

# Power Distribution Network Reconfiguration for Bounded Transient Power Loss

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**Abstract**— We revisit the loss reduction problem for network reconfiguration in power distribution systems in this paper. Besides the conventional line power loss (LPL), in our model, we introduce a new concept - the *transient power loss (TPL)*, which is mainly induced by the communication asynchronization and response delay. TPL is often overlooked in previous works because it's hard to measure in the conventional power networks. However, we can tackle this challenge in smart grid especially with the help of smart meter. In this paper, we propose a new heuristic greedy algorithm to achieve the minimal LPL with bounded TPL and we assess its performance via simulation based on the IEEE-33 nodes system.

**Index Terms**— Line Power Loss, Loss Reduction, Network Reconfiguration, Transient Power Loss, Transient Stability.

## I. INTRODUCTION

POWER distribution network reconfiguration is one of the most effective methods to achieve loss reduction and boost distribution system automation [1, 2], especially with the introduction of remote control of the switches and breakers. Formally, network reconfiguration of the power distribution systems is defined as the change in the network structure caused by closing ties and opening sectionalizing switches. When the operation conditions of the distribution systems change, the network is reconfigured for two main purposes [3, 4]:

- It can be used to balance the load on each bus in the distribution network, and
- It can help reduce the total line power loss (LPL) in the distribution system.

Network reconfiguration allows the system to serve the same load to users with less power losses on the system

lines. It can also relieve the overloads in the network, and prevent lipid overload. Network reconfiguration is an effective way to improve the power quality in the system and enhance the reliability of power voltage on the user-side.

### A. Related Work

Generally speaking, the network reconfiguration is a multi-objective nonlinear optimization problem. Due to the fact that there are a large number of sectionalizing switches in a distribution network, most of the existing methods are approximation methods either based on evolutionary knowledge or heuristics. In particular, we divide the previous works into three bodies. One uses evolutionary and knowledge-based techniques. Another uses heuristics method. And the other uses mixed methods.

Among the first body of literature, for example, in [6], Ababei, *et al.* proposed a random walk based techniques for the loss estimation in radial distribution systems, which localize the computation. In [7], Wu, *et al.* developed a method which modifies the operators of particle swarm optimization's formula based on the characters of both status of switches and shift operator to construct the binary coding particle swarm optimization for feeder reconfiguration.

Heuristic algorithms, as the second body of the literature, are among the best candidates for real-time distribution network reconfiguration for loss reduction, since they have been proven to have the best performance in a short runtime. An early work is presented by Civanlar *et al.* in [11]. They proposed a computationally attractive algorithm for power loss reduction based on the concept of branch exchange. Later, the algorithm was improved by Baran *et al.* in [3], which took the advantage of the radial structure of most of the power distribution systems. This method is known as DistFlow method and often serves as the benchmark for network reconfiguration. Its computational efficiency has also been demonstrated to be very attractive.

The final body of literature tries to make full use of both the previous two bodies and has developed very fast during the last decade. For instance, in [9], Ahuja, *et al.* designed an interesting hybrid algorithm based on artificial immune systems and ant colony optimization for distribution system reconfiguration. Shin, *et al.* presented an approach for optimal reconfiguration of distribution network using Genetic algorithm and Tabu search method.

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Different from previous works, we note that in the practical implementation of network reconfiguration, the control signal is distributed from the control center to each switcher respectively, via power line communication or wireless communication. The delay occurring in the communication, as well as the response delay in the reconfiguration process will cause disturbances in the local power grid. Thus, we need to investigate an important form of power network stability, the *transient stability* [12], which is the ability of a power network to remain in synchronism when subjected to large transient disturbances such as transient power loss (TPL). However, in previous works for network reconfiguration, *e.g.* [3-11], the researchers often overlooked TPL and only considered LPL in their model. In order to achieve the transient stability and the bounded disturbances, we propose a new approach to achieve the LPL reduction with bounded TPL. In our approach, we assume the grid operator can monitor the delays to the control signal at the users' side with the help of *smart meter*, which is foreseen to be very popular throughout the world within the next several decades.

