Feasibility Determination through Phase Balancing in Optimised Network Architectures

Caitlin Mitchell

Herbert Lu, Tyrone Fernando
School of Electrical Electronic and Computer Engineering

Mark Reynolds
School of Computer Science and Software Engineering

Shervin Fani, Noel Schubert
CEED Client: Western Power

Abstract

Western Power's transmission network has undergone a high degree of planning. However due to the somewhat ad-hoc expansion of the distribution network, particularly in rural areas, a global plan has not been utilised. As assets near their end-of-life there is the opportunity to move towards a globally optimised network, instead of traditional like-for-like replacement. By creating an optimised network, financial savings are possible through minimising the length of the lines, as the level of investment required is reduced.

This project expands on previous work in minimising line length to include electrical performance evaluation, which will enable the feasibility of the proposed network to be determined. A primary consideration of feasibility is phase balancing as an unbalanced system results in deterioration of power quality and an increase in investment and operating costs. A phase swapping approach, combined with the implementation of isolation transformers, has been utilised to develop a balanced system. The resulting cost required to obtain a balanced network can then be compared to the savings resulting from line length minimisation to determine if the investment is worthwhile. Thus an algorithm can be developed to determine an optimised network structure for rural areas to assist planning decisions.

1. Introduction

Western Power provides transmission and distribution services to people in the South West Interconnected Network (SWIN), which covers an area of 261 000 square kilometres. The transmission network has undergone a high degree of planning to determine the optimum locations for substations. However the distribution network, particularly in rural areas has expanded in a ad-hoc manner with customers being connected overtime as required.

The rural distribution network experienced a rapid expansion approximately 40 years ago and thus these assets are now nearing end of life. As a result the assets will be gradually replaced to continue to meet performance expectations. Typically this replacement occurs by undertaking a direct rebuild. However as a significant part of the network is now due for replacement there is the unique opportunity to implement an optimised network.

There is recognition by Western Power that moving to an optimised network, particularly in rural areas, would be beneficial to the company and also to customers. An optimised network would reduce the level of investment required by minimising the line length and the amount of equipment required to maintain a satisfactory voltage level.

1.1 Literature Review

1.1.1 Optimising Line Length through Genetic Algorithms

Initial progress has been made towards developing an optimisation algorithm for Western Power’s network. In this model a genetic algorithm approach has been adopted to optimise the length of the network, in order to reduce the cost of investment (Fletcher, et al. 2014). A genetic algorithm is an evolutionary algorithm that mimics the process of natural selection and has been proven to be effective in multimodal search spaces (Carrano, et al. 2006). The search process is iterative and at each generation the fitness of every individual in the population is evaluated using the objective function. In this way different weightings are assigned to individuals and the ‘best’ candidates are selected for the next generation.

In order to optimise the length of the line a cost weighting per unit distance (1km) of the single phase network is applied (Fletcher, et al. 2014). This cost weighting factor incorporates environmental zones and land subdivisions, with harsher penalties applied for protected areas. Additionally, to incorporate accessibility concerns the three-phase network was locked in place. This is usually located along roads, which will allow maintenance crews ease of access.

1.1.2 Phase Balancing

Unbalanced systems are problematic as they result in deterioration of power quality and an increase in investment and operating costs (Zhu, et al. 1998). The overall reliability of the feeder is also compromised as a certain phase (or the ground line) carries a greater load, which can cause protection devices to trip or facilities to overheat and become damaged. As a result of this the utilization factor of the existing equipment is reduced, and a higher level of investment is required as the facilities will require upgrading (Sathiskumar, et al. 2012).

There are two popular methods to balance a system; feeder reconfiguration or phase swapping. It is difficult to meet the phase balancing criteria using feeder regonfiguration due to the limited number of sectionalizing switches available. On the other hand phase swapping is a direct approach and can efficiently balance the feeder system to improve power quality and reduce power system total cost (Zhu, et al. 1998). Thus in this approach the system is balanced by re-tapping laterals to the phase lines, where the objective is to minimise the phase current deviation subjected to branch current capacity (Sathiskumar, et al. 2012).

