ENERGY STORAGE/DEMAND SIDE RESPONSE IN LV NETWORKS: DESIGN OF COST BASED PLANNING TOOLS FOR NETWORK OPERATORS

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ABSTRACT

With the high growth in distributed generation in the UK and resulting challenges in distribution, there is a need for network operators to develop cost based tools to plan for and control technologies such as energy storage. This paper presents three methods for locating storage in LV networks to solve voltage rise problems. The methods are compared and evaluated and it is shown that careful heuristic selection and storage located in homes can provide significant savings for network operators.

INTRODUCTION

Over 1.2 MW of solar photovoltaic (PV) systems were registered with the UK feed in tariff scheme in August 2012. More than 65% of these were less than 4 kW in size and installed on the rooftops of properties connected to the low voltage (LV) distribution network [1]. By averting fossil fuel generation, PV can reduce emissions of carbon dioxide as well as other harmful gases [2]. The feed in tariff incentive was designed to encourage installation of PV and to help the UK achieve its environmental target of reducing greenhouse gas emissions by at least 80% of 1990 levels by 2050 [3].

The installation of these distributed generation sources fundamentally changes the operation of the electrical power network. Within the LV network, two particular resultant issues are reverse power flow and voltage rise [4]. These become more problematic as the penetration of rooftop PV increases, and this can limit the amount of PV that should be installed in a network area [5]

Under UK regulation, distribution network operators (DNOs) cannot prevent installation of PV systems, even if they could cause specific network issues. A DNO would typically need to re-conduct or re-configure an LV network to solve a problem. The former is expensive and disruptive to consumers and the latter may have implications for other LV networks. Alternative methods include reactive power control of PV inverters and on-load tap changers [6] which are expensive and uncommon on secondary transformers [7].

Demand side management (DSM), including distributed energy storage, are also methods available to DNOs but these are not widely installed in the UK. If suitably sized, these provide benefits such as prevention/reduction of reverse power flow or overvoltage problems by absorbing energy. Storage can also provide peak shaving and reduced losses by discharging stored energy [8].

There is a need to develop planning tools for DNOs to aid the deployment of these new technologies. In this paper, a cost-based planning tool is presented for fixing voltage problems in LV networks. Although energy storage is discussed in detail here, the tool can be easily adapted to other DSM techniques. Additional revenue and operational considerations are also briefly discussed.

THEORY

The cost of energy storage is the sum of capital, operational and replacement expenditure. The capital cost, C_c can be approximated as follows—here capacity is expressed as the power rating multiplied by the storage time, (adapted from [9]).

$$C_c = C_I + (\mathbb{P}_{kW}.C_{kW}) + \frac{(\mathbb{P}_{kW}.\mathbb{E}_T.C_{kWh})}{D}$$

Where:

- $\mathbb{P}_{kW}$ is the system rating [kW];
- C_{kW} is the power cost [$/kW];
- C_{kWh} is the capacity cost [$/kWh];
- C_I is the installation cost [$];
- D is the maximum depth of discharge [%];
- $\mathbb{E}_T$ is the storage time [hours].

Energy storage may also have operational costs due to the cost of purchasing electricity and losses in the charging and discharging process. Both of these are obviously reduced by absorbing less energy.

It can be seen that capital and operational costs and are proportional to the system rating. There is a fixed power and energy requirement to solve a reverse power flow or peak shaving problem. However, since different nodes have different voltage sensitivity factors [10], the power required (and therefore costs) in managing a network problem can be reduced through careful location of DSM in the network. However, locating systems in a network is a complex problem—there are 64.7 million ways of arranging 4 DSM units in a 200 bus network.

This study presents heuristic methods which can be practically applied by DNOs to find a near optimal configuration of energy storage to solve a LV network voltage problem. This develops work in [8], where energy storage was shown to be financially feasible at the secondary transformer.

METHODOLOGY

Two radial networks are used in this study—a real UK low voltage distribution network (as used in [8]) and the IEEE 123 node test network [11]. A summary of these is provided in Table 1. Both are modelled with a high penetration of rooftop PV systems. PV systems output their full power of 2.25 kW and each property draws 290 W (which is a reasonable minimum power seen in measured network data). In both networks this causes voltage to rise beyond the UK regulatory limit of 253 V with the secondary transformer set at 240 V.

In the model of the real network, PV is sited on a random selection of South facing roofs (expanding on the current configuration) according to GIS data provided by the DNO. The published IEEE [11] test network configuration is used along with a sufficient PV and load penetration to cause a realistic voltage problem. PV is sited on all busbars on an East-West (Left-Right) orientation on the diagram provided with the IEEE network. A domestic property is modelled for every 10 kW load in the IEEE model description.

There are several scenarios whereby storage could be located in these LV networks, as opposed to the alternative approach of locating at the secondary transformer (Figure 1). Two are considered in this study:

Scenario 1: storage is located in domestic properties. These provide benefit to home owners through increasing self-consumption of PV, and could be used by the DNO for network management.

Scenario 2: Larger storage systems are located on the roadside. These would be owned by the DNO and dispatched when needed to fix the problem.