### B. Our Contributions

We revisit the network reconfiguration problem for loss reduction in radial systems. Radial model is constantly being used as the test model since it is the typical structure of distribution network. We follow the methodology proposed by Baran [3], *i.e.* the DistFlow solution approach. However, here we take the transient power loss into consideration to modify the model of network reconfiguration. This power loss model combines the distribution line power loss (LPL) and transient power loss (TPL). Based on this new model, we present a new solution to network reconfiguration problem. We summarize the contributions in this paper as follows:

- *Network model with TPL*: We consider the transient power loss in the network reconfiguration problem and develop a new computational model based on this concept, which captures disturbances caused by the delay occurring in the communication and the response delay in the reconfiguration process.
- *Heuristic Algorithm*: To efficiently solve the new network reconfiguration problem, we propose a heuristic algorithm. We demonstrate via simulation that our algorithm successfully characterizes the grid operator's tradeoff between LPL and TPL.
- *Simulation Assessment*: We implement our algorithm in the IEEE 33 nodes system. From the simulation results, we show that our algorithm gives a different result from the one DistFlow approach does. This is very interesting observation and best illustrates that TPL is not neglectable when performing network reconfiguration.

The rest of this paper is organized as follows. We first revisit the general problem statement of network reconfiguration in Section II. Then, in Section III, we present the conventional algorithm (followed by the DistFlow approach) for loss estimation, and then, formulate the optimization problem for our new model, considering the TPL. After that, we propose a heuristic greedy algorithm to solve

the network reconfiguration problem in our model in Section IV. In Section V, we implement our model in IEEE-33 nodes system and assess the proposed heuristic algorithm via simulation. Finally, the concluding remarks are drawn in Section VI.

## II. PROBLEM STATEMENT

As shown in Fig. 1, we consider the network reconfiguration problems for loss reduction, besides LPL, taking TPL into consideration, in such a distribution system. As is standard in the literature, to simplify the problem, we assume that the loads along a feeder section as constant, and all loads are placed at the end of distribution lines. We also assume that each line in the system is associated with a switch, which is for the convenience of performing network reconfiguration.

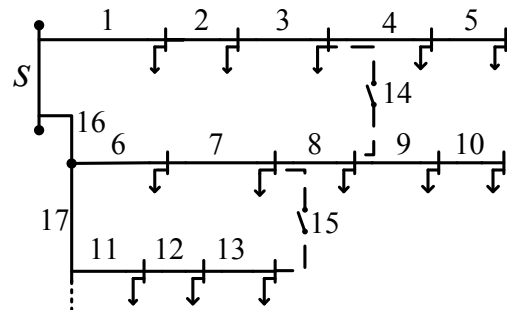


Fig. 1. A line diagram of a distribution system.

An original network can be reconfigured by closing an open branch, *e.g.* branch 15, and opening a closing switch, *e.g.* branch 11, to ensure no loop will be created in the system.

Following the terminology defined in [5], we define such a pair of basic switching operation a *branch exchange* between 15 and 11. Network reconfiguration can be achieved by several pairs of branch exchanges.

By changing the positions of switches, load transfer is involved in the network reconfiguration problems for loss reduction. We assume that all other factors remain unchanged during the network reconfiguration. Such factors include the voltage profile of the system, capacities of the lines or switches, and reliability constraints.

In the classical network reconfiguration model, only LPL on the system lines is considered. However, as we mentioned, in the practical implementation of network reconfiguration, the control signal is distributed from control center to each switcher respectively, via power line communication (PLC) or wireless communication. Due to the instability and the delay occurring in the communication, the synchronization of the control signal to each switcher cannot be guaranteed precisely all the time. Moreover, the response delay, which refers to the response time from the switcher receives the control signal to its response is finished, should also be considered. Due to the asynchronization and the response delay in the reconfiguration process, extra power loss will emerge. Therefore, we should take such TPL into account. We will formally define TPL in our model in next section.

### III. SYSTEM MODEL

Based on the conventional network reconfiguration model, we describe the distribution lines power loss (LPL) combined with transient power loss (TPL) in this section.

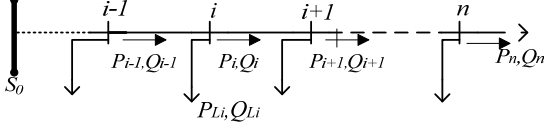


Fig 2. A line diagram of a radial distribution network.

