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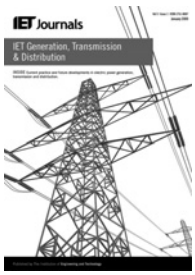

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Distribution network reliability improvements in presence of demand response

Amir Safdarian[1,2], Merkebu Z. Degefa[1], Matti Lehtonen[1], Mahmud Fotuhi-Firuzabad[2]

[1]*Department of Electrical Engineering, Aalto University, Espoo, Finland*
[2]*Department of Electrical Engineering, Center of Excellence in Power System Control and Management, Sharif University of Technology, Tehran, Iran*
E-mail: matti.lehtonen@aalto.fi

Abstract: Demand response (DR) as a key integral part of the future smart grid is gaining a great and still growing focus of attention in nowadays electric power industries. However, many potential benefits of DR, although they have been envisioned to be significant, have not been yet thoroughly and quantitatively investigated. DR provides network operators with the opportunity to mitigate operational limit violations by load modification in place of load shedding when network reliability is jeopardised. This paper aims to comprehensively assess the potential impacts of DR on major attributes of service reliability in a residential distribution network. For doing so, firstly, load profiles for major residential appliances are extracted from grossly metered consumptions. Secondly, the flexibility associated with individual load profiles is estimated using the statistical data gathered through surveys and questionnaires. Thirdly, for every contingency, appliance level load profiles are modified based on their flexibilities such that the least possible interruption cost is realised. The obtained results are finally combined to calculate service reliability indices. The proposed framework is applied to Finnish distribution system and the obtained results demonstrate the efficiency and applicability of the proposed approach in real-world systems.

Nomenclature

Indices and sets

a, A	index and set of responsive appliances
i, i', I	indices and set of network buses
t, t', T	indices and set of time intervals

Parameters and constants

$G_{i,i'}$, $B_{i,i'}$	real and imaginary parts of the respective element in the bus admittance matrix
$PD_{i,t}^{R,a}$, $QD_{i,t}^{R,a}$	active and reactive demand associated with appliance a at bus i and time t
$PD_{i,t}^{\mathrm{NR}}$, $QD_{i,t}^{\mathrm{NR}}$	active and reactive demand of nonresponsive appliances at bus i and time t
$PQR^{R,a}$	active to reactive power ratio of responsive appliance a
$PQR_{i,t}^{\mathrm{NR}}$	active to reactive power ratio of nonresponsive loads at bus i and time t
PL_i	penetration level of active consumers at bus i
$\overline{S}_{i,i'}$	capacity of the line from bus i to bus i'
$\overline{V}$, $\underline{V}$	upper and lower allowed voltage magnitudes
VOLL_i	value of lost load at bus i
$b_{i,i'}^t$	binary indicator denoting up/down status of line from bus i to bus i' at time t

Functions and variables

$P_{i,i'}^t$, $Q_{i,i'}^t$	active and reactive power flow through the line from bus i to bus i' at time t
$PC_{i,t}^{R,a}$, $QC_{i,t}^{R,a}$	active and reactive curtailed load of responsive appliance a at bus i and time t
$PC_{i,t}^{\mathrm{NR}}$, $QC_{i,t}^{\mathrm{NR}}$	active and reactive curtailed nonresponsive load at bus i and time t
$PS_{i,t,t'}^{R,a}$, $QS_{i,t,t'}^{R,a}$	active and reactive demand of appliance a at bus i which is shifted from time t to time t'
$S_{i,i'}^t$	apparent power flow through the line from bus i to bus i' at time t
V_i^t, δ_i^t	voltage magnitude and phase angle at bus i and time t

1 Introduction

In recent years, significant attention has been devoted to the role of demand response (DR) programs in enhancing the efficiency of the electric power industry. A large number of project reports, research articles and books have been published on the subject mostly focusing on DR potentials and benefits [1–8]. From a customer's points of view, DR programs provide the opportunity to manage its consumption and make cost savings on electricity bills [1]. From the market perspectives, DR helps to temper price spikes and volatility as well as to mitigate the potential of

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market powers and abuses [2]. From the view of a network operator, DR is able to reduce peak demand, thereby realising operational and capital cost savings. It will alleviate the need to operate high-cost and high-emission generating units [3, 4]. Also, it may avoid, or at least defer, the need for network reinforcement [5]. Besides, flexible loads enabled by DR are perfect complements to inherently variable energy resources such as wind and solar [6]. Finally, DR may shape load profiles to avoid widespread blackouts at critical times when service reliability is jeopardised [7, 8]. The value of these benefits, although proven to be notable, must be studied quantitatively to demonstrate their efficacy prior to any practical implementation [2, 9–11].