Table 1: Summary of Network Models

Network	Real	IEEE
Number nodes	281	123
Total line length [m]	3,953	11,991
Number loads	405	172
Number PV generators	200	91
Total demand [kW]	118	50
Total generation [kW]	556	205
Reverse Power Flow [kW]	438	155
Generation-demand ratio	471%	410%

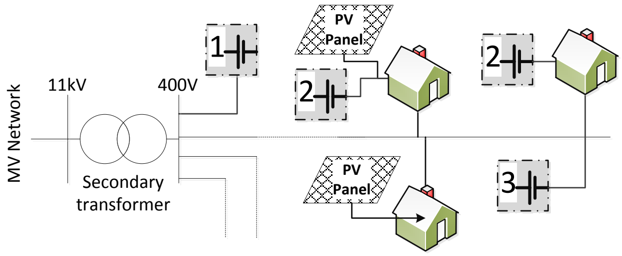

Figure 1: Energy storage in an LV network: 1) at the secondary transformer, 2) connected at the property behind the meter and 3) on the street

Heuristics

As stated, the voltage problem created in the networks can be fixed by locating a number of controllable loads within the network. In this study, the following three heuristic methods are considered for doing this:

Heuristic 1: Loads are added to the network one by one, starting at the node with the highest voltage.

Heuristic 2: Loads are added incrementally, with priority given to nodes with the highest voltage sensitivity factor.

Heuristic 3: A population of possible solutions is created randomly and then evaluated. A genetic algorithm with simulated annealing is used to improve the population and is stopped after a fixed number of iterations.

The utility (practicality) of each solution is evaluated according to a cost based objective function. A high cycle life lead acid battery is examined with costs of £250/kW, and £206/kWh taken from [9]. Inherent within this function is a penalty for exceeding voltage limits. This is the total cost of reconductoring the network (£80/m of cable). The objective is to minimise:

$$\sum_{i=1}^{N}\left(C_I + (\mathbb{P}_{kW,i}.C_{kW}) + \frac{(\mathbb{P}_{kW,i}.\mathbb{E}_T.C_{kWh})}{D}\right) + \begin{cases} L.C_r & \textit{if voltage outside limits} \\ 0 & \textit{otherwise} \end{cases}$$

Where:

- L is the network length needing reconductoring [m];
- N is the number of systems installed;
- C_r is the cost of re-conductoring [£/m].

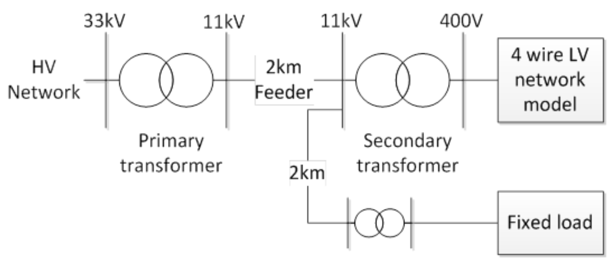

Figure 2: Network representation in simulation

Modelling Approach

All the heuristics use a network model to which they add loads (representing storage) at valid locations. A 4-wire load flow engine (Open-DSS) is used and then heuristics are implemented in a Matlab script. The model includes transformers and 11kV feeders as shown in Figure 2 and solutions are validated using a separate load flow tool. The scenarios are described in the heuristics using the following parameters and constraints.

Scenario 1—storage in homes:

- Storage can be only be located in homes with one system per home;
- Each individual unit costs the DNO £250 to install;
- The storage rating is 1.5 kW and is single phase.

Scenario 2—road side storage:

- Storage can be located at any customer connection point, or at the transformer—assuming that all are easily accessible to the DNO;
- Only one storage system per node;
- Each system costs the DNO £10,000 to install;
- 12 kW rating, divided equally across three phases.

In addition, the following assumptions are made:

- Each storage acts independently, and can draw between 0% and 100% of its rated power;
- Storage has a real power function only;
- The maximum depth of discharge is 80% to prevent complete discharge of the storage;
- 5 hours of storage is provided—equivalent to the maximum length of time of problems in [8].
- An exchange rate of $1.60 = £1 is used;
- Storage is not used in homes and on the roadside simultaneously.

RESULTS

Within all of the results, scenario one produces a cheaper solution than scenario two for a number of reasons:

- To install kerb side storage requires much more expensive civil and electrical work. Although scenario two requires few energy storage systems, this is not proportional to the much higher install cost;
- The voltage problems seen in the networks are not divided equally among the phases. Under scenario two, the higher rated systems have power divided equally across three phases and so cannot concentrate their benefits to phases where the problems occur. Future work should consider whether unbalanced, three-phase or single phase storage on the road side could solve the problem for lower cost.

Heuristics one and two produce solutions in a short timeframe on a regular laptop computer. They are also deterministic, in that they will always produce the same result. Heuristic three produces cheaper solutions than the other two heuristics. This is because it can search a much more of the problem space. However, as shown seen in Figure 6, a significantly larger number of load flows are required due to the nature of the algorithm.