1.2 Objectives

Ultimately the aim is to develop an algorithm which can determine an optimised network structure for rural areas of the SWIN. Specifically, the current focus area for this project is the Hyden feeder, which consists of a three phase backbone with single phase spurs. Building from previous work done by James Fletcher (Fletcher, et al. 2014) on optimising the line length this project incorporates electrical performance parameters. A key parameter in confirming that the network is feasible is the level of balance between the phases. Thus the objective of this project is to determine the allocoation of spurs and the equipment required to ensure the feasibility of the alternative network.

2. Methodology

MATLAB has been used to implement the algorithm as it provides high-level language and development tools (MathWorks, n.d). In order to achieve a balanced system the phase swapping method will be used. The objective is to minimise the phase current deviation while taking into account the branch current and power capacity. A balance between the phases of within 5% is considered acceptable.

2.1 Interaction with the Genetic Algorithm

In order to incorporate phase balancing with the minimisation of line length, the phase balancing code has to be called at every iteration of the genetic algorithm. Thus it must be modular and adaptive by nature. It must accept the current network architecture as an input and be able to adjust accordingly. Additionally the resulting output must be relevant to the genetic algorithm and allow for comparison between the relative importance of phase balancing versus length minimisation.

In order to accommodate these factors the phase balancing code has been written as a MATLAB function which can be called from the main genetic algorithm. To allow for comparison between line length and phase balancing a single cost weighting value is calculated for each parameter. In the case of phase balancing, this cost value is composed of the cost of each isolation transformer, the cost of rephasing and penalty costs for unbalance.

2.2 Data

In order to re-tap the laterals, the load on each spur needs to be calculated. The apparent power rating of each transformer along the feeder was obtained from Western Power's GIS database. Based on modelling estimates from Western Power planners regarding the utilisation of transformers, a diversity factor of 0.2 is assumed. Thus, as the voltage of the line is assumed to be the nominal voltage of 22kV, the current each customer draws can be calculated. Finally the total current and apparent power on each spur is determined.

2.3 Isolation Transformers

An isolation transformer is connected across two phases and thus divides the load drawn by the spur. If the total current drawn by a spur exceeds 5A an isolation transformer is required for protection. There are two types of isolation transformers which are commonly employed by Western Power. The first and most common, is a pole-top mounted 200kVA transformer, while the second is a ground based 315kVA transformer.

Initially, the spurs which require isolation transformers are identified. An appropriate isolation transformer solution is then chosen for each based on the apparent power drawn by the spur. Finally the isolation transformers need to be assigned across two phases as evenly as possible. There are three options for assignment (across phase 1 and 2, 2 and 3 or 1 and 3) and transformers are spread across all options equally. The spurs which don't require isolation transformers can now be allocated to a phase. In order to achieve balance between the phases the heaviest loaded spur is assigned to the phase which is the least loaded. This process is repeated until all spurs have been allocated to phases.

2.4 Penalty Factors

In order to find an optimised network the importance of phase balancing must be weighted against the importance of minimising line length. To make these parameters comparable a cost value is determined. For the phase balancing algorithm there are several cost parameters to consider, including the cost of equipment. Each type of transformer has a different associated cost which is summed based on the number of transformers required. There is also a small cost associated with changing the phase of a customer. Finally, the difference between the phase currents should ideally by less than 5%. If this is not possible penalty factors are applied; the more unbalanced the phases are the greater the penalty applied. In this way possible network configurations which cannot be balanced are assigned higher cost values and so become more undesirable. Thus these architectures are discarded in the next cycle of the genetic algorithm.

3. Results and Discussion

In order to test the developed algorithm, the Hyden feeder (figure 1) was selected, as it covers a remote region. Thus there is greater potential for re-routing options and hence more variability in the genetic algorithm. The genetic algorithm performs iterations and each time the minimum line length is calculated and then phase balancing occurs.

