OPTIMISING MV NETWORK DEVELOPMENT AND ENHANCEMENT USING A ROUTING ALGORITHM AND CABLE RE-RATING

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ABSTRACT

This paper outlines and illustrates the latest developments in 'VOH', an automatic network routing algorithm. The treatment of existing MV network is shown, which should prove invaluable in aiding the development of least cost investment plans. Following a brief discussion on the difference between component ratings when planning and ratings when considering the upgrade of existing components, the significant economic benefit of deferring upgrade by re-rating according to a cyclic load profile rather than a steady-state rating is shown.

Forced backup to secondary substations that are supplying important loads while the rest of the network is only backed up where it is cost effective, and the ability of the user to force the algorithm to optimise around a stipulated trunk feeder are also demonstrated.

INTRODUCTION

The algorithm outlined and illustrated in this paper is in its fifth year of development. The 'VOH' algorithm joins an extended family of network planning algorithms that have been developed by other research groups over the last decades, for example, [1] and [2]. Our aim has been to develop an automatic algorithm that can cope with real distribution networks in terms of size and complexity, take account of existing network, directly deal with reliability, allow two route choices for every connection and allow the user to stipulate route preferences if so desired.

In [3] we used the algorithm to show the effect of different planning emphases on the overall topography of an urban MV network. In this paper we will demonstrate the treatment of existing network when planning a network expansion. This leads naturally to the reassessment of components that will need replacement before the planning time horizon because of load increase or aging, and so we will show the considerable cost benefit of a cyclic re-rating of the current limits of cables. Providing backup to all secondary substations in a network can be prohibitively expensive, especially a suburban or rural network, and so we will show the ability of the algorithm to provide backup to important nodes that the user stipulates must have backup, while the rest of the network is backed up only when globally cost optimal.

The final simulation will show how the algorithm can be forced to optimise around stipulated trunk feeders in cases where network planners have strong preferences about main trunk line routing or knowledge of future network developments outside the planning horizon being considered in the present simulation. This is a feature that to some extent compensates for the fact that the VOH algorithm is not, at present, a fully dynamic or multi-stage planning algorithm, such as that developed in [4], for example.

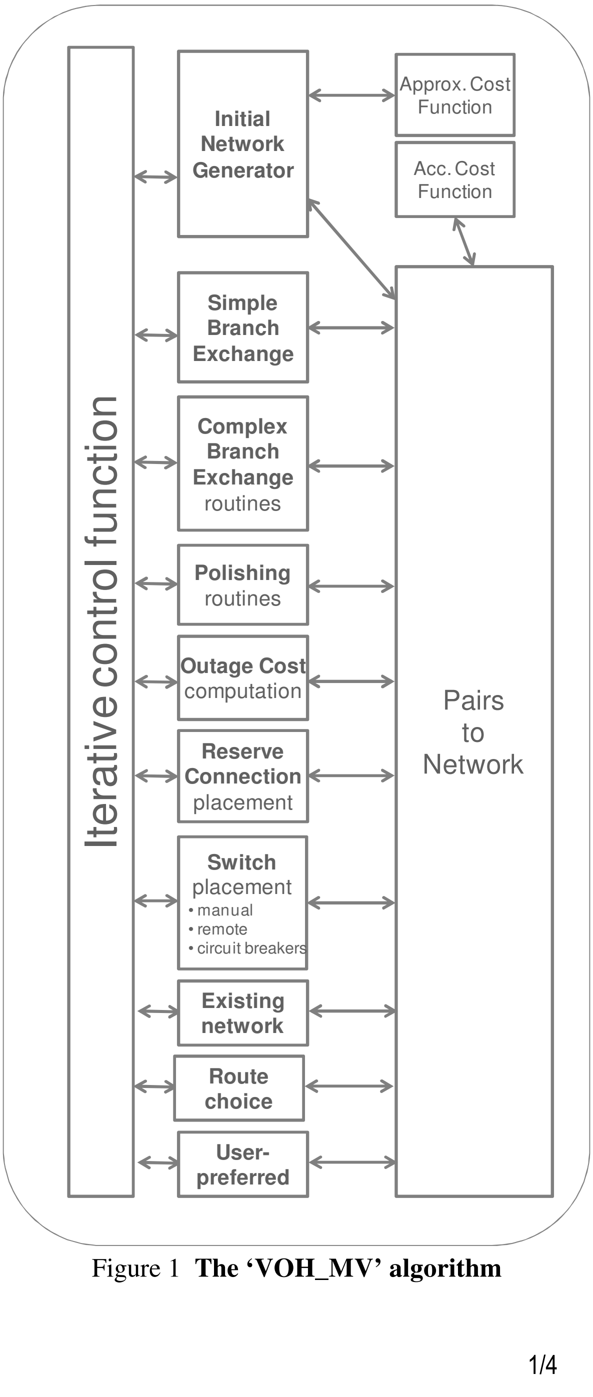

Figure 1 **The 'VOH_MV' algorithm**

ALGORITHM OVERVIEW

VOH has been built from the ground up, and includes initial network generation, complex but deterministic network improving functions, switch optimising functions and reserve connection functions. The optimising functions are specifically built for the job at hand, optimising distribution network routing. The working of the algorithm was outlined in [3]. Figure 1 shows the main components in the algorithm and some of the new developments are now mentioned.

