APPLICATION OF DEMAND SIDE RESPONSE AND ENERGY STORAGE TO ENHANCE THE UTILIZATION OF THE EXISTING DISTRIBUTION NETWORK CAPACITY

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ABSTRACT

Traditional, largely passive operating paradigm of distributed networks is being challenged by expectations of load growth. As a response, distribution networks operation is moving towards a more active and dynamic approach, in order to enhance security of supply, improve utilisation of existing network assets and to minimise the need for network reinforcements. A spectrum of enabling technologies such as Demand Side Response (DSR) and Energy Storage (ES) can be used to provide distribution network support services, for example voltage and load flow control. In this paper, a methodology for assessing the potential benefits of using ES and DSR to postpone reinforcements of the existing network assets is presented. The methodology is based on a non-linear multi-period optimal power flow (OPF), where DSR and ES are modelled as a part of the optimisation constraints. DSR is built on a shifting algorithm applied to wet appliances. Storage model optimizes size and location of the ES. The approach is tested on a 11kV distribution network. The obtained results show that DSR and ES may be used for network assets investments deferral, thus more efficiently using the existing network capacity.

INTRODUCTION

The trends of increased distributed generation, load growth, and the electrification of heat and transport, are augmenting the stress in distribution networks that are already operated near their technical limits. For example, it has been demonstrated that in the UK, the incorporation of electric vehicles (EVs) and heat pumps (HPs) could increase total electric energy consumption by 50%, while nearly doubling the system peak [1]. This much larger increase in demand peak, compared that of energy demand, will cause a reduction in asset utilisation such that network reinforcement alone will be difficult to justify in economic terms. For this reason new, cost effective approaches to the design and operation of distribution networks need to be explored. This may mean that distribution network operators have to change their largely passive approach to network operation, protection and control, to a more active and dynamic paradigm to enhance security of operation, improve utilisation of the existing network assets, and minimise the need for network reinforcements [2].
Active management can be realized through the combined use of traditional means for network control, such as on-load tap changing transformers, voltage regulators, reactive compensators, etc., optimal network topology, as well as non-networks solutions, such as controllable distributed generation (DG). In addition, a spectrum of enabling technologies such as storage and demand side response (DSR) can be used to provide distribution network support services, such as voltage and load flow control.
Previous work has mostly focused on storage utilization for system balancing in high levels of intermittent generation penetration [3] or coordination with individual wind farms [4] to reduce its output variability. DSR's role has been mostly confined to system peak shaving [5-6]. These investigations did not however consider distribution network constraints or optimize the use of the flexibility from the demand side to perform an adequate quantitative assessment of the value of such approaches. This question has been unexplored, in part, due to the lack of appropriate methodologies and simulations tools. The current paper proposes a novel framework to assess the potential benefits of storage and DSR to optimise existing network capacity.

METHODOLOGY

A methodology to quantify the reduction in operation costs, proposed in this work, is based on the increased system flexibility attained by integrating the demand side and storage into network operation. Network operation is simulated using a multi-period AC optimal power flow (OPF) algorithm able to schedule both storage and flexible demand to reduce congestion costs. Controllable loads are scheduled throughout different network buses so the network constraints violations are eliminated.
The optimization involves examination of the system operation over a time horizon of a day and considers:

- Constraints, such as: power balance, thermal limits, voltage limits, generators constraints, storage and DSR capabilities;
- Coordinated actions across multiple time periods that are required to optimize operation of storage and DSR

The objective function is to minimize network operation costs.
The optimization problem is a mixed-integer non-linear problem whose dimension depends on network size. Non-linear problem is loaded and solved using Successive Linear Programming (SLP) module within Commercial optimization software FICO Xpress [7].

Demand Response Model

In this paper a shifting algorithm is developed and implemented on 'wet' appliances, and the problems related to network congestion are addressed. In order to explore the benefits that DSR could potentially bring to managing congestions in distribution networks, the following batch of smart appliances (SA) is selected:

- Washing machine (WM)
- Dish washer (DW)
- Washing machine with tumble dryer (WM+TD)

The input data requirements when considering SA are: diversified profile, operation cycle, energy consumption per cycle and control possibilities for each type of SA, detailed in [8]. The other SA characteristics are described in Table 1. Penetration factor and shifting capabilities in Table 1 are based on the customer survey [9].

