Developing and Evaluating Alternative Network Architectures

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Abstract

Western Power's distribution network has typically grown over time in a somewhat ad-hoc manner with the focus of design on local expansion rather than global optimisation. Currently, there are large portions of the distribution network assets in rural regions that are nearing end of life and will need to be replaced in the near future. This provides an opportunity for Western Power to redesign the routing of the network based on the knowledge of all existing customer locations. Previous work towards optimising the rural distribution network has identified a potential financial benefit through the use of a genetic algorithm (GA) to determine an optimal path.

The primary objectives for this project are to expand and improve upon the current model for optimising the rural distribution network, and to investigate the transition to alternate network architectures. The benefits in achieving the objectives include a further reduction in network asset investment, a more accurate model of the rural distribution network by the consideration of additional constraints, and evidence of the efficacy of distributed technology such as stand-alone power systems (SPS).

1. Introduction

Western Power is responsible for the transmission and distribution of electricity within the South-West Interconnected Network (SWIN), located in the south-west quadrant of Western Australia. Western Power's distribution network underwent a significant and rapid expansion throughout the SWIN region during the late 1960s to early 1980s, while the network was originally being established. As a result, over the next 20 years a significant portion of the originally installed distribution network will be subject to renewal as assets reach end of life. Additionally, the distribution network underwent a relatively lower level of planning due to the somewhat ad-hoc expansion of the network to facilitate connecting new customers over time as and when they emerged. As the ad-hoc expansion was more prominent in rural areas, it can be inferred that the distribution network in rural areas has undergone a lower level of planning. This presents the opportunity to redesign the routing of the network based upon knowledge of present customer locations.

In rural areas the customer density is significantly lower than metropolitan areas, thus the return on investment (ROI) for the network is also significantly reduced. To minimise the required network investment, SPS can be strategically placed throughout the network to remove isolated customers, thereby removing sections of the network with poor ROI. On a larger scale, micro-grids can be incorporated to remove, or have the ability to remove, isolated sections from the network, such as townsites.

Previous work towards optimising the routing of Western Power's distribution networks in rural areas has used a problem specific genetic algorithm, utilising an objective function, weighted grid system, selection operators, problem specific mutations and additional constraints. The objective function was based on a single total cost, which was composed of the cost of implementing the single phase and three phase network as well as an additional weighting cost determined by environmental zones, land subdivisions and construction type. A grid based system was used to record the weightings throughout the selected test area by allocating weights inside environmental zones and small subdivisions. The results from the GA indicated a potential reduction in cost of approximately 9.3% for the given test area in just over an hour of simulation time. These results indicate that by rerouting the network there is a potential benefit by reducing investment costs.

1.1 Project Objectives

The core objectives for this project are to address the routing limitations of the current GA, to provide a more accurate model for optimising the distribution network within rural areas and to investigate alternate network architectures. Similarly to the 2014 project, the costs of implementing the new network will be weighed against the cost of the current replacement approach. If the new network reduces the total costs with respect to the current approach, it will be passed to network designers at Western Power for further analysis.

1.2 Literature Review

The primary objective of distribution system planning (DSP) for electrical network utilities is to supply power to electrical customers at their required location while operating within design constraints, minimising costs, and meeting reliability and safety criteria. There have been a number of techniques applied to the various areas of distribution system planning optimisation, which can commonly be split into two categories; mathematical programming and heuristics (Smith & Walters 2000). Heuristics are optimisation methods which can provide optimal solutions for highly complex and non-linear problems (Haffner et al. 2008). One heuristic commonly applied to the DSP problem is the evolutionary algorithm known as the genetic algorithm, which mimics the evolutionary process through the use of genetic operators. It is known that GAs can deal with complex, discontinuous and multimodal search spaces efficiently (Bandyopadyhay & Saha 2013), and have shown to do so through the various works of (Carrano et al. 2006; Levitin, Mazal-Tov & Elmakis 1994).

A Steiner point is the interconnection point that connects three nodes in the minimum distance. Steiner points only exist if the maximum interior angles of the triangle formed by the three nodes are less than 120 degrees. Otherwise direct connections provide the minimum distance. The minimum distance is obtained via the Minimum Spanning Tree (MST), which is a deterministic method of finding the minimum weighted path connecting all nodes given a finite set of nodes and edge weights. The maximum potential reduction in length offered by the inclusion of the Steiner tree is shown by equation (1) (Prendergast, Thomas & Wang 2007). The minimum value of the Steiner ratio occurs only for points distributed in an equilateral triangle.

$$\rho = \frac{L_S}{L_T} = \frac{\sqrt{3}}{2} \qquad (1)$$

Where

- ρ is the minimal Steiner ratio
- L_S is the length of Steiner minimum tree
- L_T is the length of minimum spanning tree

2. Process

The model is constructed through a problem specific genetic algorithm as the core component in a similar manner as that described in (Carrano et al. 2006). The objective function is based on a single total cost, composed of an investment cost, operational cost and reliability cost. The investment costs are the new and upgraded network assets required, including the three phase and single phase conductors, distribution poles and the power quality equipment. Lastly, the reliability costs are described by the costs associated with the frequency and duration of outages and the network equipment designed to improve the reliability of the system, such as sectionalisers and reclosers. The reliability costs and economic costs may be separated into separate objectives if further investigation into literature deem it necessary, thereby establishing a multi-objective scenario.

