Phase Swapping for Distribution System Using Tabu Search

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Abstract: In power distribution systems, feeders frequently exhibit some imbalance between phases. Feeder imbalance occurs when the currents (I_a, I_b and I_c) of a three-phase system do not have the same magnitude at any load point along the feeder, because some phases are more heavily loaded than others. A state of imbalance in power systems may cause excessive voltage drops, unnecessary energy losses, and increased risk of feeder overload. It may also affect system power quality and electricity price. In order to correct this state of disproportion, phase balancing can be utilized. One solution to phase balancing is to swap single-phase loads from one phase to another to make the currents identical at each load point on the feeder. This technique is called phase swapping. Balancing loads in a distribution system can enhance utilities competitiveness by improving reliability and by reducing costs. The determination of the optimal swapping scheme is a non-linear problem. The efficiency of using Tabu Search to solve this non-linear phase balancing problem is demonstrated. Tabu Search is a heuristic method that enhances the performance of a basic local search technique by using a memory structure. The Tabu Search algorithm to find the optimal phase swapping scheme with the minimal cost was developed using a model from an unbalanced feeder from a typical Local Distribution Company (LDC).

Key-Words: Phase Swapping, Phase Balancing, Distribution Systems, Tabu Search.

1 Introduction

Distribution systems consist of substations, which supply feeders that have three phases (a, b and c). Feeders supply power to different loads that can either be single or three phase. The majority of loads are transformers that deliver power to a business or a small number of customers (typically 10 households). A certain number of transformers are single phase and thus must be connected to only one of the three lines of the feeder. Often the transformers are connected to the closest line by electrical technicians, as it makes the installation easier and faster. As a consequence, one phase can become overloaded, which causes larger neutral currents and avoidable power losses.

Even now in the 21st century, most utilities still use manual control and a minimum of monitoring systems [1]. This makes it difficult to locate and quickly repair faults or even to minimize losses by evenly loading feeders and substations. However, as the number of customers within a service area grows, feeders get overloaded or close to being overloaded. At that point, phase balancing is crucial to ensure that overheating and damages are avoided, and that good service is delivered to end-users. Because phase balancing releases line capacity for additional loads, it can enhance utilities' competitive capabilities, as well as reduce their costs by deferring feeder expansion projects. Hence, utilities will be able to provide high quality power at a lower price, which may boost their competitive ability in a deregulated environment [2].

To solve load imbalance, utilities are frequently limited to a trial and error method, as they usually do not have a software model of their distribution system [1]. Often, the only information they have is what is measured at the source of each feeder. Thus, they can see which of the three phases is the most heavily loaded, but they cannot accurately determine which loads to swap to which phase to reduce the imbalance. They then proceed by switching one load at a time until the currents at the feeder level are balanced. The problem with this technique is that the feeder may be balanced at the time of the changes, but a load's new position might create a greater imbalance at another moment in time. Hence, it is important to consider more than just one factor when determining an optimal swapping scheme, including seasonal daily load variations, costs, current imbalance and power losses.

If there are L single-phase loads in a distribution system, there are 3^L possible swapping combinations. In modern distribution systems with thousands of single-phase loads, finding the optimal solution becomes an arduous challenge.

2 Problem Formulation

The phase imbalance problem in a distribution system is to find the optimal load swapping scheme that reduces imbalance and losses on the line, while minimizing the cost of the swaps. The load configuration in a distribution system can be modified by swapping single phase loads from one phase to another, as demonstrated in Figure 1.

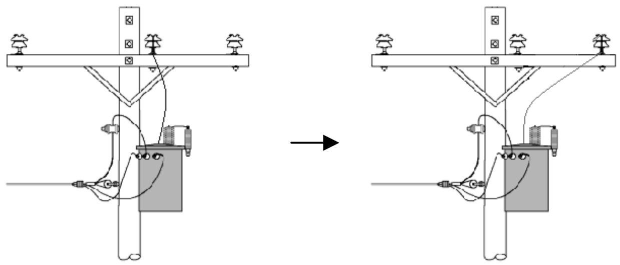

Fig. 1 A single-phase transformer phase swap

By reconnecting single-phase transformers to a less heavily loaded phase, the distribution line capacity is released for additional loads. In practice, phase swapping is generally conducted intuitively by distribution engineers, as they decide which single-phase transformers to switch, based on their experience. This time-consuming procedure is certainly not optimal and can be improved, and the transfer of loads must be done such that certain objectives are attained.