Table 1: Summary of device types

Device type	Shifting Capability	Consumption pattern duration [h]	Penetration factor [%]	Number of devices
WM1	1h	2	25	750
WM2	Up to 2h	2	25	750
WM3	Up to 3h	2	25	750
DW	Up to 6h	2	80	2400
WM+TD	Up to 3h	4	25	750

Flexible demand reduction and recovery are optimally scheduled in terms of time, amount and location (bus) over the whole optimization period.

Storage Model

A generic model of a battery storage device is used, with power rating, energy capacity and efficiency parameters. The main concern of storage is active power requirements support, as VAR control from energy storage is not economically justified [10]. More specifically, bus voltages and reactive power flows in distribution networks can be effectively controlled with much lower cost devices such as capacitor banks, under-load tap changing transformers (ULTC) or static VAR compensators (SVC).

CASE STUDIES

The optimization algorithm is tested on a radial 11kV distribution network with 38 buses and 37 branches, presented in Figure 1.

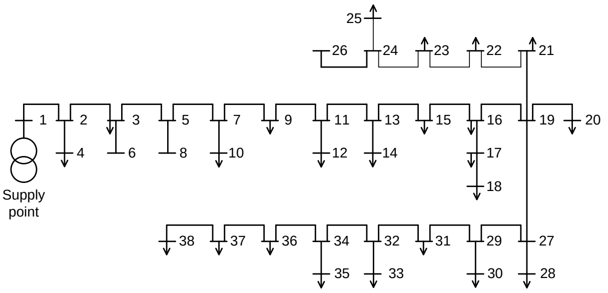

Figure 1: Distribution network 38 bus test system

The system has a peak of 2.96MW, daily energy consumption of 56.9MWh and power factor 0.98. Voltage limits are within ±6% of the nominal value. The transformer at the supply point has a voltage regulation capability in the range ±10%. The network lines are underground cables. Demand is given as hourly time series data. A typical winter day is selected for analyses. The capacity of the Supply Point is assumed to be large enough, thus the only network constraints are the branch thermal limits and bus voltage magnitudes.

Reference Case Results

This analysis is focused on the permanent long-term load growth with assumed annual demand growth rate of 1.3% and its effects on network conditions. Load growth leads to over-loading of network branches and under-voltages.

The analysis is performed by increasing load from 0% to 30% in steps of 1%, which covers a total period of around 20 years. The costs incurred in each year are referred to the present (starting) year and are compared using present worth analysis [11]. The interest rate is assumed to be 5%.

Table 2 tabulates network lines for which the thermal capacity constraint is violated as load increases.

Table 2: Line overloading (reference case)

Load Growth [%]	Year	Overload line From Bus – To Bus	Length [m]	Replace Cost (PV) [£]
5	4	1 - 2	275	18960
14	10	13 - 15	50	2527
21	15	2 - 3	1900	76664
21	15	15 - 16	200	8070
25	17	5 – 7	211	7530
27	19	3 - 5	326	10956
27	19	7 - 9	7800	262142
TOTAL:		7 lines	10762	386849

The assumed unit cost for replacement of 11kV underground cable is £82,900 [£/km] [12].

Under-voltage starts in buses that are most distant from the supply point, e.g. buses 37 and 38 when load grows by 5% (Year 4). As load continues growing, under-voltages propagate toward the supply point. In the considered 20 year period, a total of 23 buses experience under voltage conditions (Bus 16 to Bus 38, inclusively).

DSR Results

The number of customers in the network is estimated to be 3,000 based on the total network peak (3MW) and assuming that diversified load peak for households is about 1kW [13].

Expected number of SA starting consumption at each hour of the day and for each type of device is estimated using diversified curve disaggregation technique [14].

