INTEGRATING WET APPLIANCES WITH DELAY FUNCTIONALITY IN DISTRIBUTION NETWORK OPERATION AND PLANNING

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ABSTRACT

Due to the lack of observability and controllability in existing distribution networks, the traditional operation and planning framework makes the oversimplifying assumption that customers' demand can be either supplied or shed at a cost determined by a benchmark value of lost load (VoLL). For most load appliances however, the users are more likely to shift their operation in time than completely avoiding using them. Driven by the advanced metering and control capabilities of the emerging smart grid, this paper develops a model of distribution network operation and planning integrating this time-shifting flexibility and accounting for the associated customers' inconvenience cost. The paper focuses specifically on wet appliances (WA) with delay functionality, given their significant penetration, energy consumption and time-shifting flexibility. Case studies on a typical UK HV distribution network demonstrate the value of such flexibility in reducing network operating costs and postponing network reinforcements.

NOMENCLATURE

Indices and Sets

$n \in N$	Index and set of network nodes
$b \in B$	Index and set of network branches
$f \in F$	Index and set of network failures
t	Index of time periods
T_f	Set of time periods including the periods during which failure f occurs and the first $\max_j \delta_j^{max}$ periods after the end of failure f
$i \in I$	Index and set of customers
I_n	Set of customers connected to node n
$j \in J$	Index and set of WA cycles
$J_{i,f}$	Set of WA cycles activated by customer i during T_f
τ	Index of steps of WA cycle

Parameters

$\underline{v}, \overline{v}$	Minimum and maximum voltage magnitude
$\zeta_{b,t}$	Integer parameter indicating the state of branch b at period t
T	Time duration of simulated failures in years
$P_{i,t}$	Baseline active demand of the inflexible load of customer i at period t
pf_i	Power factor of customer i
$P_{j,\tau}^{cyc}$	Active power demand at step τ of WA cycle j
E_j^{cyc}	Energy requirement of cycle j
T_j^{dur}	Duration of cycle j in time periods
τ_j^{act}	Activation time period of WA cycle j
δ_j^{max}	Maximum delay limit of WA cycle j
a_j	Slope of inconvenience cost associated with WA cycle j

Variables

u_b	Binary variable expressing whether branch b is reinforced ($u_b = 1$ if it is, $u_b = 0$ otherwise)
$\boldsymbol{v_t}$	Vector of voltage magnitudes $v_{n,t}$ at node n and period t
$\boldsymbol{\theta_t}$	Vector of voltage angles $\theta_{n,t}$ at node n and period t
$p_{i,t}$	Supplied active demand for the inflexible load of customer i at period t
$q_{i,t}$	Supplied reactive demand for the inflexible load of customer i at period t
$z_{j,t}$	Binary variable expressing whether WA cycle j is initiated at time period t ($z_{j,t} = 1$ if it is, $z_{j,t} = 0$ otherwise)
Z_j	Binary variable expressing whether cycle j is carried out ($Z_j = 1$ if it is, $Z_j = 0$ otherwise)
$p_{j,t}^{cyc}$	Supplied active demand to WA cycle j at time period t
$q_{j,t}^{cyc}$	Supplied reactive demand to WA cycle j at time period t
δ_j	Delay in initiating the cycle j

Functions

$C_b^{inv}(\cdot)$	Annuitized reinforcement cost of branch b
$p'_{n,t}(\cdot)$	Active power injection at node n and period t
$q'_{n,t}(\cdot)$	Reactive power injection at node n and period t
$s_{b,t}^{sen}(\cdot)$	Apparent power flow leaving the reference sending node on branch b and period t
$s_{b,t}^{rec}(\cdot)$	Apparent power flow reaching the reference sending node on branch b and period t

INTRODUCTION

The objective of distribution network planning lies in balancing the network investment cost against the *customer interruption cost* (CIC) in order to minimize the total network expenditure [1]-[3]. As the level of network capacity increases, reliability of supply is increased (i.e. CIC is decreased) at the expense of higher network investment costs. The optimal network capacity provides the best trade-off between these two cost components.