'Existing network' is represented in the form of line segments, each with its corresponding line type, electrical characteristics, removal cost, upgrade cost and age. Whether or not they are used depends on whether they can cope with the projected load flow for at least one year and whether their use, up to their end of life if that is earlier than the planning horizon, is economically justified. Reliability of the existing (versus new) line may also influence optimal upgrade times.

The user can also specify two route choices. This enables the algorithm to choose between, for example, a more direct connection with higher installation costs over a routing that may be cheaper, but more subject to faults. Line types can also differ in the route options, but this would be subject to technical compatibility, which the user, typically an experienced network planner, should be aware of. The user can also stipulate trunk routing from primary substations.

SIMULATIONS

The first simulation shows a network expansion including new substation areas and some infilling of the existing network. Figure 2 shows the existing network, 1.4x1.4 km, and the new primary and secondary substation positions.

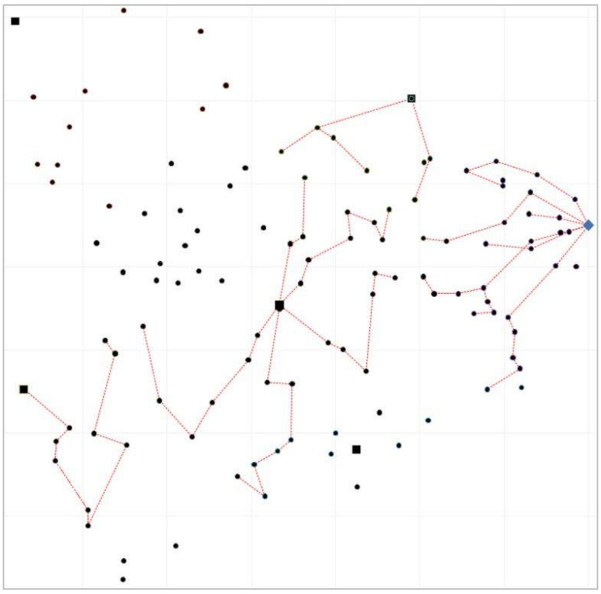

Figure 2 Existing network and new subst. positions

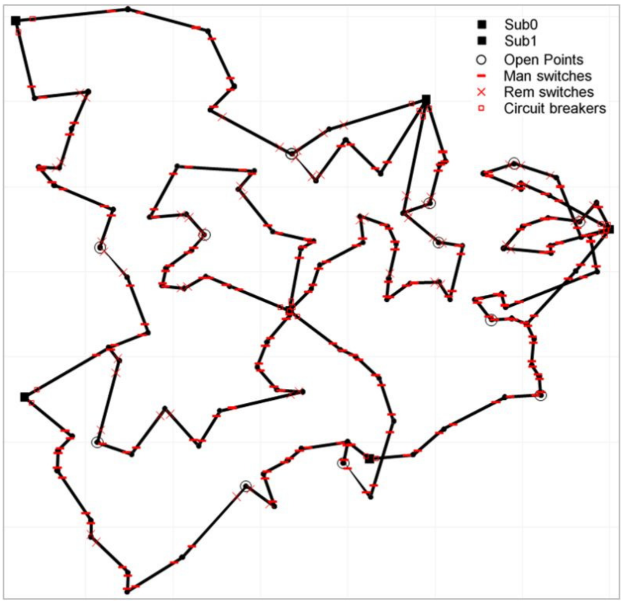

Figure 3 Expanded network, with full backup.

Figure 3 shows the expanded network, which utilises, where appropriate, the existing network, which makes up 64% of whole, from Figure 2. Part of a text output is shown in Table 1, which indicates line types (in this case 1 refers to suburban cable), conductor sizes, route option, whether or not each line section makes use of an existing line and, if so, what the upgrade time for the existing line should be.

Table 1 Output line specifications

Upstream node	Downstr. node	Line types	Conductor sizes	Route option	Existing pair tag	Upgrade times
16	6	1	3	1	1	20
8	7	1	3	1	0	0
2	8	1	4	1	1	18
10	9	1	3	1	0	0
23	10	1	3	1	0	0
7	11	1	3	1	0	0
3	12	1	3	1	1	14 etc

Similarly, an output file covering the reserve connections is shown in Table 2.

