Developing and Evaluating Alternative Network Architectures

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Abstract

There are currently sizeable sections of Western Power's rural distribution network nearing or exceeding design life and requiring replacement in the near future. These aging network sections developed and continued to expand through organic growth over the past 40 years. As a result, Western Power has an opportunity to further optimise their network through considering alternative approaches to supplying power to customers in affected areas. In 2014-15 an algorithm for optimising network topology was created and applied to a rural feeder. The results were promising, however further work was necessary to improve the model's applicability. The primary objective of this continuing PhD project is to consider alternative approaches to optimising the distribution network by expanding upon the previous network optimisation algorithm and developing a model for identifying stand-alone power systems (SPS). The SPS model was created in MATLAB and applied to the rural areas of Western Power's distribution network. The results from one section of the rural distribution network is presented in this paper. The results suggest that strategically placed SPSs are a cost effective alternative to replacing certain sections of Western Power's rural distribution network.

1. Introduction

Western Power is responsible for constructing, maintaining and operating the transmission and distribution power network within the South-West Interconnected System (SWIS) in the South-West of Western Australia. The SWIS supplies electricity to over one million customers through 261,000 km of power lines, which are distributed throughout both rural and metropolitan areas. Approximately 40 years ago the SWIS experienced a rapid expansion period. As a result there are currently sizable sections of Western Power's network that are approaching or have already exceeded design life and therefore require replacement in the near future (Western Power, 2016). Additionally, the network has continued to grow in an ad-hoc manner over the years as new customers connect to the network. With the knowledge of the present network asset locations and condition, it provides an opportunity for Western Power to investigate alternative, optimised network architectures, which were not feasible when the network was originally established.

In 2014-15 an algorithm was created for the purpose of optimising the topology of sections of Western Power's rural distribution network. The optimisation was built upon the idea of genetic algorithms as a means of dealing with the combinatorial problem inherent when determining the optimal network topology of power distribution networks. The algorithm optimised with regards to a total cost objective, which is composed of capital costs, operational costs and penalty costs. The constraints considered include voltage limits, network radiality, phase balancing, locking of the three-phase backbone, and geographical areas. The algorithm iteratively improved the total cost objective by modifying branch connections, adding intermediate nodes and removing isolated loads from the network. A case study involving a feeder on the edge of the grid suggested the total cost could be reduced by approximately 20% in comparison with rebuilding the existing network. The results from the case study were promising, however several assumptions and estimations were made which may reduce the practicality of the output. Focus has since shifted to developing more practicable network solutions while improvements to the network optimisation model are ongoing.

Distributed generation including stand-alone power systems (SPS) and micro-grids were largely not viable at the time the network was developed. Over the past decade there has been a growing requirement for network operators to cater for an increasing shift from centralised generation and facilitate the uptake of distributed technology, while maintaining the inherent requirements of delivering the monopoly service of interconnected supply to customers. In theory, SPSs will provide improved reliability, reduced bushfire risk and may reduce the cost of supplying power to customers in isolated areas. However, in order to realise the benefits it will be necessary to disconnect the customers from the centralised grid. Western Power is presently running a pilot programme of six SPSs throughout the rural areas of Western Australia to investigate SPS viability within SWIS. Varying degrees of decentralisation have been suggested for the Western Power network; however it remains likely that SPS and micro-grids will be incorporated in some form in the future, noting that the national and jurisdictional regulatory frameworks currently largely prohibit anything other than the provision of interconnected network services.

1.1 Project Objectives

The primary goal of this project is to investigate the viability of alternative approaches to replacing aging sections of Western Power's rural distribution network. The alternative approaches investigated include the topological optimisation of the network as well as the use of stand-alone power systems to supply isolated customers. As there is a greater need to find more cost effective and reliable solutions in rural areas, the alternative network approaches will be applied to the rural areas of the SWIS. The costs for each of the different approaches will be compared against the cost for rebuilding the existing network.

1.2 Literature Review

Distribution system planning (DSP) focuses on the following areas: substation sizing and positioning; topological layout of HV feeders, laterals, and LV secondary circuits; number and positioning of reliability based equipment; and the number and positioning of power quality equipment (Ganguly, Sahoo & Das, 2013). Optimisation of DSP is a complex combinatorial task involving a large number of parameters and constraints, and as a result is considered NP-hard (Ladner, 1975). Large-scale NP-hard problems cannot be solved in deterministic time, thus heuristics are often used.

One of the commonly used algorithms for addressing the DSP issues is the metaheuristic known as the genetic algorithm (GA). GAs are a form of evolutionary algorithm which mimic the evolutionary process through the use of genetic operators. The key operators for GAs include selection, crossover and mutation. GAs use problem specific information to determine an acceptable global optimal value through the use of a fitness function and can deal with complex, discontinuous and multimodal search spaces. GAs must achieve two objectives in order to be successful: they must guide the search towards the Pareto optimal solution and they must maintain a diverse population to avoid premature convergence and achieve a well distributed Pareto front (Deb, 2002). In other words, they must be able to converge on a solution while maintaining a diverse population of possible solutions.