However, the traditional operation and planning framework makes oversimplifying assumptions regarding customers' supply valuation and flexibility. More specifically, this supply valuation is generally expressed in the form of a constant *value of lost load* (VoLL), which represents the marginal cost the customers place on an additional unit of unsupplied demand. This means that each unit of customers' demand at each time period is either supplied or shed at a cost determined by the VoLL.

A large number of researchers have demonstrated however that customers' supply valuation and flexibility cannot be fully captured through the concept of VoLL [4]-[6]. For most load appliances, instead of simply avoiding using them and "losing" their energy requirements, customers are more likely to shift their operation in time. This temporal redistribution of their appliances' operation certainly implies an inconvenience cost for the customers, which is however lower than the cost associated with a "lost" unit of demand (VoLL). In order to properly take into account this *time-shifting flexibility* potential, two aspects need to be incorporated in distribution network operation and planning: i) the time-coupling operating constraints of time-shiftable appliances, and ii) the inconvenience cost associated with time-shifting, which can be defined as a function of the duration of time the customers shift the operation of their appliances by.

The main reason behind the above shortcomings of the current framework is the lack of observability of customers' supply valuation and flexibility as well as the lack of real-time controllability of their demand. However, the emerging *smart grid* paradigm and the envisaged roll-out of *smart metering* [7] provides a unique opportunity for customers to communicate their flexibility and valuation characteristics to the distribution network operators (DNOs) and the latter to automatically coordinate the customers' demand accordingly.

Building on this opportunity, this paper outlines a novel distribution operation and planning framework integrating the above two aspects of customers' time-shifting flexibility. The paper focuses specifically on *wet appliances (WA) with delay functionality*, including dishwashers, washing machines and tumble dryers, given their significant penetration, energy consumption and time-shifting flexibility [8].

MODELING WET APPLIANCES WITH DELAY FUNCTIONALITY

The operation of WA is based on the execution of user-called cycles with generally fixed duration and fixed power profile that cannot be altered. Traditional WA were operated inflexibly; in other words, as soon as the users activated their WA, the latter would start immediately their respective cycles. However, technological developments have enabled automated delay of their cycle initiation; the users can pre-determine the latest time by which the cycle should be ended (latest desired termination time) and the cycle can be initiated any time after the appliance is activated, as soon as it ends before the latest termination time. Fig. 1 illustrates this flexibility characteristic, with the solid and the dashed power profiles corresponding to two different options regarding the cycle initiation.

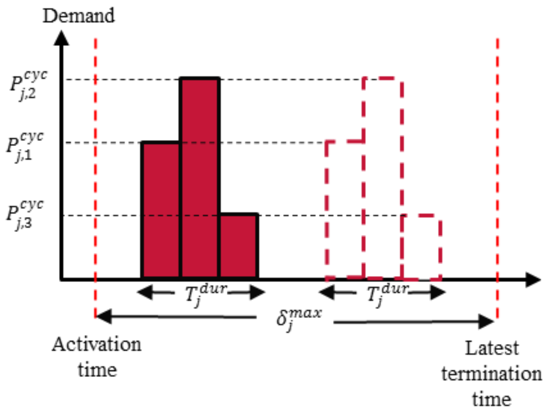

Fig. 1: Illustration of time-shifting flexibility of WA with delay functionality

However, the delay of the cycle initiation implies that customers experience an inconvenience cost which is naturally increasing with the duration of the delay. In this work, this inconvenience cost is assumed linearly increasing with the duration of the delay, as illustrated in Fig. 2. The inconvenience cost is naturally zero if the cycle is not delayed; furthermore, the inconvenience cost corresponding to the maximum delay limit set by the users is assumed equal to VoLL as beyond this limit the WA cycle cannot be carried out and the WA energy requirement will be shed. Therefore, the slope of the inconvenience cost function associated with WA cycle j is expressed as:

$$a_j = VoLL/\delta_j^{max} \tag{1}$$

It should be noted that accurate modeling of the inconvenience cost function requires suitable surveys, interviews or field trials, which are out of the scope of this paper.