In recent years, remarkable efforts have been dedicated to quantify DR potentials and benefits. A comprehensive review of published research on the topic of DR was provided in [12] where DR benefits and implementation challenges were discussed as well. A review of the concept of DR, its benefits and costs, and some real-world experiences was presented in [13]. It was reported that DR programs, applied to very-large industries, represent 6.5% of peak power in Italy [13]. In [10], it was reported that application of DR reduces UK peak demand by more than 15%. According to a survey conducted by Federal Energy Regulatory Commission in 2012, the potential of USA DR was estimated to be about 9.2% of USA peak load [11]. In [14], it was estimated that USA energy efficiency and DR programs can realise an annual incremental reduction of 0.4–0.85% in the rate of increase in electricity consumption per year. Lui *et al.* [5], using a rule of thumb, estimated the economic and environmental benefits provided by displacing the operation period of major residential appliances. All of the reported works are valuable but they overlooked DR impacts on service reliability. This is despite of the significant reliability benefits of DR which convinced the North American electric reliability corporation to establish a regular data collection system and a semi-annual report to measure and announce the contribution of DR to service reliability issues [11].

In the existing literature, few studies have addressed the impacts of DR programs on service reliability. In [7], DR capabilities of a large producer of aluminium products in providing reliability services were studied. This study was focused on a single customer with certain characteristics. In [8], the required amount of available load reduction at different load points was estimated such that voltage collapse is prevented. In [15], service reliability indices were compared before and after modifying a load profile in response to wholesale market prices. In fact, this work focused on DR potentials which can be enabled by time-varying prices, but not by direct load control. A qualitative analysis on the impact of DR on distribution system reliability was provided in [16]. In [17], a simple DR model was used to estimate unreliability cost in transmission expansion studies.

Based on the above discussions, it is necessary to gain a more precise insight into the problem. This paper presents a framework to quantify the reliability benefits of activating DR potentials. It is worthwhile to mention that enabling DR potentials has direct and indirect benefits to electricity service reliability. DR allows network operators to alleviate operational limit violations in place of load shedding when network reliability is jeopardised. The reduced amount of load shedding during operational limit violations is referred to as direct benefits of DR to service reliability. On the other hand, realisation of DR, by reducing demand at peak periods, can reduce thermal stress on network assets, thereby reducing the number of outage events. Needless to say, the reduced number of outage events is an indirect benefit of DR to service reliability. Although indirect benefits can also be significant, the focus of this paper is to quantify the direct benefits caused by preventing load shedding when network operational limits are violated.

In order for the conclusions to be practical, a clear understanding of load characteristics is vital. Hence, hourly metred consumption of a large group of residential customers from Kainuu, Finland is studied and respective features are extracted. Then, the obtained features along with customers' flexibility, derived from survey data, are used to estimate available DR at different time intervals. Thereafter, for each likely contingency, the estimated DR potentials are employed such that the least possible damage cost is realised. Finally, the obtained results are used to calculate service reliability indices.

2 Assessment of DR capability

Knowledge of DR capability is a prerequisite for evaluating its potential benefits. DR capability, as the amount of load that is deferrable over various time scales, is directly related to customers' willingness to vary their electric usage in response to the signals released by utilities. In the past, there existed a limited DR capability since customers were passive players with inflexible demand. Passive customers plug in their devices, consume electricity and pay their bills. They do not receive any signal from their utility and accordingly they do not care about the things that are happening in the electric generation and delivery systems. However, thanks to smart grid technologies, more active customers are envisioned in the near future [1]. Active customers simply modify the operation of their responsive appliances upon receiving a signal from their utility [5]. Responsive appliances are those whose operation time and/or energy usage can be changed without sacrificing customers comfort. For instance, a dish washer, whose owner is not in a hurry (thus, its operation can be deferred), is a responsive load.