2.1 Objective Function

When trying to find the best swapping scheme for an imbalanced distribution system, many objectives are important for LDCs. The objective function considered in this study considers different factors that are described as follows.

2.1.1 Number of Swaps Factor

The total number of swaps, N_{swaps}, is the number of load re-phasing actions that have to be conducted between the initial and the final configuration divided by the total number of loads on the feeder:

$$N_{swaps} = \frac{C_{nm}}{TL} \times 100\% \qquad (1)$$

where C_{nm} is the total number of phase reconnections to be conducted and TL is the total number of loads in the system.

Distribution engineers want to minimize the number of swaps, as each swap represents the physical action of sending a team of technicians to reconnect some single-phase transformers.

2.1.2 Current Imbalance Factor

The current imbalance is a major concern for LDCs, as it directly leads to feeder overload and relay tripping. The current imbalance is expressed as:

$$\Delta I = \sum_{j=1}^{n} \frac{\left|I_{aj} - I_{bj}\right| + \left|I_{bj} - I_{cj}\right| + \left|I_{aj} - I_{cj}\right|}{I_{aj} + I_{bj} + I_{cj}} \times 100\% \qquad (2)$$

where I_{aj}, I_{bj} and I_{cj} are current magnitudes on phase a, b and c measured of the j^{th} segment on the feeder and n is the total number of segments on the feeder.

2.1.3 KVA Imbalance Factor

The kVA imbalance on a feeder is closely related to the current imbalance. It can easily be calculated at the start of the feeder, as load information is available at the substation level in most LDCs. It does not represent how the imbalance is spread along the feeder, so a feeder could look balanced at the starting point, but show some imbalance at different points along the feeder. The kVA imbalance is expressed as:

$$\Delta kVA = \frac{\left|L_a - L_b\right| + \left|L_b - L_c\right| + \left|L_a - L_c\right|}{L_a + L_b + L_c} \times 100\% \qquad (3)$$

where L_a, L_b and L_c are load values in kVA for phases a, b, and c respectively, measured at the source of the feeder.

2.1.4 Power Losses Factor

Power losses in a distribution system are worth minimizing, as loss minimization can lead to energy savings. However, utilities have little incentive to reduce their kW losses since they are distributed and paid for by customers. As electricity demand increases, so, too, does the environmental awareness and the consciousness for energy conservation. Therefore, governments are starting to subsidize LDCs for conducting optimization procedures that reduce the amount of wasted energy. This initiative in Ontario, Canada is called the conservation and demand management project.

Because there is an increased interest in reducing power losses in distribution systems, they were included in this study as an objective function. Power losses, as a percentage value, are expressed as follows:

$$P_{loss} = \frac{\sum_{j=1}^{n} \sum_{p=a}^{c} \left(I_j^p\right)^2 \cdot R_j^p}{TP} \times 100\% \qquad (4)$$

where I_j^p and R_j^p are the current and the resistance of phase p of the j^{th} feeder segment, respectively. Parameter n is the total number of segments on the feeder, and TP is the total power in kW supplied at the start of the feeder.

3 Problem Solution

3.1 Multi-objective Function

The four objectives functions described above are typically what distribution engineers are interested in minimizing, to optimize their system. To consider these objectives, a multi-objective cost function was used in this study to solve the phase imbalance problem in distribution systems. This weighted cost-function is expressed as follows:

$$f = \left(w_1 \cdot P_{loss}\right) + \left(w_2 \cdot \Delta I\right) + \left(w_3 \cdot N_{swaps}\right) + \left(w_4 \cdot \Delta kVA\right) \qquad (5)$$