Another field for optimising distribution systems which has seen increasing popularity over the past decade is distributed generation (DG). DG refers to generation systems which supply power to customers at the point of demand rather than from a centralised generation source. The issues involved include optimising the size, type, number and location of the generators (Georgilakis & Hatziargyriou, 2013). Guo (Guo et al. 2014) considered the application of micro-grids in the form of SPSs to supply rural loads. A stochastic model for the SPS was established and optimised via the NSGA II algorithm with objectives of minimising total net present cost and greenhouse gas emissions. Beere (Beere, McPhail & Sharma, 2015) focuses on the optimisation of distributed energy resource siting within micro-grids. Beere determines the optimal DG siting through the use of the HOMER software and a case study in Cairns (Australia) provides evidence of increased reliability due to the use of micro-grids.

2. Methodology

2.1 Initialisation

The investigation into the viability of SPSs across Western Power's rural distribution network has been the main focus over the duration of the project thus far. A method for identifying SPS candidates has been created in MATLAB using data provided by Western Power. The method involves identifying edge of network customers and calculating the net present cost for the SPS and the network rebuild, and comparing the two.

Prior to considering candidates for SPS, the cost to supply customers via both an SPS and the traditional network connection needs to be established. To calculate the cost to rebuild a section of line, the network needs to first be modelled within MATLAB. Network assets including poles, transformers, bays and electrical meters are obtained via database queries and exported into excel. Attempts to model the network within MATLAB using bays, which are the conductors between poles, did not succeed due to data quality issues. As an alternative the network connections are constructed through the use of a Minimum Spanning Tree (MST), where the MST finds the minimum distance to connect a set of nodes in a radial network. This approximation has shown to be an accurate method for modelling the existing rural distribution network. Following the construction of the network within the MATLAB model, a per kilometre net present cost is then applied. This cost value takes into account all capital and operational costs of the network over a period of time.

To determine the cost per SPS per customer the consumption data provided by the electrical meters is used. As the majority of customers in rural areas do not have electrical meters capable of recording hourly data it is not possible to determine the hourly load profile per customer. Instead the monthly consumption data, taken over the prior two calendar years, is used to calculate the average daily consumption for each customer. Based on the average daily consumption data, an estimate for the required SPS size and cost is given. The SPS size and net present cost figures used in the model are provided by Western Power. This net present cost includes both capital and operational costs over a period of time as per the network rebuild net present cost above.

2.2 SPS Identification

SPS candidates are identified by tracing upstream from an edge customer until another customer or intersection is reached, or until the SPS cost exceeds the line cost. A simplified view of the procedure is given by Figure 1 and is described below:

1. The network and metering information is read into MATLAB for a selected rural feeder. The input data is read on a feeder by feeder basis due to memory restrictions.

2. The network is constructed using the MST and all edge of network customers are identified and stored for the constructed network.

3. An edge of network customer is selected and traced upstream, node by node, storing the network length traversed and the asset information. When considering an edge of network customer which originally had downstream nodes, the full SPS and line costs are considered. That is, all downstream costs are included. Dijkstra's shortest path algorithm is implemented as a means of tracing downstream sections of the network.

4. Stop tracing upstream when the node encountered is an intersection (i.e. connects to two or more other nodes), or if the node is another customer.

5. Compare the cost of rebuilding the selected network section against the cost of supplying the edge of network customer with an SPS. If the SPS option is cheaper, remove the selected network assets from the model and store the customer as a potential SPS candidate. Otherwise, ignore the customer.

6. Repeat steps 3-5 until all edge of network customers have been tested and output the data to Excel.

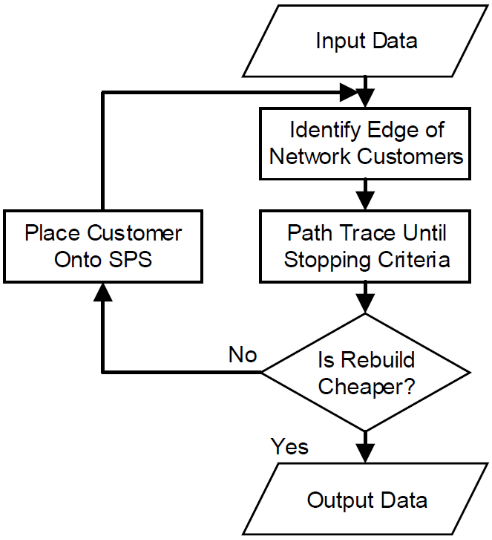

Figure 1 Simplified procedure for identifying an SPS candidate.

The procedure is repeated until there are no viable edge of network customers which can be taken off the network and placed onto SPS. The constraints considered throughout the procedure include assigning zero cost to underground sections of the network, limiting the maximum load an SPS can supply, and various assumptions to manage data quality issues.