Available DR capability at a specific time depends on the responsive appliances that are operating at that time and their flexibility in operation. The flexibility of each appliance depends on its own characteristics and the owner preferences. In order to estimate DR capability, the three questions described in the following should be answered.

2.1 Which appliances are responsive?

Potential responsive appliances are identified considering their performance, their energy use profile and purposes for which they are to be used. As discussed earlier, responsive appliances are flexible in operation time and/or energy usage. For example, the operation time of a dishwasher can be postponed as long as its washing cycle is completed by the next meal. As another instance, consider a clothes dryer whose operation period can be prolonged by choosing a program with a lower desired temperature in order to reduce its power demand. Finally, the operation of an air conditioner can be simply interrupted for a certain period as far as the room temperature is within a desirable range. All of these appliances are flexible in their operation; hence, they are responsive.

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In contrast to the responsive appliances, normal operation of some appliances cannot be interrupted, or even displaced in time, since it may cause an adverse impact on customers comfort. These are referred to as nonresponsive loads. A personal computer, cooking appliances and entertainment facilities are examples for nonresponsive loads.

Besides the mentioned loads that can be clearly assigned to the mentioned two categories, there exist few other appliances whose operation is more complex. In fact, they are neither pure responsive nor pure nonresponsive. Refrigerators and freezers are samples for these loads. For the sake of illustration, consider a typical refrigerator whose energy use profile over a 24 h period is shown in Fig. 1 [5]. As can be seen, the refrigerator consumes electricity for compressor, defrost and ice maker cycles [18]. Although the load profile of the refrigerator depends on some out of control factors such as its efficiency and ambient conditions, it can also be manipulated artificially by displacing defrost and ice maker cycles in time. However, interrupting the compressor operation for a long period may influence the food quality or even cause spoilage. In other words, the portion of energy consumed for defrost and ice maker cycles is responsive and the remaining is nonresponsive. Hence, a refrigerator is a partly responsive appliance.

Interested readers are referred to [18] for comprehensive data on the performance of major residential appliances. The most popular responsive appliances in nowadays homes are dishwashers, clothes washers, clothes dryers, heating and ventilation systems, freezers and refrigerators [18].

2.2 What is the operation time of each responsive appliance?

Since responsive appliances can respond to utility signals at the time they are operating, knowledge of their individual operation time is essential for investigating their DR capability. However, operation time of a responsive appliance is tied to the owners' habits and life style which widely vary among customers and also during the time. Accordingly, historical data can be used to get a fair insight into the average operation times. Data mining techniques such as conditional demand analysis and neural network can also be utilised to extract appliance level profiles from grossly metered profiles.

In this paper, the hourly consumption of 1630 customers from Kainuu, Finland, for the time span from mid-2008 to mid-2009 is utilised. A questionnaire was sent to the customers from which useful information on the heating and ventilation systems, electric appliances and consumption habits were gathered. The conditional demand analysis method [19] was applied to the collected data, and two average load profiles per season for individual major appliances were obtained. These two profiles correspond to weekdays and weekends. Figs. 2 and 3 show the average energy consumption profiles for dish washing and heating and ventilation during weekdays in a typical house.

In the above, appliance level load profiles for weekdays and weekends in different seasons are derived. Clearly, the total load profile for a typical customer can be obtained by summing up the load profiles. Figs. 4 and 5 demonstrate the share of the major appliance groups in the total load profile for weekdays in summer and winter, respectively. Note that refrigerators and freezers are cold appliances, whereas dishwashers and clothes washing machines are wet appliances.

Having prepared the above data sets, responsive and nonresponsive load profiles are determined using the appliance and customer habits data. Figs. 6 and 7 show the obtained profiles in weekdays of summer and winter, respectively. As can be seen, much more DR is available during the cold season exactly when it is highly requested. This is because of the fact that a great portion of electricity usage during winters is accounted for heating and ventilation which is assumed to be responsive.