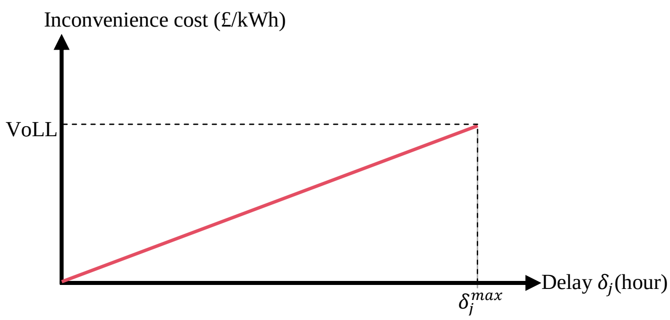

Fig. 2: Inconvenience cost function

DISTRIBUTION NETWORK PLANNING MODEL

The objective of distribution network planning lies in determining the optimal network investments minimizing the total network expenditure. Employing an AC power flow model, the planning procedure is expressed by the following optimization problem:

$$\min_{\boldsymbol{V}} \sum_{b\in B} C_b^{inv}(u_b) + \left(\frac{1}{T}\right)\left(\sum_{i\in I}\sum_{f\in F}\left(\sum_{t\in T_f} VoLL \times (P_{i,t}-p_{i,t}) + \sum_{j\in J_{i,f}}\left((1-Z_j)\times VoLL \times E_j^{cyc} + Z_j \times a_j \times \delta_j \times E_j^{cyc}\right)\right)\right) \quad (2)$$

Subject to:

$$\boldsymbol{V} = [u_b, \forall b \in B] \cup [p_{i,t}, \forall i \in I, \forall f \in F, \forall t \in T_f] \cup [z_{j,t}, \forall f \in F, \forall t \in T_f, \forall i \in I, \forall j \in J_{i,f}] \cup [v_{n,t}, \theta_{n,t}, \forall n \in N, \forall f \in F, \forall t \in T_f] \quad (3)$$

$$0 \le p_{i,t} \le P_{i,t}, \forall i \in I, \forall f \in F, \forall t \in T_f \quad (4)$$

$$q_{i,t} = (p_{i,t})\tan(\cos^{-1}(pf_i)), \forall i \in I, \forall f \in F, \forall t \in T_f \quad (5)$$

$$z_{j,t} = 0, \forall\, t < \tau_j^{act} \text{ or } t > \tau_j^{act} + \delta_j^{max}, \forall f \in F, \forall t \in T_f, \forall i \in I, \forall j \in J_{i,f} \quad (6)$$

$$Z_j = \sum_{t\in T_f} z_{j,t} \le 1, \forall f \in F, \forall i \in I, \forall j \in J_{i,f} \quad (7)$$

$$\delta_j = \left(\sum_{t\in T_f} z_{j,t} \times t\right) - t_j^{act}, \forall f \in F, \forall i \in I, \forall j \in J_{i,f} \quad (8)$$

$$p_{j,t}^{cyc} = \sum_{\tau=1}^{T_j^{dur}} z_{j,t-\tau-1} \times P_{j,\tau}^{cyc}, \forall f \in F, \forall t \in T_f, \forall i \in I, \forall j \in J_{i,f} \quad (9)$$

$$q_{j,t}^{cyc} = (p_{j,t}^{cyc})\tan(\cos^{-1}(pf_i)), \forall f \in F, \forall t \in T_f, \forall i \in I, \forall j \in J_{i,f} \quad (10)$$

$$p'_{n,t}(\boldsymbol{v_t}, \boldsymbol{\theta_t}) = \sum_{i\in I_n}(p_{i,t} + \sum_{j\in J_{i,f}} p_{j,t}^{cyc}), \forall n \in N, \forall f \in F, \forall t \in T_f \quad (11)$$