Consider a radial network shown in Fig. 1. We represent its line diagram in Fig. 2. There are  $n$  power distribution lines in the network and each power line  $k$  is represented by impedance  $z_k = r_k + jx_k$ , and the power load  $S_k = P_k + jQ_k$  on bus  $k$  is assumed to be constant. In the distribution system, the total LPL is

$$LPL = \sum_{k=1}^n r_k \frac{P_k^2 + Q_k^2}{V_k^2} \approx \sum_{k=1}^n r_k (P_k^2 + Q_k^2) p.u., \quad (1)$$

where  $n$  denotes the total branches number in the network, and we use the fact that  $V_k^2 \approx 1 p.u.$

We use the simplified DistFlow equations [1] in this section to find solution of a given network configuration. These equations are:

$$\left\{ \begin{array}{l} P_i = \sum_{k=i+1}^n P_{Lk}, \\ Q_i = \sum_{k=i+1}^n Q_{Lk}, \\ V_i^2 = V_{i-1}^2 - 2(r_{i-1}P_{i-1} + x_{i-1}Q_{i-1}). \end{array} \right. \quad (2)$$

Generally, in a given radial network, closing each open switch correspond to a unique loop in the network. For example, in Fig. 3, closing switch  $i$  leads to the entire network becoming a loop.

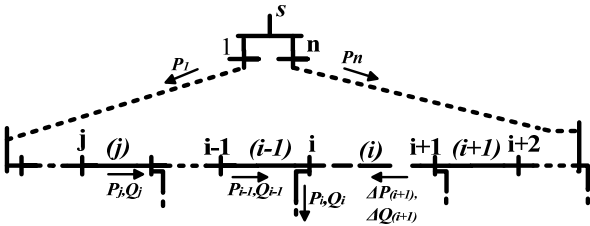


Fig. 3. A loop related to the opening switch  $i$ .

Denote the branches extend between the nodes from the source  $s$  to the left side of an open switch  $i$  as set  $\mathcal{L}_i$ . That is,

$$\mathcal{L}_i = \{1, \dots, j, \dots, i-1\}. \quad (3)$$

Correspondingly, we can define the other branches as set  $\mathcal{R}_i$ , where

$$\mathcal{R}_i = \{i+1, \dots, n-1, n\}. \quad (4)$$

Based on the system of equations in (2), the LPL reduction in the distribution network due to branch exchanges is

$$\begin{aligned} \Delta LPL_{(i,j)} = & 2P_j \left( \sum_{l \in \mathcal{L}_i} r_l P_l - \sum_{l \in \mathcal{R}_i} r_l P_l \right) + \\ & 2Q_j \left( \sum_{l \in \mathcal{L}_i} r_l Q_l - \sum_{l \in \mathcal{R}_i} r_l Q_l \right) - (P_j^2 + Q_j^2) \left[ \sum_{l \in \mathcal{R}_i \cup \mathcal{L}_i} r_l \right] \end{aligned} \quad (5)$$

Without loss of generality, we assume  $j < i$  here. Then, the TPL incurred by the branch exchanges is

$$TPL_{(i,j)} = D_{ij} \sum_{k=j}^i P_k, \quad (6)$$

where  $D_{ij}$  represents the delay of the branch exchanges of switch  $i$  and switch  $j$ . Thus, we could define the total power loss (PL) reduction due to branch exchange as

$$\Delta PL_{(i,j)} = \Delta LPL_{(i,j)} - TPL_{(i,j)}. \quad (7)$$

Furthermore, we define a valid pair of branch exchanges as  $(o,c)$ , where  $o$  denotes the original open switch,  $c$  denotes the original closing switch, and the operation won't create any loop in the network. Thus, a series of  $r$  valid branch exchanges is a network reconfiguration  $C$ , where

$$C = \{(o_1, c_1), \dots, (o_r, c_r)\}, \quad (8)$$

and all such network reconfigurations form a set of  $\mathcal{C}$ . We can now formulate the optimization problem as minimizing LPL with bounded TPL for network reconfiguration as follows,

$$\begin{aligned} \max_{C \in \mathcal{C}} \quad & \sum_{(o,c) \in C} \Delta LPL_{(o,c)} \\ \text{subject to} \quad & TPL_{(o,c)} \leq UB, \forall (o,c) \in C, \end{aligned} \quad (9)$$

where  $UB$  denotes the upper bound of TPL, and the constraint in this optimization problem denotes the transient stability constraint.

### IV. HEURISTIC ALGORITHM

Note that the search space in the optimization problem is exponential in  $n$ . Moreover, due to the load's fast change in each node, we need a real time algorithm to ensure that when we perform the network reconfiguration, all the factors in the network don't change too much. Otherwise, even if we successfully solve the optimization problem (8), the solution will still be an invalid network reconfiguration. Therefore, heuristic algorithms dominate the solution for network reconfiguration. Based on the save concern on the dimension curve, in this section, we develop a heuristic and greedy algorithm to solve this optimization problem, which iteratively finds the maximal branch exchange in each step of network reconfiguration.

