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Initial layout of power distribution systems for rural electrification: A heuristic algorithm for multilevel network design

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ABSTRACT

We describe the first heuristic algorithm that selects the locations and service areas of transformers without requiring candidate solutions and *simultaneously* builds *two-level* grid network in a green-field setting. The algorithm we propose minimizes overall cost of infrastructure costs; specifically the combined costs of transformers and the two-tiered network together by solving transformer location problem as well as network design problems in a single optimization framework. In addition, it allows one to specify different costs for the higher throughput lines upstream of the transformer as compared to downstream of the transformer. Simulations are carried out based on real-world spatial distributions of demand points from rural locations in Africa, specifically in places without any pre-existing infrastructure to test the algorithm and generalize the results.

1. Introduction

In a technological landscape that is altered by the emergence of off-grid and distributed approaches, there is a need amongst infrastructure planners to evaluate the costs of networked or grid approaches vis a vis off-grid approaches to be able to make rapid assessment of the progress in rural electrification.[1] The investment costs of networked approaches are more difficult to estimate than the costs of off-grid approaches because it takes into account both the spatial distribution of demand and the optimal placement of infrastructure to meet that demand. This paper through its algorithm provides a new methodology to estimate the cost of green-field networks rapidly and with high accuracy.

The algorithm we present in this paper combines the transformer location problem and the low voltage (LV) and medium voltage (MV) network design problem into a single problem and solves them in a single optimization framework. We propose a heuristic algorithm to design a two-level radial power distribution system. The *first level* includes the determination of the numbers, locations and capacities of transformers that feed an LV distribution network. The transformers represent load points for an upstream MV network and the MV network is also determined as a part of the first level. The *second level* includes the determination of the layout of the low voltage network between the transformers and the specified ultimate demand points. Note that the high voltage (HV) network (for that matter source points) further upstream of the MV network are assumed to be known.[2] One could have further generalized the problem to include the determination of the HV networks as well, making it a three level problem, but here we consider the HV network as pre-specified for simplicity.

The algorithm we propose does not require a set of candidate locations to be considered as transformer locations. The maximum service distance in a low voltage distribution network is also pre-specified and determined from engineering practice. Given these costs, the demand points, the location of the HV network, and the maximum distance of the demand point from the transformer, the algorithm automatically finds the locations and service areas transformers as well as the LV and MV network layout with the goal of minimizing the total costs.

Understanding the cost involved with electrification is important in designing a proper smart grid structure. This algorithm can serve as a tool for network engineers and planners to make rapid assessments assisting them with (a) estimates of total cost of distribution, (b) layouts of initial designs and (c) breakdown of

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[1] The International Energy Agency estimates that the number of people who do not have access to electricity is nearly 1.6 billion and this number is expected to increase over the next 30 years unless investments in providing modern energy services are expanded significantly.

[2] The medium voltage network connects these transformers to electricity sources further upstream where they could either be sub-stations of a high voltage transmission network or power generating stations. Note that the costs associated with what we call here for convenience high voltage networks or transformations from high voltage to medium voltage are not considered here.

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total costs into transformer cost and medium and low voltage line costs and giving them a good starting point for more detailed smart grid projects. The methodology we propose ignores transmission losses, load flow considerations and local topography and hence the proposed designs are not meant to replace detailed engineering analyses of grid rollout. Therefore, this tool should be considered as a guide for planning within utilities to be used with large datasets rather than a tool that provides every detail. However, for completeness possible extensions of the algorithm to include more details of power distribution systems are also discussed in Section 5.4.

The sections of this paper are outlined as follows: the remainder of this section provides background information including literature review; a more precise statement of the problem is given in Section 2; our approach to the problem is explained in Section 3; algorithm results are provided in Section 4; and a discussion of our algorithm is presented in Section 5.

1.1. Background

Electricity access is one of the most important components of rural developments. It has been shown that better living conditions in developing countries cannot be achieved without investments in electricity [1]. In rural areas where renewable energy resources are widely available, small off-grid standalone systems appears to be an attractive alternative [2]. Moreover, decentralized technologies seems to be more suitable for rural and remote areas due to the fact that it helps avoid long distribution lines with low load densities, underutilized transformers and losses in distribution. It also has been discussed that whether decentralized alternatives which use locally available resources provide more reliable supply of energy [2,3]. Thus, most of the earlier research aims to investigate primarily renewable energy alternatives and off-grid technologies [4–9]. It is worth noting that, although there has been a lot of attention to rural electrification projects, literature on the networked approaches is very limited. In this paper, an attempt is made on estimating the cost of rural networks to facilitate the rural energy decision making based on purely cost comparison without considering other consequences of off-grid and grid approaches.