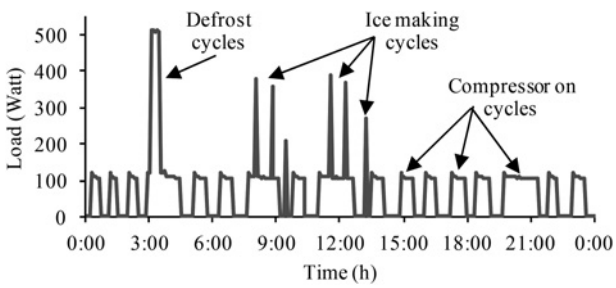

Fig. 1 *Possible electricity use profile for a typical refrigerator*

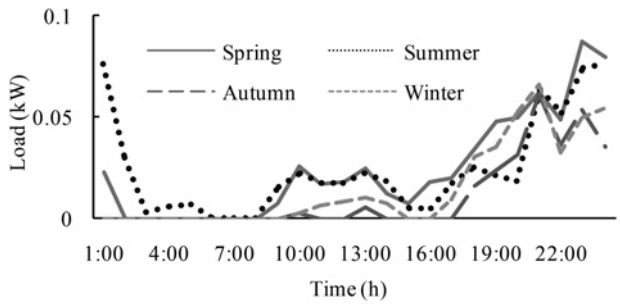

Fig. 2 *Weekdays load profile for dish washing in a typical house*

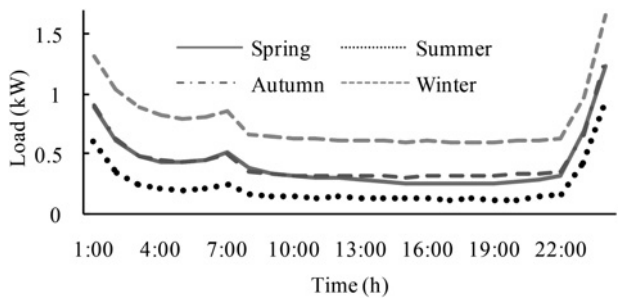

Fig. 3 *Weekdays load profile for heating and ventilation*

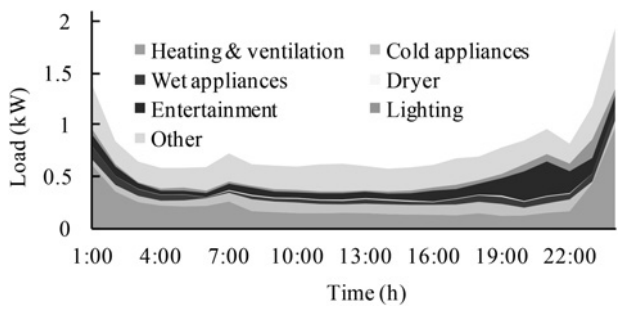

Fig. 4 *Appliance level load profiles (summer weekdays)*

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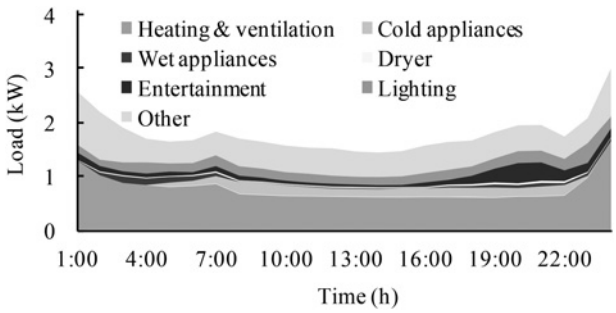