To put it formally, suppose we are at the end of the  $r$  round network reconfiguration, and the current network reconfiguration set is  $\{(o_1, c_1), \dots, (o_r, c_r)\}$ , denoted by  $C^r$ . In the  $r+1$  round,

- Step 1: Solve a single increment optimization of the optimization problem in (8). Mathematically, we have

$$\begin{aligned} & \max_{C^r \cup (o_{r+1}, c_{r+1}) \in \mathcal{C}} \Delta LPL_{(o,c)} \\ & \text{subject to } TPL_{(o,c)} \leq UB, \end{aligned} \quad (10)$$

- Step 2: Perform the solution  $(o_{r+1}, c_{r+1})$  of (10) into the network reconfiguration. Thus, we have

$$C^{r+1} = C^r \cup (o_{r+1}, c_{r+1}) \quad (11)$$

- Step 3: Wait the response from sensors at nodes  $o_{r+1}$  and  $c_{r+1}$ . After the  $r+1$  round network reconfiguration is complete, update the new load information at each node and go back to Step 1 to start the  $r+2$  round network reconfiguration.

This is a greedy heuristic real time algorithm for network reconfiguration, taken TPL as a constraint in the optimization problem. In the next section, simulation results show that it is indeed a very good heuristic algorithm and based on these results, we discuss how to achieve a good tradeoff when performing network reconfiguration.

## V. SIMULATION

We use IEEE 33-node system in the simulation, as in Fig. 4. It consists of 33 nodes, 5 tie lines all with switches and 32 branches all with sectionalizing switches. Node 1 is the source node. To clearly demonstrate the influence of TPL, we only consider two of the five tie lines. All delays are generated randomly in uniform distribution between  $[0,1]$  ms. The whole system is implemented by MATLAB<sup>®</sup> 2009.

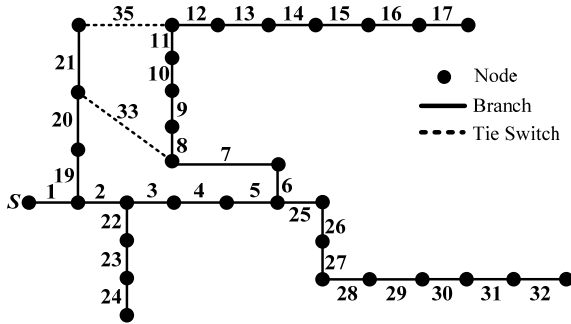


Fig 4. Original configuration

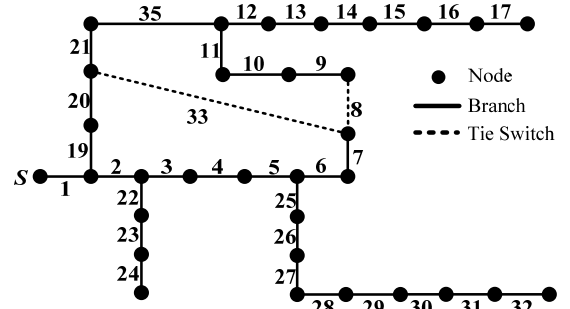
To introduce in the transient loss, we define the transient power loss coefficient between each pair of switches as shown in the Table 1. For simplicity, we only list each switch to switch 33 and 35 as an example. All other TPL coefficients are generated similarly at uniformly random between  $[0,1]$  ms. And throughout our simulation, we assume these coefficients are time invariant. In practice, the value of these coefficients is determined by topological property of each pair of switches, as well as the power load distribution on each bus corresponding to the switches.

In Fig. 5, we present the temporal solutions after first iteration of search. Note that by considering TPL, the proposed model gives a different solution (Fig. 5(b)) from the one that conventional model does (Fig. 5(a)).