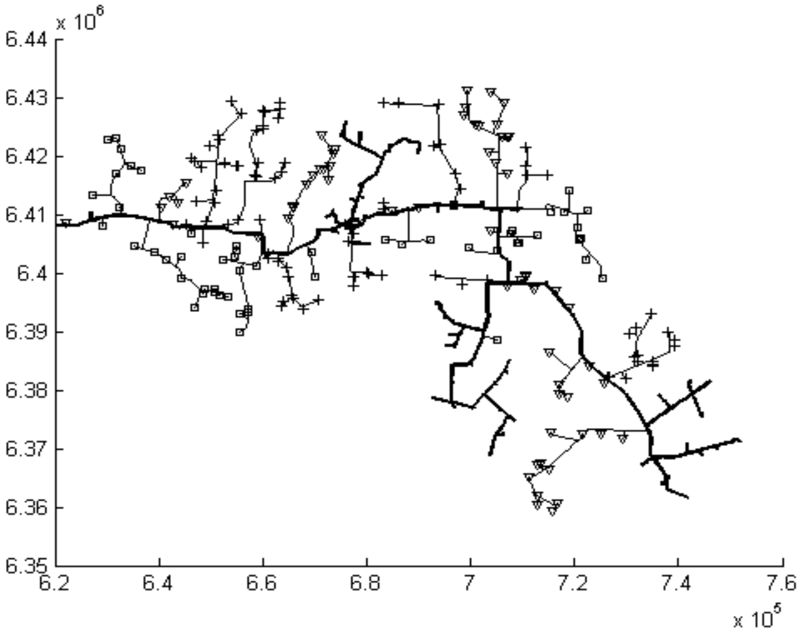

Figure 1 The current Hyden feeder configuration where the solid black line represents the three phase backbone and the squares, triangles and crosses represent the phase (1,2, or 3) of each spur respectively

In this case a cost of 0.47 per unit (referenced to the cost of 1km of single phase overhead line) is required for isolation transformers, of which there is only one 200kVA transformer required. The cost of rephasing is found to be 0.22 per unit, which means 33 customers have been reallocated to a different phase (out of the 316 customers on the feeder). Finally it is found that all of the phases are balanced to within the 5% margin. Thus the final cost weighting factor is 0.69 per unit. For this network the cost savings due to line minimisation is 139.6 per unit and thus this configuration is highly optimised and feasible. Figure 2 shows the optimised network; the three phase backbone remains the same (as it is locked in place), however the spurs have been re-routed and re-tapped to the backbone to achieve optimisation.

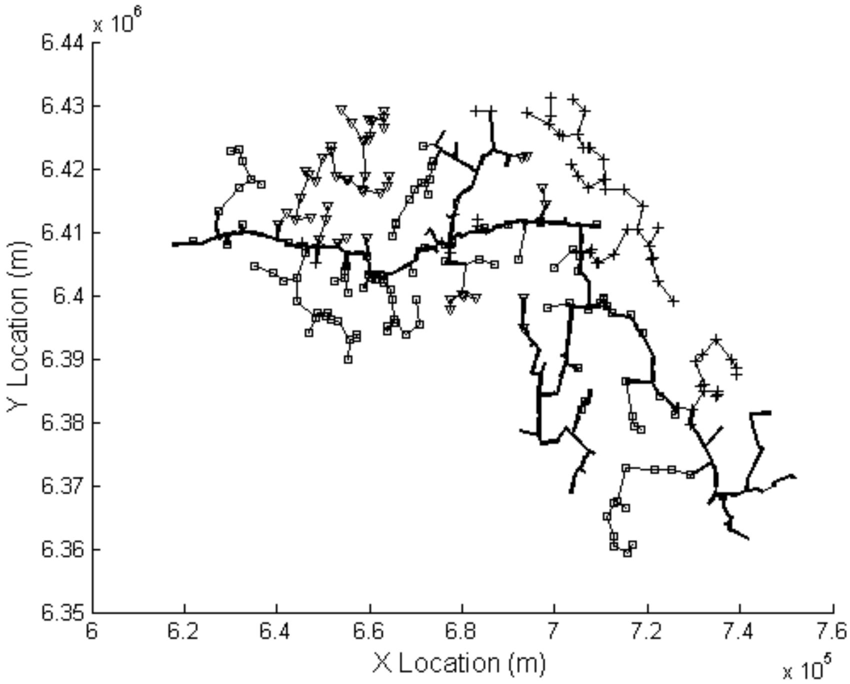

Figure 2 Optimised architecture after line minimisation and phase balancing where the solid black line represents the three phase backbone and the squares, triangles and crosses represent the phase (1,2, or 3) of each spur respectively