$$q'_{n,t}(\boldsymbol{v_t}, \boldsymbol{\theta_t}) = \sum_{i\in I_n}(q_{i,t} + \sum_{j\in J_{i,f}} q_{j,t}^{cyc}), \forall n \in N, \forall f \in F, \forall t \in T_f \quad (12)$$

$$\underline{v} \le v_{n,t} \le \overline{v}, \forall n \in N, \forall f \in F, \forall t \in T_f \quad (13)$$

$$s_{b,t}^{sen}(\boldsymbol{v_t}, \boldsymbol{\theta_t}) \le \overline{s_b}(u_b, \zeta_{b,t}), \forall b \in B, \forall f \in F, \forall t \in T_f \quad (14)$$

$$s_{b,t}^{rec}(\boldsymbol{v_t}, \boldsymbol{\theta_t}) \le \overline{s_b}(u_b, \zeta_{b,t}), \forall b \in B, \forall f \in F, \forall t \in T_f \quad (15)$$

The objective function (2) represents the expected annual network expenditure, given by the sum of: i) the annuitized investments costs (first term) and ii) the expected annual operating costs which are in turn given by the summation of ii.a) the expected annual interruption costs associated with inflexible demand (second term), ii.b) the expected annual interruption costs associated with WA cycles (incurred when the respective cycle is not carried out) and ii.c) the expected annual inconvenience costs associated with WA cycles (incurred when the respective cycle is delayed).

The decision variables (3) include: i) the binary reinforcement decisions for each network asset, ii) the supplied power to the inflexible load of each customer i, iii) the binary WA cycle initiation decisions and iv) the nodal voltage magnitudes and angles.

The constraints include: i) the constraints of the inflexible demand of each customer i (4)-(5) (assuming that each customer is characterized by a constant, uncontrollable power factor), ii) the operating constraints associated with each WA cycle j (6)-(10) and iii) the power balance (11)-(12), voltage (13) and thermal (14)-(15) constraints of the network.

Failures of each network asset for a period of T years are generated by employing *Sequential Monte Carlo* (SMC) simulation [9], given probability distributions for failure occurrence and repair time corresponding to each asset. Only the time periods $t \in T_f, \forall f \in F$ and only the WA cycles activated during these periods are considered in the above optimization problem. The set T_f includes the periods during which failure f occurs as well as the first $\max_j \delta_j^{max}$ periods after the end of failure f, in order to account for inconvenience costs of cycles that are deferred to times after the end of failures. The integer parameters $\zeta_{b,t}$ determine the state of branch b at each of these time periods t, according to the generated failures. In the case of substations, these parameters determine the number of transformers that operate normally, while in the case of feeders, these parameters determine whether the feeder operates normally ($\zeta_{b,t} = 1$) or experiences a failure ($\zeta_{b,t} = 0$).

CASE STUDIES

Test System and Implementation

Case studies are carried out on a typical UK HV distribution network, composed of a primary substation with two 33/11kV transformers with an on-load tap changer providing voltage regulation in the range of $\pm 10\%$ of the nominal value, and two 11kV cable feeders, with the length of each feeder section assumed equal to 1km (Fig. 3). Nodal voltages need to be maintained within the UK statutory limits of $\pm 6\%$ of the nominal value. Under normal operation conditions, the network operates with a radial configuration. If a failure occurs at one of the feeders, the normally open switch (NOS) is closed instantly to provide alternative infeed. The substation can be reinforced by adding a third transformer of the same size with the existing ones, with an investment cost of £10,000/MVA/year. Feeders can be reinforced by replacing simultaneously all sections with cables of double size, with an investment cost of £1,000/km/year.

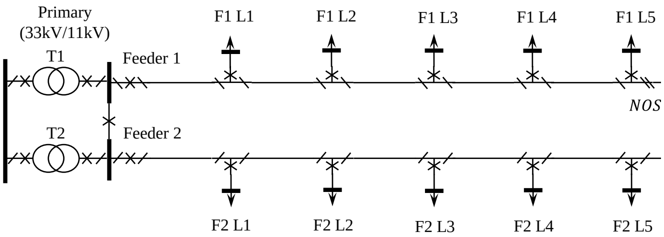

Fig. 3. Test distribution network

Three different scenarios are considered regarding the reliability of the network, each characterized by a different combination of failure rate and repair time for each of the transformers and feeder sections (Table I). For each of these scenarios, failures of each transformer and feeder section for a period of $T = 1000$ years are generated by the SMC simulation model @Risk [10].