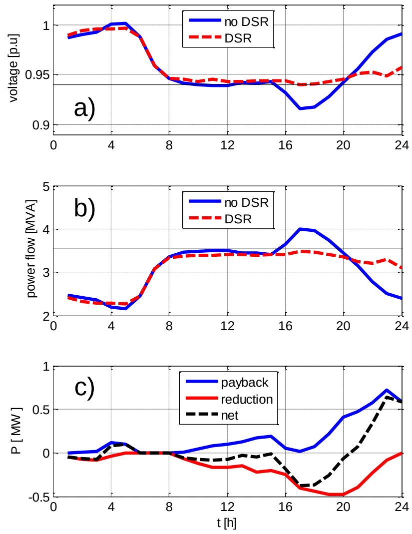

Figure 2: DSR effects on network

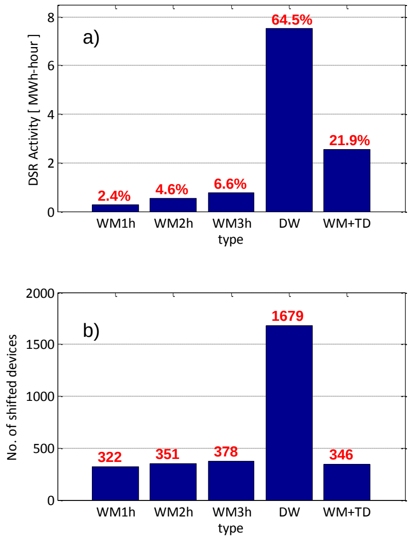

Figure 3: DSR activity and number of shifted devices

Table 3 lists the overloaded network lines.

Table 3: Line overloading (DSR case)

Load Growth [%]	Year	Overload line From Bus – To Bus	Length [m]	Replace Cost (PV) [£]
18	13	1 - 2	275	12200
27	19	13 - 15	50	1680
TOTAL:		2 lines	325	13880

From the results obtained, it can be concluded that for this network the application of DSR allows us to defer the investments in network reinforcement for about 9 years, as compared to the reference case.
When load increases 18%, Bus 37 and Bus 38 go under-voltage. In Year 20 under-voltage is detected in 12 buses versus 23 in reference case.
Figure 2a shows voltage in Bus 38. With DSR, voltage does not fall below its limit. Figure 2b shows apparent power flow through line Bus 1 – Bus 2, observed from Bus 1 side (this power includes all network losses). With DSR, apparent power does not exceed the line limit. DSR has a tendency to flatten load, reducing network losses. An example where this happens is during the period of low demand from 1-5am. Figure 2c shows DSR reduction and payback at system level. The dashed line in Figure 2c represents net DSR, obtained as a sum of load reduction and load payback. The total payback energy during a day is equal to the total reduced energy because, in this model, load shifting is not based on any form of energy storage.
Results of DSR activity are shown in Figure 3a for the case of 17% load increase. The red numbers over the bars represent percentage of total DSR activity (DSR activity is defined as amount of shifted energy multiplied by the shifting time). It can be noticed that more flexible devices exhibit higher DSR activity. Also, devices with higher energy consumption per cycle manifest higher DSR activities (compare WM3h and WM+TD). DW demonstrates highest DSR activity mainly as it is the most flexible device (it may be shifted up to 6h) but also due to assumption that it has higher energy consumption per cycle than a washing machine. Number of shifted devices for each type of appliance is shown in Figure 3b.

Optimal Storage size and location

This section addresses the following questions:

– What is the maximum load growth that can be resolved by storage utilization?
– What are the optimal rated power and optimal energy capacity for storage to support that maximum load growth?
– Where (which bus) should the storage with parameters found above be placed?

The selection of eligible buses for storage placement depends on the space available for storage and auxiliary equipment installation, bus infrastructure, etc. For the algorithm testing, a set of twelve buses eligible for storage installation is selected: 2, 6, 11, 18, 23, 26, 27, 28, 29, 34, 36, and 38, and the number of storage devices in the feeder is limited to one.
The obtained optimal storage location is Bus 29; optimal storage size is 750kW with capacity 3.7MWh. With this storage, the network can endure load growth up to 25%.
Table 4 lists the overloaded network lines with the specified storage.