Table 2 Reserve connection output file

Closed node	Open node	Switch types	Line type	Backup cond. size	Reserve route option	Existing reserve connection	Upgrade time
99	95	1	1	3	1	0	0
53	50	1	1	3	1	0	0
42	45	1	1	3	1	0	0
66	63	0	1	3	1	0	0
17	19	0	1	4	1	0	0 etc

Part of the switch output file is shown in Table 3. Each line section is referred to by its downstream node. An indication is given if there is switching of some sort on the line section, if there is a switch on the line section close to the downstream reference node and if there is a switch at the far (upstream end) of the line section. The operating times are given for each switch, and these times reveal whether the switch is manual, remote or automatic, or a circuit breaker, i.e. 3 levels of switches are supported by this algorithm.

Table 3 Switch matrix output

Downstream reference node	Switch indicator	Close switch indicator	Close switch time	Far switch indicator	Far switch time
6	1	1	0.75	1	0.75
7	1	1	0.75	1	0.75
8	1	1	0.75	1	0.0015
9	1	1	0.75	1	0.75
10	1	1	0.75	1	0.75

The switch placement in VOH may not be the 'last word' in switch optimisation, but it is quite comprehensive, at least 'close to optimum' and is sophisticated enough to put the line routing in the right place. The main role of VOH is as a 'close to optimum' line routing algorithm that takes into account line faults and their mitigation, and gives network planners good guidance on when aging lines should be upgraded or removed from operation.

The economic benefit that may be derived from re-rating existing lines using a cyclic rather than steady-state analysis will now be shown. We suggest that steady-state component rating is still pragmatic when planning new networks, given the unpredictability of load forecasting far into the future. However, lines that are approaching their steady-state limits, but are in other respects still serviceable, can have their life significantly extended with great economic benefit. Cable rating is itself a large topic, with which the authors have some experience, but here we will simply assume that the steady-state ratings used in the simulations that produced Figure 3 can safely be increased by 20%. This is, in fact, often feasible when using cyclic rating, as long as the environmental parameters the original steady-state ratings were based on are reliable. Note that the inherent safety margin of using steady-state ratings is lost when using cyclic rating and so care must be taken.

Figure 4 Network with increased remaining life and thermal rating on existing network

Table 4 Cost summary for Figs. 3 and 4

	Investment and running costs	Interruption costs	**Total Costs**
Figure 3	€2 664 593	€190 486	**€2 855 079**
Figure 4	€1 718 108	€203 587	**€1 921 695**

More questionable, but still within the realms of reality, is to increase the life expectancy of the cables from 10 years to 30 years. It is clear that there are many oil-paper cables still giving good service after 50 or 60 years. The cables in question are XLPE, which deteriorates over time. Nevertheless, they have water barriers and aluminium sheaths. The dielectric strength can cope with some deterioration given that it is way in excess of the voltage stress the cables undergo, and so, if an XLPE cable is giving good service after 40 years, it would seem reasonable to keep it in service for a substantially longer period.

The cost saving from using cyclic rather than steady-state rating for the existing lines and increasing their remaining life from 10 to 30 years implies a 32% (€933 384) present value reduction in total costs over the 40 year review period. In the future, the actual load profiles of each line section will be better known due to hourly AMR data. The cost savings are quite remarkable, and applications that are being developed to process this data, such as state estimation tools, will become increasingly valuable. This simulation implies that 19 of the existing 57 line sections should be taken out of service in the near future. In its present single-stage form, the algorithm is best suited for network expansions that will meet maturity in the near future – a period of a few years compared to the review period of some decades. The costs associated with the networks in Figs. 3 and 4 are summarised in Table 4.

Figure 5 shows a smaller network with two primary substations. This is a Greenfield simulation with optimal levels of switching and backup. Figure 6 supposes that the pair of customers (secondary substations or MV customers) in the north-east of the network are considered to be vitally important and must, regardless of cost, have backup.

The final simulation, shown in Figure 7, demonstrates one aspect of using 'user stipulated' network. In this case, a trunk feeder is run directly between the primary substations. Branch nodes, which are supported by the algorithm, are positioned along the route. The branch nodes, which can be set to be either optional or mandatory, can be used to direct line routing along street grids or around obstacles. If the branch nodes are optional, they will be removed if they serve no useful purpose in the final network. Internodal fixed cost adjustments, fault frequencies and repair times can also be used to force routing around obstacles. If, as in this simulation, map or user derived internodal data is not available, point to point line lengths are scaled up to allow routing along street grids, etc.