TABLE I
EXAMINED NETWORK RELIABILITY SCENARIOS

Reliability scenario	Asset	Failure rate	Repair time
Low	Transformer	0.2 f/year	5 days
	Feeder	0.2 f/year/km	10 hours
Medium	Transformer	0.2 f/year	1 day
	Feeder	0.1 f/year/km	5 hours
High	Transformer	0.02 f/year	1 day
	Feeder	0.05 f/year/km	3 hours

The network customers include 10000 households with a *current* total peak demand of 9.9MW, equally divided between the ten load points. The households are assumed to exhibit the same daily inflexible demand (excluding WA) profile. The VoLL has been set equal to £16.94/kWh [10]. Different scenarios regarding the size of inflexible demand are considered in order to systematically investigate the value of WA flexibility in distribution operation and planning.

Three different types of WA are considered, namely dishwashers (DW), washing machines (WM) and integrated washer-dryers (WD), operated in 53%, 35% and 60% of the households respectively, according to the statistics presented in [8]. Typical power demand profiles of their cycles and diversified activation times are taken from [8], assuming that each WA is activated once every day. The power factor of both inflexible demand and WA is assumed equal to 0.9. In order to systematically investigate the value of WA flexibility, two different sensitivity analyses are carried out around i) the penetration of WA with delay functionality as a percentage of the total number of WA and ii) the maximum delay limit of WA with delay functionality (Table II).

TABLE II
WA SENSITIVITY ANALYSES

	Penetration	Maximum delay
Study 1	Varying (0%, 50%, 100%)	Fixed (10h)
Study 2	Fixed (100%)	Varying (0h, 5h, 10h)

Given the failures generated by @Risk, the optimal distribution network planning problem (2)-(15) is solved using the optimization software FICO Xpress [12].

Fig. 4-5 present the expected annual operating costs of the existing network (without reinforcement of the substation or the feeders) in sensitivity studies 1 and 2 respectively, for each of the examined network reliability scenarios and different scenarios regarding the size of inflexible demand (a scenario of X% implies that the inflexible demand at each time period is X% higher than the current demand).

For every network reliability and inflexible demand scenario, a higher penetration of WA with delay functionality, results in significantly lower operating costs (Fig. 4). This is because the DNO can defer the cycles of these WA to periods when failures have been restored instead of shedding demand during these failures, and the inconvenience cost associated with WA cycle delay is lower than the interruption cost expressed by the VoLL.

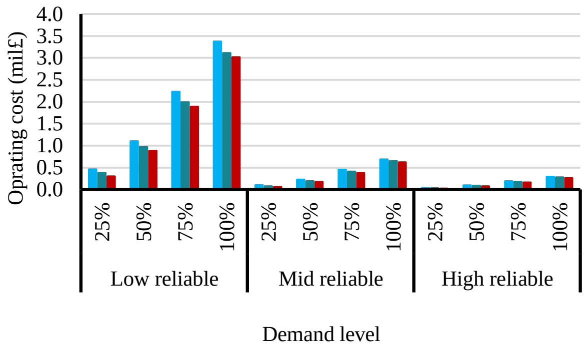

Fig. 4. Expected annual operating costs of existing network for different penetrations of WA with delay functionality

The operating costs are also reduced as the maximum delay limit of WA is increased (Fig. 5), since the DNO has higher flexibility in deferring the WA cycles and the slope of the inconvenience cost function is lower (1), implying that a certain delay of a WA cycle yields lower inconvenience cost.