3. Results and Discussion

The SPS identification method was applied to all rural sections of the SWIS, taking approximately 9 hours to complete a full simulation. For this paper, the results for one of the rural feeders is presented. The selected feeder supplies power to 191 customers across 580 km of poles and wires in an area of approximately 4800 km^2, and is shown in Figure 2 below. In the figure, triangles and circles represent “load sources” and “load sources too large for SPS”, respectively. The SPS loads range in size from approximately 0 kWh to 50 kWh a day. Of the 191 customers, 99 were identified as viable SPS candidates. By placing these selected customers onto SPS it is estimated that the total net present cost will be reduced by approximately 50% with respect to rebuilding the existing network. Note the 50% reduction is for the rural feeder under investigation and does not apply to other areas of the SWIS.

However, the costs provided above are for all cases where SPSs are cheaper and do not represent a practical scenario, as not all of the network assets selected to be removed are in poor condition and in need of replacement in the near future. To be more realistic, assets greater than 40 years old are targeted, as these are likely to require replacement in the near future. A margin of error of 20% is also applied to the costings, so that candidates must have SPS costs at least 20% cheaper than their network rebuild cost. While these constraints improve the practicality of the output, there are still additional factors to be modelled, such as the costs associated with the removal of redundant assets. The addition of the age constraint and margin of error reduces the number of viable SPS candidates to 61, however the cost reduction remains approximately 50% with respect to rebuilding the existing network. In other words, the financial benefit from supplying the more realistic 61 SPS candidates is similar to the original 99 SPS candidates, suggesting that certain SPS candidates are more viable than others. Ultimately, it is evident that SPSs are likely a cost effective alternative to replacing specific aging sections of Western Power’s rural distribution network in the future.

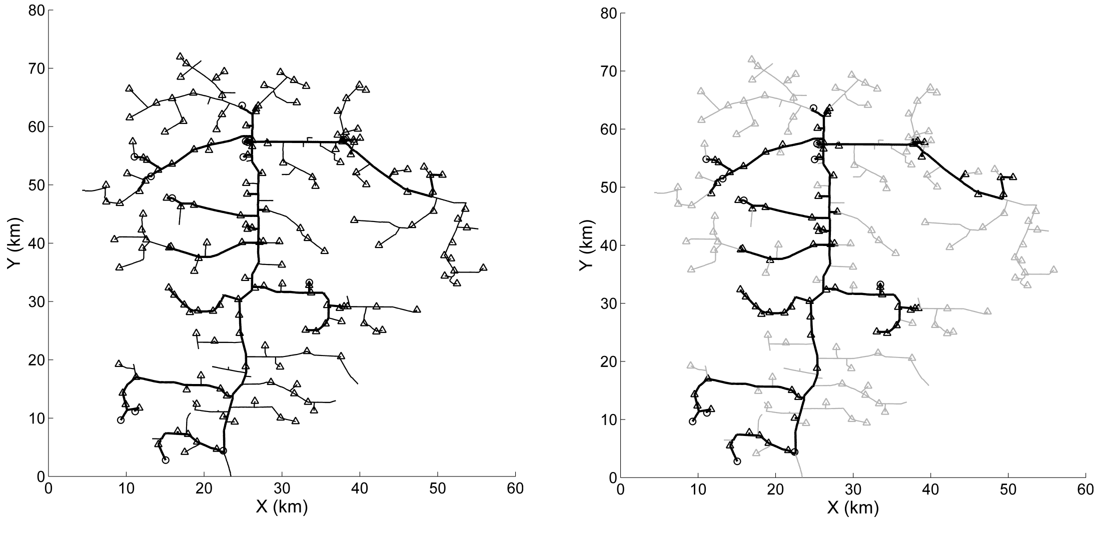

Figure 2 **Left – Existing distribution network for a selected feeder.**
Right –Network following the SPS identification model.

4. Conclusions and Future Work

Based on this investigation itappears likely that SPS will be a cost effective alternative to replacing aging sections of Western Power's rural distribution network. The model built throughout this project has identified the sections where SPS present a more cost effective solution as opposed to network replacement. Based on input costs, strategically placed SPS can be significantly cheaper than rebuilding the network in rural areas, which can not only benefit individual users, but reduce capital expenditure funded by the broader tariff base.

The remainder of the project will focus on finalising the SPS identification model, implementing the SPS model into the network optimisation algorithm, and addressing data quality issues. Future work beyond the scope of this year's project will involve the expansion of the SPS model to consider groups of customers as opposed to the current one-by-one method. By adding a customer clustering mechanic to the SPS algorithm, there is a greater likelihood of encapsulating all possible SPS candidates and additionally may be able to identify micro-grid candidates within a section of an existing network. Lastly, GIS data can be extracted during the initial database queries to further filter the SPS candidates based on risk and reliability.

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