Weight values (w_1 through w_4) can easily be changed to assign more, or less, importance to any of the objectives. For a cost function that takes into account all four objectives, weight values were chosen as follows: w_1 = 0.18, w_2 = 0.24, w_3 = 0.34 and w_4 = 0.24. These weight values were chosen based on the needs of the distribution engineer from a LDC. The main concern for utilities is the number of swaps, because they want to reduce the cost of implementing changes to balance the phases on their feeders, and that is why w_3 has the highest value. Then, the two next objectives that are important are the load and the current imbalance, which are directly related. They are an indicator of how much the feeder is actually loaded, and by reducing these imbalances, customers can be added to the existing feeder, reducing the need for new feeders and or substations. Finally, the last objective is to reduce power losses on a feeder, and thus w_1 has the smallest value, because utilities have little incentive to reduce their kW losses. By changing the values of the weights, the importance of each factor in the objective function can be increased or decreased.

3.2 Tabu Search

Tabu Search (TS) is an optimization algorithm, in the local search technique class, developed by Glover in 1986. Since 1990, tabu search has been established as an optimization method which can compete with different known techniques such as Genetic Algorithms or Simulated Annealing and which, because of its flexibility is better than many classical procedures [3].

TS guides the user to an optimal solution using an adaptive memory structure that keeps track of recent searching steps. The TS algorithm forbids going back to previously visited solutions and allows a larger portion of the solution space to be visited. To reduce the risk of cycling, the TS strategy consists of creating a dynamic list of tabu moves that are recorded for a number of iterations, depending on the tabu list size. By making those moves which have led to improvement, a variety of new neighbourhood solutions are visited, and the chance of getting trapped in local minima can be reduced [4].

At each iteration in the TS process, a neighbourhood function *N(i)* is defined from the current solution *i*. The current solution is a phase configuration for the feeder. *N(i)* contains all solutions that are close to the current one, and differ from it by only one phase swap. Both *i* and *N(i)* are matrices with three columns, each of which represents a phase.

From the pool of potential solutions grouped in *N(i)*, the best one is selected according to the cost function *f* expressed above. This process of generating a neighbourhood function and selecting a new solution is repeated until an optimal solution is found or a stopping criteria is met.

3.3 TS Phase Balancing Algorithm

Below is the TS phase balancing algorithm designed as part of this study.

Step 1: Assume an initial phase configuration
Step 2: Load the database MSAccess file and the model of the feeder
Step 3: Initialize Tabu parameter (*Tabu_size*)
Step 4: Initialize counters (k for iterations and k_{ni} for non improving steps)
Step 5: Initialize stopping criteria (*max_i*, max_{ni} and *optimal_cost*)
Step 6: Set initial phase configuration as current solution *i*
Step 7: Run a power flow and determine cost of current solution *f(i)*

Step 8:
while ($k < max\_i$) and ($f(i) > optimal\_cost$)
increment iterations counter (k)
if ($k_{ni} > max_{ni}$)
then
generate the neighbourhood function,
choose best solution j according to modified cost function $g(j)$; and
reset k_{ni} counter
else
then
generate the neighbourhood function,
select 6 best solutions according to ΔkVA,
run a power flow on the feeder; and
choose best solution j in the neighbourhood according to f that is not on the tabu list
Step 9:
if (cost of new solution $f(j)$ < cost of current solution $f(i)$) **and** (new configuration reduces phase imbalance for other seasons)
then
update new solution to be current solution ($i=j$),
overwrite feeder database with new configuration
update tabu list; and
reset k_{ni} counter
else
then
increment k_{ni}
Step 10: Output current solution i

First, initial parameters have to be set. The tabu list size (*Tabu_size*) has to be determined. A smaller tabu list requires less memory and allows the search to be less restrictive. A tabu list of size 5, for example, will require the 5 most recently visited solutions, and overwrite the oldest one at each iteration.

The maximum number of iterations in the search process, *max_i*, and the maximum number of consecutive non-improving iterations, max_{ni}, are set, and vary depending on the size of the feeder to be balanced. Another stopping criterion that has to be set is the optimal cost at which a solution would be considered good enough to be kept as the final one without any further search (*optimal_cost*).

Given an initial phase arrangement system configuration, a neighbourhood function, $N(i)$, that contains all solutions that are one swap away from the current one is generated. From that pool of solutions, the algorithm determines the cost of all new solutions, according to a weighted cost function "f".