The so-called power distribution system problem, in general, has been studied extensively in the literature [10–19]. Techniques developed in prior efforts for this complex problem usually divide the problem into sub-problems at each level and then solve each sub-problem separately using various optimization techniques [10–14]. These studies differ from each other in how they represent the problem components as well as in the algorithms utilized. None of these studies address the problem of designing both LV and MV networks in a single framework. However, dividing the problem into sub-problems and solving them separately reduces the probability of reaching an optimal solution and prevents us from seeing the effects of different cost parameters on the final network layout. The methods that have been proposed in the literature are based on either mathematical programming techniques such as Mixed Integer Programming, Branch and Bound Method [12,13,17] or heuristic algorithms such as Genetic Algorithm [11,18,19]. However, complexity of the models and the algorithms reduces their applicability to estimate the cost of networked approaches in rural electrification discussions when spatial distribution of a very large data set (demand points) is available. In addition, regardless of the solution methods, all studies mentioned here, except for [11], includes pre-assumption of candidate locations for transformers or feeders. These studies do not provide a method to update the candidate transformer locations during the search for an optimum solution. Therefore, the final feeder network is strictly dependent upon the initial selection of candidate locations. In practice, however, determination of candidate locations is not always a simple task, and if the methodology has to scale to a larger number of demand points, clearly the transformer locations should be an outcome of the optimization process.

2. Problem statement

Locations of ultimate consumers are called "demand points" in the rest of the paper. The cost parameters are (1) the cost per meter of LV line, C_{LV}; (2) the cost per meter of MV line, C_{MV}; and (3) the unit cost of a transformer, C_T. The maximum service distance, modeled as the radius of coverage of a transformer, is specified[3] and called $D_{\max}$. No similar constraint is placed on the length of the MV line from the source point. The unit costs are assumed to not vary with load, a clear simplification of the reality. In the same vein, each demand point is assumed to have the same load and the load is assumed not to change over time making the problem "static".

Distribution system is designed to be radial, to have one path between demand points and transformers, due to the fact that it is the most widely used form of distribution design and it is the cheapest and the simplest alternative compared to loop and networked designs [20]. In radial design, since there is only one path between demand points and transformers, power flow is certain and the system can be operated easily. The major drawback to radial feeder design is reliability. Any equipment failure will interrupt service to all customers downstream from it. However, low statistical rate of failure of equipment on the low voltage level makes the adaptation of radial systems easier [12].

Within the service areas of the transformers, the low voltage network is permitted to be multi-point, in that, in order to minimize costs the wire to a demand point further in distance can first go through one or more intermediate demand points. This architecture is called a "multi-point" LV network here (see Fig. 1b). Maximum distance capacity of an LV line is then defined as another design parameter and called $L_{\max}$ (i.e. the maximum LV line used to connect a demand point to the transformer directly or through other demand points should be less than $L_{\max}$[4]). $L_{\max}$ value should be used to limit the maximum total load on LV line and should be greater than or equal to $D_{\max}$ so that each demand point within the service area of a transformer gets connected.

Given the cost parameters and subject to the constraints described above, the desired outputs of the algorithm are:

- Number and locations of the transformers.
- Medium voltage (MV) network that connects a source point to the transformers; and
- Low voltage (LV) network between the demand points and transformers.

Our objective function is the minimization of total system cost, which includes cost of transformers, cost of low voltage and medium voltage networks. Schematic illustration of our problem formulation can be seen in Fig. 2.

3. Methodology

Given the difficulty of the problem, a heuristic algorithm is developed to place transformers and locate the networks. The algorithm relies on a "greedy" approach that starts with a stage that each demand point has one transformer (i.e. for n demand points, there would be n transformers) and iteratively decreases the number of transformers. Initially, transformers are connected to

[3] This distance would vary over the network with local geography and topography but is assumed constant here.

[4] $L_{\max}$ can also be considered as a constraint on distribution losses in LV level as the losses and wire lengths are linearly related.