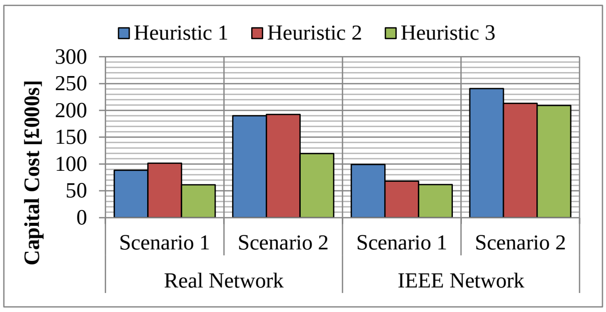

Figure 3: Capital costs of solutions

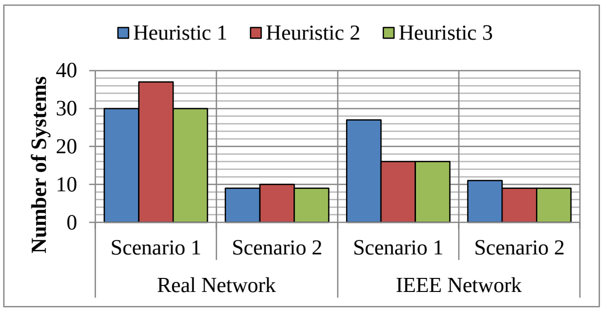

Figure 4: Number of systems for each solution

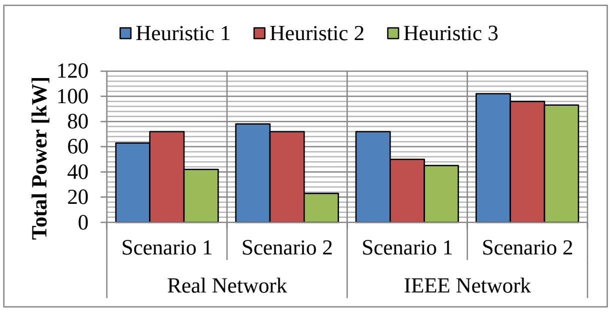

Figure 5: Total power required for each solution

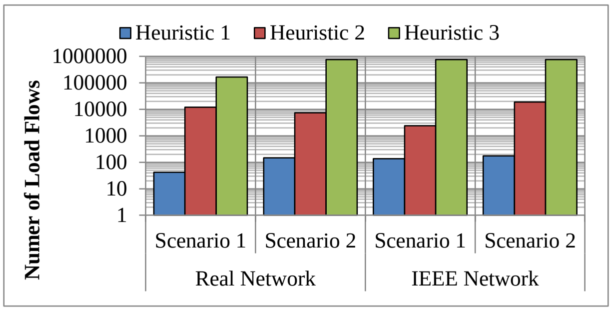

Figure 6: Number of load flows for each heuristic

DISCUSSION

It is shown that locating storage in the network uses less power than required at the secondary transformer (150 kW storage was used in [8] compared with 23 kW here). The results show the capital cost of distributed storage relates to both the choice of algorithm and the storage configuration (domestic or kerb side). In the real network, the voltage problem (which occurs on one way) can be solved with a reconductoring cost of £77,000. The results for scenario 1 (domestic storage) require a comparable capital cost—provided heuristic three is used.

Relevance to DNOs

The results show that storage located in customer homes should be supported by DNOs on cost terms. This scenario incurs lower install costs whilst providing benefits to the DNO and the home owner. For example, the home owner can offset home energy bills by storing excess generation and the DNO can achieve peak shaving, loss reduction, and voltage control in the network. This may also be used to manage load growth.

There are few practical implementations of multiple-unit energy storage in UK LV networks and none within the DNO network considered. Accordingly, human resources and procedures would need to be developed for control, design and maintenance of these systems. Clear regulatory and commercial arrangements would also need to be developed to operate storage for network benefits—in particular if these are sited at a customer property.

Further Algorithm Development

Deterministic and stochastic algorithms have been used in this study. The stochastic algorithms do not produce the same result each time and require significantly longer computational time, but are able to search a much larger problem space. As such, stochastic approaches are more able to find cheaper solutions: for example by reducing the number of systems and the install cost. Due to their speed, heuristics one and two, which use measurable network parameters may be suitable for use in control.

Work is currently being conducted in reducing the speed of the genetic algorithm and also adding to the problem space by including reconfiguration of networks, other demand side management technologies. This also includes other benefits within the objective function such as peak shaving and loss reduction. Further, the operational parameters to allow storage to be discharged and not cause voltage rise need to be investigated.

CONCLUSIONS AND FURTHER WORK

This paper shows how distributed energy storage can be used to solve voltage problems in an LV network for comparable costs to reconductoring. Three feasible cost based planning tools are presented for locating such systems and two installation scenarios are compared. The methods can easily be adapted for other demand side response systems e.g. water heaters. This work shows that distributed storage in LV networks may be financially viable for DNOs—particularly storage in customer homes. Further work will consider how other benefits and regulatory changes could support this.

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