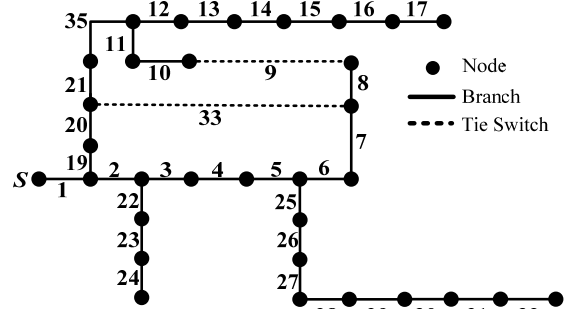
Table 2 shows a summary of all the simulations. We mainly compare the differences in branch exchange as well as loss

Table 1. Transient power loss coefficient between each pair of switches

m/b	33	35	m/b	33	35
1	0.074	0.908	18	0.861	0.907
2	0.136	0.011	19	0.589	0.974
3	0.72	0.738	20	0.767	0.186
4	0.684	0.297	21	0.494	0.538
5	0.378	0.264	22	0.062	0.191
6	0.187	0.458	23	0.060	0.031
7	0.600	0.548	24	0.257	0.944
8	0.542	0.081	25	0.601	0.100
9	0.285	0.047	26	0.016	0.775
10	0.175	0.812	27	0.824	0.896
11	0.214	0.104	28	0.734	0.993
12	0.249	0.298	29	0.822	0.336
13	0.863	0.133	30	0.177	0.236
14	0.525	0.093	31	0.455	0.110
15	0.104	0.970	32	0.894	0.347
16	0.834	0.695	33	0.370	0.521
17	0.264	0.906	35	0.273	0.071



(a) Solution in conventional model



(b) Solution in proposed model

Fig. 5. Simulation Results after the first search level.

reduction between the conventional model and our proposed new model. Formally, in Table 2, the conventional model only considers the LPLR reduction (LPLR) in the distribution system, while our proposed model takes the transient power loss (TPL) into consideration, and includes it as a constraint in the optimization problem (9) and (10).

In order to compare the results, we listed the LPLR and TPL due to a pair of branch exchange in both of the model. In our system, we set  $UB$  as 20/kW.

We can see that after each search level, two candidate solutions are given to reconfigure the two tie lines. And the branch exchanges chosen are listed in the row after each

Table 2. Simulation Results

Search level	Conventional Model without transient constraint				Proposed Model with transient constraint			
	solution	LPLR/kW	TPL/kW	Exceed UB	solution	LPLR/kW	TPL/kW	Exceed UB
1	33-7	<b>62.23</b>	47.94	<b>Yes</b>	none <sup>1</sup>	---	---	---
	35-8	<b>69.63</b>	36.56	<b>Yes</b>	35-9	<b>68.33</b>	17.52	<b>No</b>
Branch exchange	<b>35-8</b>				<b>35-9</b>			
2	33-7	<b>60.99</b>	50.03	<b>Yes</b>	33-7	<b>8.64</b>	14.25	<b>No</b>
	none <sup>1</sup>	----	---	---	none <sup>1</sup>	---	---	---
Branch exchange	<b>33-7</b>				<b>33-7</b>			

search level. From LPLR and the TPL in both models, we can see that, in the conventional model, all branch exchanges' results exceed *UB*, while all results in the proposed model satisfy the transient stability constraint. The simulation results demonstrate that to achieve the transient stability and avoid triggering complex or even cascading failures in the network, TPL plays a crucial role in loss reduction.

Furthermore, based on the simulation results in Table 2, we have the following observations:

- In the cases where the transient power loss is considered, the total loss reduction is less than the cases that transient power loss is ignored. This observation is proper due to the definition of the total power loss, defined in (7).
- Different branch exchange solutions were obtained in the two cases. This is because influenced by the transient power loss, each branch exchange is not determined only by the need for minimizing the power loss on lines, but also minimizing the operation costs during the reconfiguration procedure.
- We may find that solutions of the conventional model have greater LPL than those of our proposed model. However, large reconfiguration operation cost, which is shown as TPL here, makes the advantage in LPL reduction neglectable.

In the second search level, a negative total power loss reduction is obtained when the transient power loss is considered. Note that the negative power loss here does not mean "loss increases", but means the reconfiguration costs are so large that exceed the LPLR temporarily.

## VI. CONCLUSIONS

In this paper we propose a new power loss estimation model considering the transient power loss due to network reconfiguration. Based on this new model, we propose a heuristic greedy algorithm to solve the new network reconfiguration problem. Simulation results show that the heuristic algorithm gives different solutions for network

reconfiguration in our model from the one DistFlow does in conventional models.

We want to extend our work in several directions. For example, TPL may cause voltage profile of the distribution system fluctuate greatly, which may lead to further power loss during the reconfiguration procedure. We may also want to further investigate the trade-off between LPL and TPL in decision makings for network reconfiguration in the future.

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<sup>1</sup> The word "none" means there is no solution related to the particular tie lines which will leads to LPL reduction, or no solution satisfies the transient stability constraint. That is, current configuration is already optimal.