Fig. 5 *Appliance level load profiles (winter weekdays)*

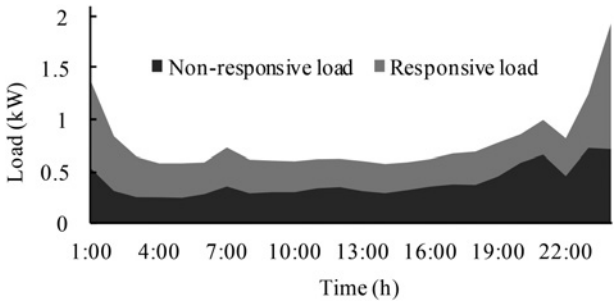

Fig. 6 *Responsive and nonresponsive load profiles (summer weekdays)*

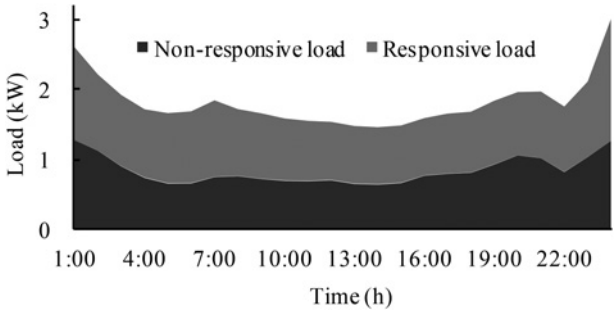

Fig. 7 *Responsive and nonresponsive load profiles (winter weekdays)*

2.3 How flexible is each responsive appliance?

The potential responsive appliances and their availability were determined. Flexibility of the responsive appliances, as another parameter affecting DR capability, is discussed in this section. In this paper, the flexibility is modelled by the customers' acceptable delay time (ADT) and active customer penetration level.

ADT denotes the maximum period of time that operation of an appliance can be postponed without sacrificing customer comfort. Clearly, ADT for nonresponsive loads is zero since any delay in their operation disturbs customers. In general, ADT value differs between customers and appliances. But, because of the lack of information and in order to avoid computational complexities, average ADT values over the customers can be utilised. Information on ADT values for different appliances can be estimated from survey data. Stamminger [18] also provides typical ADT values for the major residential appliances. Table 1 gives the ADT values utilised in this study.

Table 1 ADT value (minute) for the responsive appliances

Appliance	ADT	Appliance	ADT
heating and ventilation	120	dishwasher	300
clothes dryer	40	freezer	25
clothes washer	90	refrigerator	30

Active customer penetration level represents customers' willingness to respond and is the ratio of active customers to the total number of customers. Lack of effective automation systems and knowledge among customers about how to respond are major barriers preventing the customers to become active [1]. Although the penetration level is small these days, thank to smart grid technologies, larger levels are envisioned in the near future.

3 Reliability evaluation procedure

This section provides the algorithm employed for assessing the reliability of distribution networks. The flowchart of the algorithm is depicted in Fig. 8. The procedure devised in this figure is as follows.

Step 1: The first step is to gather data about the network under study and its operational logics. The operational procedures should be clearly known for different conditions that may occur in the network.
Step 2: The algorithm has a loop going over the set of likely fault scenarios. A fault scenario, in this paper, denotes the respective fault location and time. Fault time is important since the system load and DR capability are not the same over time.
Step 3: A network reconfiguration analysis is carried out taking into account the fault location, normal operating

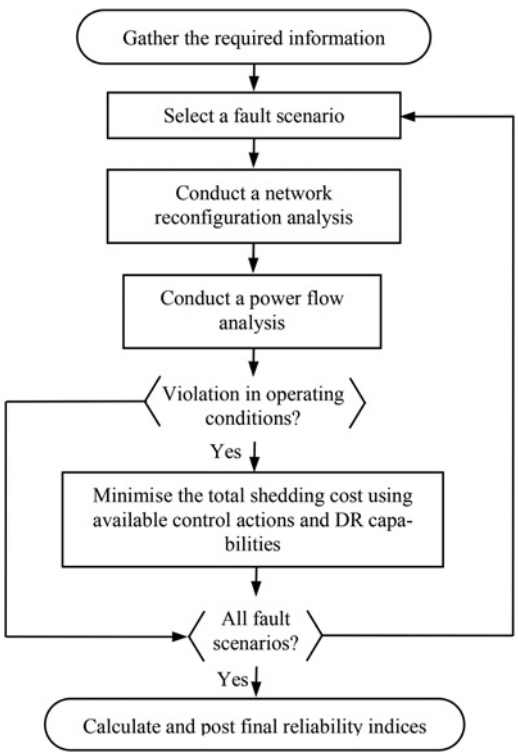

Fig. 8 *Flowchart of the algorithm used for network reliability*

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status and type of switching devices, switching time and repair time. The network is reconfigured such that the number of load points whose service is affected by the fault is minimised. In this step, network configurations before and after the switching time, and after repair time of the faulted line are determined. In other words, the value of $b^t_{i,i'}$; $\forall i, i' \in I, \forall t \in T$ is determined in this step.