Table 4: Line overloading (storage case)

Load Growth [%]	Year	Overload line From Bus – To Bus	Length [m]	Replace Cost (PV) [£]
26	18	1 - 2	275	9522
26	18	13 - 15	50	1731
TOTAL:		2 lines	325	11253

In Year 18, Bus 37 and Bus 38 go under-voltage. There are a total of five buses going under-voltage during the observation period (Bus 34 to Bus 38, inclusively).
From the results presented, it can be concluded that for this network with Energy Storage (750kW, 3.7MWh, Bus 29), network reinforcement may defer for about 14 years comparing to the Reference Case.

Economic benefits of Demand Side Response and Energy Storage

In this section, a comparison of economic benefits between alternative methodologies is presented. It is assumed that economic benefits come from savings in underground cables reinforcement costs. All the costs are expressed as a net present value (PV). Table 5 gives a summary of the results.
The net benefit is calculated under certain assumptions. First, it is assumed that the storage investment cost is £1,000/kW [15].
Investments related to DSR assume there are:

- mass deployment of smart appliances
- existence of smart meters in households
- existence of communication network between smart meters and central DNO dispatching centre
- investment cost per appliance is £4 [3], including the communication between smart meter and appliance (estimated number of SA in this network is 5,400, therefore the investment cost is 5,400·4=£21,600)

The net benefit is then calculated when the investment cost is deducted from the cost savings.

Table 5: Comparison of economical benefits DSR vs. Storage

	Methodology		
	Base Case	DSR	Storage
Year of 1st investment	4	13	18
Lines to replace	7	2	2
Total length [m]	10,762	325	325
Total replacement cost (PV) [£]	386,849	13,880	11,253
Replacement cost savings [£]	-	372,969	375,596
Investment cost [£]	-	21,600	750,000
Net benefit [£]	-	351,369	-374,404

From Table 5 and obtained results, it can be concluded that storage of 750kW, 3.7MWh is still not economically justified, taking into account present cost of investment. DSR is economically justified under the above-mentioned assumptions. However, note that in this analysis the only source of economic benefit comes from savings in replacement costs. Other streams of revenue for storage and DSR may also come from wind energy integration, ancillary system services provision, reduction in losses and CO_2 emissions etc.

CONCLUSIONS

In this paper, a methodology to support distribution network operation using demand side response and storage technologies is developed and successfully employed to control the voltages and power flows in the network, bringing the benefits to the network operator. The methodology is applied to an 11kV distribution network feeder where the problems related to the lack of network capacity and under-voltages in distant buses emerge.

It was demonstrated that the proposed approach with enabling technologies facilitates active network management in terms of:

- optimizing the existing network capacity utilization
- deferring network reinforcement
- reducing network losses
- improving power quality and
- improving security of supply

DSR and storage location models in AC networks are non-linear mixed integer optimization problems solved by using Sequential Linear Programming within a commercial optimization software. The benefits that smart appliances and storage bring to the network in terms of reinforcement costs savings are quantified using cost avoidance criteria considering a period of 20 years. Present value equivalents are used to compare the costs. The key drivers for DSR are found to be network congestion level, penetration of SA, their flexibility and energy consumption per cycle. The key drivers for the value of storage are its power rating, size, efficiency and location.

For this particular system, reinforcement may be postponed for about 9 years by utilization of DSR. Value per device is found to be around £70 for the whole period. Annualized value is about 3.5 £/device/year. It was found that storage of 750kW and 3.7MWh located in Bus 29 maximally postpones network reinforcement for about 14 years. However, it was also shown that this storage would not be economically justified within the period of 20 years with present cost of battery technology.

Both technologies have advantages and drawbacks and the benefits they bring to the network operation are very system-specific. DSR is distributed throughout the network, but requires communication infrastructure and is less flexible than storage. Storage is more beneficial to the network operation due to higher flexibility. On the other hand, it has inherent energy losses and requires space and maintenance. The use of storage is constrained by space availability, which is limited in urban areas. DSR is a more adequate solution for such areas since it does not require additional space.

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