Improvements to the accuracy of the optimisation model are addressed through the following tasks. The electrical performance including the voltage profile and line capacity constraints is to be incorporated through the addition of voltage regulators, capacitor banks and isolation transformers, as well as rerouting of the network. The system reliability of the new network will set constraints based on the circuit length, the number of customers affected, construction type, environmental conditions and the voltage profile through the addition of sectionalisers and reclosers, as well as reliability metrics and rerouting of the network. SPSs are also included in the GA to remove isolated customers from the network and thus reduce the required network investment or potentially improve the voltage profile or reliability.

GIS based data will be used to supplement the costs defined by the objective function with weighting factors due to environmental and spatial restrictions. The initial population of the GA will be formed through the use of an MST as it has shown to be an effective starting population (Carrano et al. 2006). Stochastic Tournament selection randomly splits the solutions into subgroups, keeping the best solution per group while discarding the low fitness (high cost) results. No crossover will be performed for the GA and instead problem specific mutations will be used to maintain diversity. These mutations include directly and indirectly connected Steiner points, Steiner point removal and randomised reconnections. A simplfied flowchart outlining the GA to be implemented in this project is provided in Figure 1.

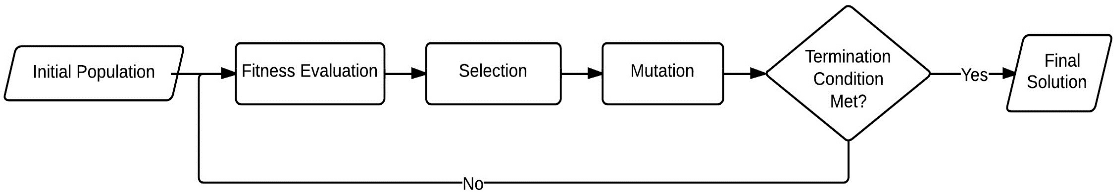

Figure 1 Genetic algorithm procedure.

3. Results and Discussion

The results from the complete model are currently being processed and are not yet available, however preliminary results have been obtained. The existing network to be optimised is an edge of grid, radially connected feeder, and is shown in Figure 2. The selected existing network connects 316 customers via a total line length of approximately 945 km, covering an area of 140 km by 90 km. Thus the level of investment per customer is very high with respect to other regions in SWIN. The rebuild cost for the existing network is 1100 units, where a single unit is defined as the cost of 1 km of single phase line.

Figure 3 indicates the optimised network after the genetic algorithm has been applied. The three phase backbone has been locked in place to avoid issues with accessibility, thus the optimisation is largely performed through the modification of single phase spurs. The majority of the single phase nodes have been reconnected via different spurs as can be seen by comparing Figure 2 and Figure 3. Additionally, there are now several larger spur connections with many customers over long distances. These longer connections may cause issues with the reliability of the network, which will be addressed when the reliability component is incorporated into the model. The GA results indicate that the various alterations to the structure of the network are beneficial and have reduced the investment cost by 162 units, or 14.50%.

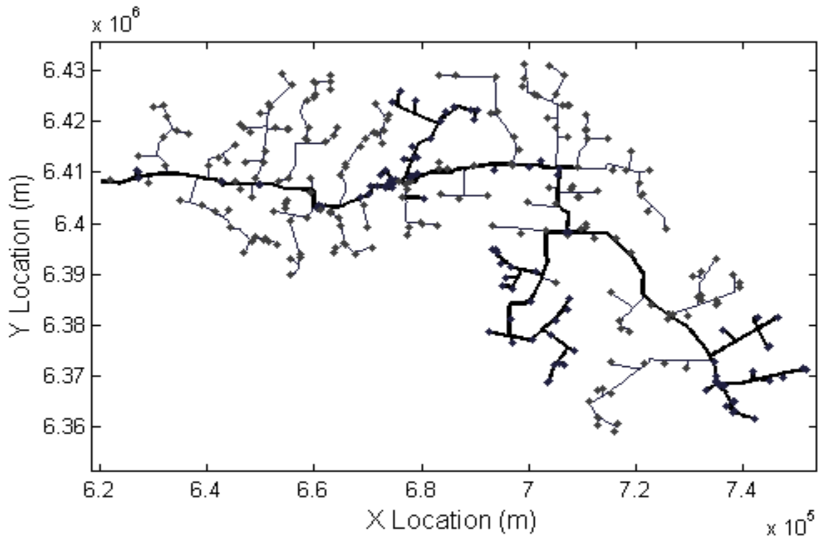

Figure 2 The existing network to be optimised. The black lines and points represent the three phase line and customers, while the gray lines and points represent the single phase line and customers.