In Step 8, a neighbourhood function, $N(i)$, is defined that contains all new solutions that differs from the current solution by only one phase swap. From this pool of solutions, the 6 solutions that minimize the load imbalance best are selected. The load imbalance in kVA is chosen as the evaluation criterion, as it can be calculated without the need of a power flow. This pre-selection of solutions is necessary to ensure that only some solutions are evaluated, as updating the feeder database and running a power flow takes computational time.

After a power flow is run for the six solutions selected earlier, the best overall fitting solution, j, according to a modified cost function "g" is chosen, as long as it does not appear on the tabu list. If the new solution is better than the current one, it is then applied to the feeder model for other season scenarios. If the new configuration reduces the phase imbalance on the feeder for all seasons, then the new solution becomes the current best solution. The feeder database with load information is then overwritten according to the new phasing configuration.

Each time a new solution is visited, it is recorded on the tabu list to allow the exploration of new regions of the search space. This whole search process is repeated until one of three things happens: (a) the maximum number of iterations is reached (*max_i*); (b) a solution that is considered optimal is found (*optimal_cost*); or, (c) the maximum number of consecutive non-improving iterations is attained (max_{ni}).

In the case of non-improving consecutive iterations, a new cost function g is used to determine the most fit solution in the neighbourhood function. Intensification and diversification are two concepts in Tabu Search that help to ensure that the search does not get trapped in a local minimum and that no portion of the search space is left unexplored. Essentially they penalize solutions that have been visited often, and reward solutions that had a low cost function by using a modified cost function g in order to reorient the search.

3.4 Results

Small utilities have only a limited number of load monitoring devices, which makes the design of an accurate software model for their systems hard to achieve. Therefore, using extensive wide-ranging load databases does not benefit them, as they do not have the resources to record and compute all this data.

A model of one feeder from a LDC was built, using data that was easily accessible and information on the equipment itself that could be collected and input into the model. The TS phase balancing algorithm developed as part of this study was designed to help distribution engineers to

optimize their power distribution systems through phase balancing.
Historically, utilities have focused on finding a feasible phase reconfiguration scheme with as little search effort as possible [6]. To demonstrate the effectiveness of the TS phase balancing algorithm developed as part of this thesis, it was applied to a feeder from a local distribution company. This feeder had 24 single-phase loads. For this system, there are 3^{24} possible phase swapping configurations. However, some configurations are not valid, as they would overload one phase or be physically impossible due to the high number of phase swaps to be conducted.

Some transformers are three-phase loads and their presence did not affect the search, as they were considered already balanced. Two-phase loads were ignored when designing the algorithm, as they were not present in the distribution system from the local distribution company chosen for this study.

The TS phase balancing algorithm always converged, and it always found an optimal solution. Since the system to be balanced was relatively small, the optimal solution was found by doing an exhaustive search of the solution space. Solutions found by the TS phase balancing algorithm were compared with the one generated by the exhaustive search, and both methods found the same solution, except the solution was found much faster with the TS algorithm.

As a consequence of applying the TS phase balancing algorithm to a feeder from a LDC, the current imbalance was reduced by 17%, the power losses on a peak day were reduced by 15%, and the kVA imbalance was reduced by 14%, from the initial phase configuration. All these improvements were achievde by swapping 4 loads on the feeder.

The financial benefit gained from the use of the TS phase balancing algorithm would be of interest to a utility. It allows them to save power, protects equipment from tripping and overloads, and reduces the need for building new infrastructure to accommodate more customers, which can all be summarized as ways to save money. It is difficult to evaluate the exact cost benefit of these changes, as making a swap itself encounters costs because technicians have to be employed to perform re-phasing tasks. However, these are one-time costs, and are not large.

4 Conclusion

As part of this study, a phase balancing algorithm using tabu search has been constructed based on the needs of a small utility with few monitoring systems.

Furthermore, in order to keep simulations as close to reality as possible, testing and tuning phases were conducted on an actual feeder model instead of a fictitious one. The objective function was adapted to fit the needs of distribution engineers by including a penalty for the number of total swaps, as well as terms to minimize power losses, current imbalance and load imbalance (in kVA).

Results when applying the TS phase balancing algorithm were conclusive.

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