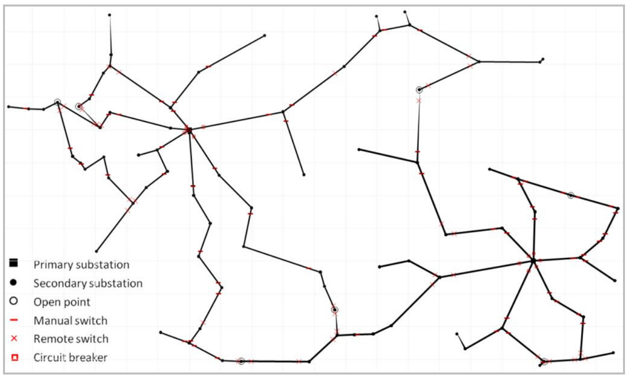

Figure 5 Greenfield network plan with optimal switching and backup

A cost summary of Figures 5-7 is given in Table 5. Naturally, every successive restriction on the network from the globally cost optimum solution imposes additional cost. Given that map derived internodal data (not shown in this paper) and branch nodes will make the network routing follow street grids or natural geographic corridors, the main purpose of the user preferred network option will be for the network planner to try and do better than the VOH algorithm, or to make provision for future developments that are not clearly defined on the planning horizon.

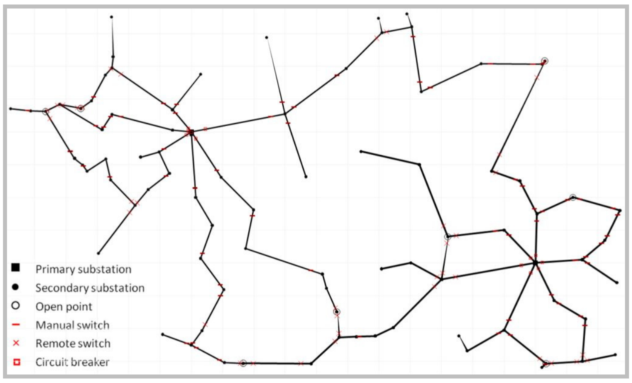

Figure 6 Forced backup to north-east nodes

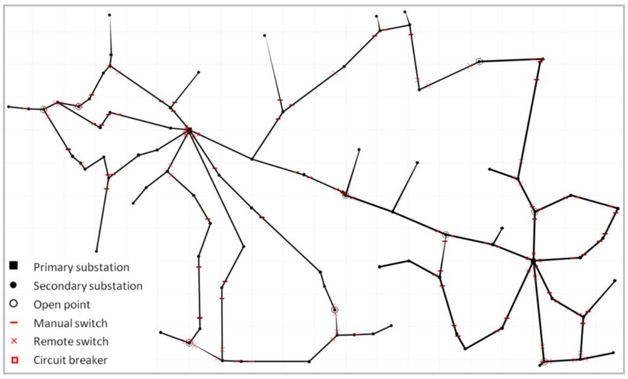

Figure 7 User preferred network between the two primary substations

Table 5 Cost summary for Figs. 5-7

	Investment and running costs	Interruption costs	**Total Costs**
Figure 5	€2 129 114	€259 774	**€2 388 888**
Figure 6	€2 171 891	€251 959	**€2 423 850**
Figure 7	€2 317 173	€273 155	**€2 590 328**

That is, if VOH produces a network that appears suboptimal in some respect, the user can put the entire network into the user preferred pairs file, make the changes that make the network look more sensible, and then run VOH to see if the (heuristic) change does produce a cheaper network. Such an outcome is possible, but unlikely.

SUMMARY AND CONCLUSIONS

Present networks are ageing and have often been constructed on a year by year basis with a lack of long-term overview. Moving into the future making the best use of existing infrastructure is a challenging planning task. The VOH algorithm facilitates network investment by considering the present situation and giving a close to optimal network on the planning horizon, which, as the years unfold, presents a constantly moving target.

Increasing costs for interruptions have a major impact on the routing of a distribution network – more feeders, more backup and more sophisticated switching – and so we have had to directly include all this in the algorithm. This paper has not touched on the development of VOH to optimise LV and MV-LV network, which is now working, and it is clear that we must also accommodate distributed generation in the future development of this algorithm.

Acknowledgments

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REFERENCES

[1] I. J. Ramírez-Rosado, 2006, "New Multiobjective Tabu Search Algorithm for Fuzzy Optimal Planning of Power Distribution Systems", *IEEE Transactions on Power Systems,* vol. 21, no. 1, 224-233.

[2] G. Celli et al, 2005, "An heuristic technique for the optimal planning of meshed MV distribution network", *Power Tech, IEEE,* Russia, 1-7.

[3] R.J. Millar et al, 2009, "Urban distribution networks - Some general planning observations," *20th International Conference and Exhibition on Electricity Distribution - Part 1, CIRED*, 1-4.

[4] S. Haffner et al, 2008, "Multistage Model for Distribution Expansion Planning with Distributed Generation–Parts I and II, *IEEE Transactions on Power Delivery,* vol. 23, no. 2, 915-929.