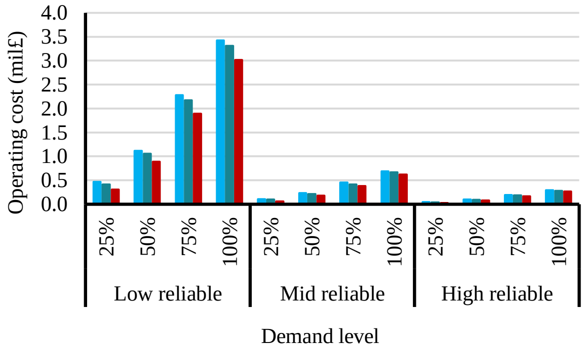

Fig. 5. Expected annual operating costs of existing network for different maximum delay limits of WA with delay functionality

Furthermore, this operating costs reduction is more prominent in scenarios with a lower level of network reliability and a higher level of inflexible demand, since the requirements for demand shedding in the absence of flexible WA are aggravated. This result indicates that operating benefits of WA flexibility are enhanced in networks with less reliable assets (assets characterized by higher frequency of failures and longer repair time), and low redundancy levels (operating closer to their statutory limits).

As a result of this operating costs reduction, WA flexibility tends to postpone the need for network reinforcements. This is demonstrated by Fig. 6-7, which present the level of inflexible demand increase (in % with respect to the current demand) for which reinforcement of the substation and the feeders is required, in sensitivity studies 1 and 2 respectively and for each of the examined network reliability scenarios. A higher percentage implies that the respective network reinforcements can be further postponed in time and therefore implies economic benefits, due to the diminishing value of money in time.

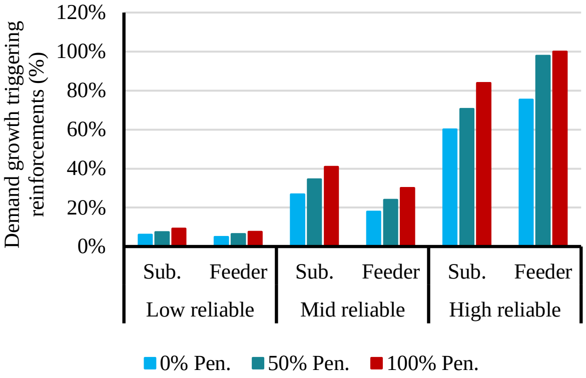

Fig. 6. Demand increase triggering network reinforcement for different penetrations of WA with delay functionality

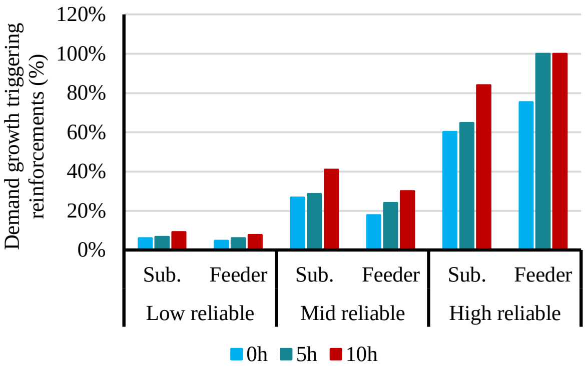

Fig. 7. Demand increase triggering network reinforcement for different maximum delay limits of WA with delay functionality

For every network reliability scenario, a higher penetration of WA with delay functionality and a higher maximum delay limit postpone network reinforcements further. Furthermore, this reinforcement deferral effect is less prominent in scenarios with a lower level of network reliability, since the higher operating costs justify much sooner network reinforcements.

CONCLUSIONS

Although customers' demand has been traditionally assumed as either supplied or shed at a cost determined by a benchmark value of lost load, the largest part of their demand can be shifted in time. This paper has proposed a model of distribution network operation and planning integrating the time-shifting flexibility of load appliances and accounting for the associated customers' inconvenience cost. The paper has focused specifically on wet appliances with delay functionality, given their significant penetration, energy consumption and time-shifting flexibility. Case studies on a typical UK HV distribution network have demonstrated that the operation of time-shiftable WA can be deferred to periods when failures are restored, reducing customers' interruption costs and consequently postponing network reinforcements.

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