 7-16	634.3	0.6244	17.919	0.954
33-bus	7-8, 9-10, 14-15, **16-17**, **27-28**	154.2	1.0593	3.78	0.928
70-bus	14-15, 26-27, 44-45, **63-64**, 65-66, **9-50**, 9-38, 15-46, **43-38**, 39-59, **15-9**	209.1	1.1799	78.44	0.920

Simultaneous optimization of active power loss, SAIFI and EDNS is achieved by specifying non-zero values for all the weights. We only present the results obtained for the 33-bus system. Power loss objective is normalized with respect to its base-case value (202.7 kW), SAIFI and EDNS are normalized with respect to their maximum values 3.4689 and 13.6114 kW/year respectively. The actual value of power loss and SAIFI are plotted against w_1 in Figure 1. The values of w_2 and w_3 are taken to be equal while obtaining the plot.

A higher weight for the power loss minimization results in a configuration with the total losses close to its global minimum value. Similarly for lower values of w_1, SAIFI and EDNS are close to their minimum values obtained in Table III, but the total losses have increased considerably from its minimum value. Utilities can choose the weights to align with priorities for specific systems.

Total power loss objective in (11) can be minimized with the reliability indices as constraints using the formulation in

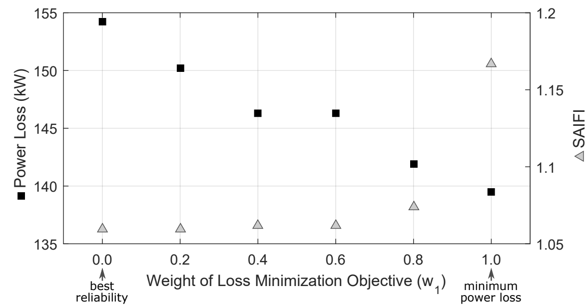

Figure 1. Plot of power loss and SAIFI as a function of weight of loss minimization objective. Shows the trade-off between the objectives in the optimization.

Section IV-B. System performances are given in Table IV. A comparison with performance indices in Table II and Table III shows how the optimal topologies have resulted in power losses close to the minimum loss values while satisfying the reliability constraints.

The computation times are expected to grow along with the system size as the number of paths to be considered for a large system can become quite high. But the SAIFI and EDNS constraints help to limit the number of paths explored and hence improve the computation times. For example, CPU time for power loss minimization of the 33-bus system is 169.10 seconds which reduces to 0.56 seconds when reliability constraints are included.

TABLE IV. RELIABILITY CONSTRAINED, LOSS MINIMIZED CONFIGURATIONS

System	Open Lines	Losses (kW)	SAIFI	EDNS (kW/year)	V_{min} (pu)
14-bus	8-10, 9-11, 7-16	606.6	0.6247	17.929	0.956
33-bus	7-8, 9-10, 14-15, **28-29**, 32-33	139.97	1.4871	5.524	0.941
70-bus	**8-9**, 14-15, 37-38, **40-44**, **62-65**, **9-50**, 15-46, 29-64, **39-69**, **21-27**, **15-9**	207.8	1.1845	78.96	0.924

C. Reliability Evaluation Using Monte Carlo Simulations

The reliability indices for the optimized configurations are evaluated using (9) and (10); and verified via Monte Carlo simulations. Non-sequential method [25] is used as the failures are assumed to be independent of each other. The failure rates are used to construct Poisson distributions for a component's availability and 5000 samples are drawn for each component in the system. An instance of the entire system is constructed using randomly chosen set of samples for availabilities of different components. The average of the indices' values for all such 5000 instances is then calculated. Table V compares the indices obtained analytically and via simulations for different systems and different configurations. Close agreement between the values indicates the suitability of using analytical methods to model reliability in the context of DFR.

TABLE V. RELIABILITY EVALUATION USING MONTE CARLO SIMULATIONS

	14-bus				33-bus				70-bus			
	SAIFI		EDNS (kW/year)		SAIFI		EDNS (kW/year)		SAIFI		EDNS (kW/year)	
	Analytical	MC	Analytical	MC	Analytical	MC	Analytical	MC	Analytical	MC	Analytical	MC
Initial Configuration	0.6338	0.6355	18.189	18.238	1.2753	1.2865	4.5181	4.776	1.2145	1.2301	80.9	81.94
Loss Minimization	0.6247	0.6253	17.929	17.946	1.1670	1.1539	4.1816	4.173	1.1953	1.2015	79.65	80.06
Reliability Optimization	0.6244	0.6249	17.919	17.933	1.0593	1.0601	3.780	3.812	1.1799	1.1856	78.44	78.82
Reliability Constrained-Optimization	0.6247	0.6253	17.929	17.946	1.4871	1.4593	5.524	5.507	1.1845	1.1898	78.98	79.33

VI. CONCLUSIONS

We have introduced MIQP formulations for the DFR problem using a path-based model for the distribution system. A "path-to-branch" incidence matrix is proposed which simplifies the inclusion of standard reliability indices in the DFR problem. The capability of the multi-objective framework proposed in the paper is demonstrated via combined optimization of power losses and reliability indices. It is shown that the reliability oriented optimization improves the system performance without adversely affecting the power loss and voltage magnitudes. Since the modeling assumptions adopted for component failures may induce such a conclusion, further investigations are needed to validate this claim.

The proposed approach has the following advantages: (1) the "path-to-branch" incidence matrix captures critical topology information useful in reliability evaluation and flow computations; (2) since reliability indices are realistic operating constraints for utilities, reliability constrained DFR can form an integral part of the distribution management system.

Since information about direction of power flow in each branch is retained, the approach can be extended to study the effect of distributed generation in DFR problem. Pareto optimality of the multi-objective case with power loss and reliability indices can be explored to define the trade-off between performance indices.

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