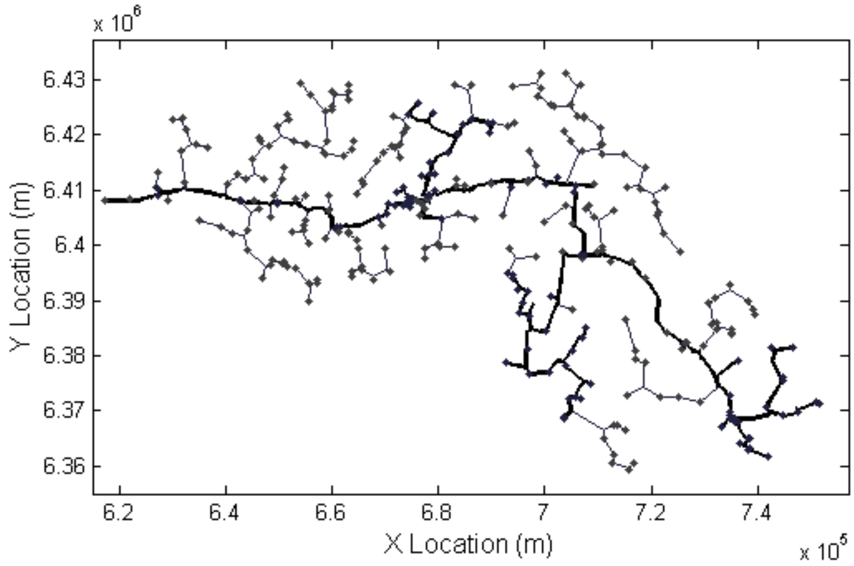

Figure 3 Network formed through the GA. The black lines and points represent the three phase line and customers, while the gray lines and points represent the single phase line and customers.

Lastly, Figure 4 details the connections which have been found to be replaceable by SPSs. As indicated by the large amount of marked nodes, there are many cases for which it is more optimal to remove the edge of the grid customer and implement an SPS. It is therefore likely that SPSs provide a suitable means of reducing network investment for rural networks.

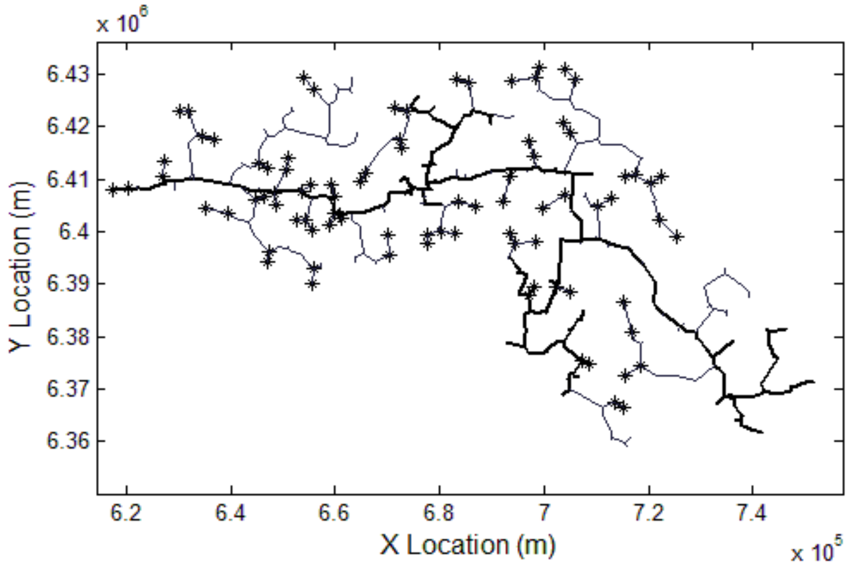

Figure 4 Network formed through the inclusion of SPS. Markers represent the nodes for each edge to be replaced with an SPS.

Network	Distance	Cost	Cost Reduction
Existing Network	945 km	1100 units	-
GA Network	813 km	938 units	162 (14.50%)
SPS Network	745 km	870 units	230 (20.91%)

Table 1 Simulation results.

4. Conclusions and Future Work

The optimisation model is presently undergoing various improvements and the final results have not yet been obtained, however based on the preliminary results, the optimised network will provide a more cost effective solution than the current replacement method. Initial results infer that the structure of the network must be modified in order to obtain the optimum solution. Additonally, the inclusion of SPSs have proved to be a source of substantial reduction in network investment. Therefore, the network formed through the GA model provides a more optimal network, with the primary source of cost reduction arising from restructuring and SPSs.

The ongoing work to be completed by the end of the project centres around two tasks. Firstly, the inclusion of the load flow analysis to test the electrical performance of the optimised network and ensure it meets the standards from Western Power. Secondly, to provide a function to transition from the existing network to the optimised network. The transitioning function will be based around the selection and sorting of single phase spurs to determine physically which sections should be replaced first and when.

Further work to be investigated following the completion of the 2015 project is the inclusion of reliability into the objective function and a more detailed look into the network transitioning functionality. The reliability work will include updating the GA to the muli-objective scenario as well as incorporating reliability equipment into the model as a means of improving the reliability of the system. The network transitioning methodology will require further research to determine how Western Power can practically switch to the optimised network topology.

5. References

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