4. Conclusions and Future Work

In the past the rural distribution network expanded in a ad-hoc manner with new customers connected as required. Thus it was not possible for a globally optimised plan to be implemented. Now with customer locations known it is possible to determine an optimised architecture to reduce the length of the line required. While line length minimisation is important to reduce investment costs it is vital that the feasibility of the reconfigured network is determined. A key aspect of this is phase balancing which is vital to prevent equipment damage, poor power quailty, reduced reliability and under utilisation of existing equipment. In order to achieve a system which is as closely balanced as possible, penalty factors are applied for any unbalance greater than 5%. Isolation transformers are also implemented to improve the balance and reliability of the system. Thus an overall cost weighting factor is calculated which is then compared to the savings cost resulting from line minimisation to determine if implementation is practical.

Currently the algorithm can deal with spurs with loads of up to 315kVA through the use of isolation transformers. However if the load on a spur is greater than 315kVA a single phase line is no longer adequate and needs to be replaced with a three phase line. Implementation of this three phase extension is ongoing as there are a number of factors to consider. For instance it is not cost effective to extend the three phase along the entire spur, instead it is only built far enough that the remaining load can be supplied with a 200kVA isolation transformer. Another factor to consider is branching of the spur as the best route must then be selected.

While the algorithm currently ensures the network is balanced in terms of current considerations it is also important to consider voltage balancing. In order to do this a load flow analysis on an unbalanced three phase system must be performed. This is currently being investigated. The best option seems to be to use a MATLAB package called Matpower. As Matpower can only deal with single phase systems the network will be modelled using symmetrical components (positive, negative and zero phase sequence) and run three times before combining the results.

As the algorithm has been constructed to be modular there are many avenues for expansion in the future. Aside from line length minimisation and phase balancing there are a considerable number of other parameters which can be incorporated. Key options include risk and reliability determination and stand-alone power systems or micro grids. The work is also highly scalable, with the ultimate goal being to model the entire rural network to provide a planning tool to designers.

5. Acknowledgements

Throughout this project I was fortunate enough to have the support of many people, both from the University of Western Australia and from Western Power. Firstly I would like to recognise Jeremy Leggoe and Amanda Bolt from the CEED office for their tireless work in organising and implementing the CEED projects. To my UWA supervisors, Tyrone Ferdando, Herbert Lu and Mark Reynolds thank you for your continued knowledge and guideance. I would also like to thank my co-worker, James Fletcher, for his support and assistance throughout the project. Finally, to Shervin Fani and Noel Schubert from Western Power, you provided clear direction from the onset of the project and your expert knowledge was invaluable.

6. References

Carrano, E & Soares, L & Takahashi, R & Saldanha, R & Neto, O 2006, ‘Electric Distribution Network Multiobjective Design Using a Problem-Specific Genetic Algorithm’, *IEEE Transactions on Power Delivery*, vol. 21, no. 2, pp 995-1005.

Fletcher, J & Fernando, T & Iu, H & Reynolds, M & Fani, S 2014, ‘A Case Study on Optimising an Electrical Distribution Network Using a Genetic Algorithm’

Sathiskumar, M & Nirmal Kumar, A & Lakshminarasimman, L & Thiruvenkadam, S 2012, 'A self-adaptive hybrid differential evolution algorithm for phase balancing of unbalanced distribution system', *Electrical Power and Energy Systems*, vol 42, no. 1, pp 91-97

The MathWorksInc. n.d., *MATLAB The Language of Technical Computing*. Available from: <http://au.mathworks.com/products/matlab/features.html#programming_algorithm_development>. [23 February 2015].

Zhu, J & Chow, M & Zhang, F 1998, 'Phase Balancing using Mixed-Integer Programming', *IEEE Transactions on Power Systems*, vol 13, no. 4, pp1487-1492