Step 4: A power flow analysis is performed. If any violation in the network operating conditions, for example, overload and/or under voltage, is recognised, appropriate remedial actions are taken where the load shedding is the last resort. It is worthwhile to mention that, in the case of under voltages, if they are not much severe such that loads can work properly, no remedial action should be taken into account. In more severe cases, adjusting reactive power controllers can be used to mitigate under voltage violations as an effective remedial action. DR, as a remedial action, should only be utilised after this step. The objective of the remedial actions is to minimise the total damage cost of the load shedding. This procedure is simulated with an optimisation problem whose objective is to find the optimal load shaping and shedding. The formulation of the optimisation problem is presented in the following of this section.

Step 5: Once the above steps are iterated over the set of likely contingencies, reliability indices can be calculated.

3.1 Formulation

The optimisation problem, introduced in Step 5, is formulated as follows

$$\text{Minimize} \sum_i \sum_t \text{VOLL}_i PC^{\text{NR}}_{i,t} + \sum_i \sum_t \sum_a \text{VOLL}_i PC^{R,a}_{i,t} \tag{1}$$

The first and second parts in (1), respectively, represent the load curtailment cost of nonresponsive and responsive loads. The following two sets of equations are considered to ensure the bus-level power balance

$$PD^{\text{NR}}_{i,t} + \sum_a PD^{R,a}_{i,t} + \sum_a \sum_{t'} PS^{R,a}_{i,t',t} + \sum_{i'} P^t_{i,i'} = PC^{\text{NR}}_{i,t} + \sum_a PC^{R,a}_{i,t} + \sum_a \sum_{t'} PS^{R,a}_{i,t,t'}; \quad \forall i \in I, \quad \forall t \in T \tag{2}$$

$$QD^{\text{NR}}_{i,t} + \sum_a QD^{R,a}_{i,t} + \sum_a \sum_{t'} QS^{R,a}_{i,t',t} + \sum_{i'} Q^t_{i,i'} = QC^{\text{NR}}_{i,t} + \sum_a QC^{R,a}_{i,t} + \sum_a \sum_{t'} QS^{R,a}_{i,t,t'}; \quad \forall i \in I, \quad \forall t \in T \tag{3}$$

The following equations are used to calculate active and reactive line power flows

$$P^t_{i,i'} = b^t_{i,i'} G_{i,i'} V^{t2}_i + b^t_{i,i'} V^t_i V^t_{i'} G_{i,i'} \cos(\delta^t_i - \delta^t_{i'}) + b^t_{i,i'} V^t_i V^t_{i'} B_{i,i'} \sin(\delta^t_i - \delta^t_{i'}); \quad \forall i \in I, \quad \forall i' \in I, \quad \forall t \in T \tag{4}$$

$$Q^t_{i,i'} = -b^t_{i,i'} B_{i,i'} V^{t2}_i + b^t_{i,i'} V^t_i V^t_{i'} G_{i,i'} \sin(\delta^t_i - \delta^t_{i'}) - b^t_{i,i'} V^t_i V^t_{i'} B_{i,i'} \cos(\delta^t_i - \delta^t_{i'}); \quad \forall i \in I, \quad \forall i' \in I, \quad \forall t \in T \tag{5}$$

The following three sets of expressions are incorporated to ensure that the power factor remains constant when a portion of load is curtailed or shifted to another time

$$PC^{\text{NR}}_{i,t} = PQR^{\text{NR}}_{i,t} QC^{\text{NR}}_{i,t}; \quad \forall i \in I, \quad \forall t \in T \tag{6}$$

$$PS^{R,a}_{i,t} = PQR^{R,a} QS^{R,a}_{i,t}; \quad \forall i \in I, \quad \forall a \in A, \quad \forall t \in T \tag{7}$$

$$PC^{R,a}_{i,t} = PQR^{R,a} QC^{R,a}_{i,t}; \quad \forall i \in I, \quad \forall a \in A, \quad \forall t \in T \tag{8}$$

Bus voltage limits are taken into account as follows

$$\underline{V} \le V^t_i \le \overline{V}; \quad \forall i \in I, \quad \forall t \in T \tag{9}$$

The following sets of constraints compel line flows to be within the associated limits

$$-\overline{S_{i,i'}} \le S^t_{i,i'} \le \overline{S_{i,i'}}; \quad \forall i \in I, \quad \forall i' \in I, \quad \forall t \in T \tag{10}$$

$$S^t_{i,i'} = \sqrt{P^{t2}_{i,i'} + Q^{t2}_{i,i'}}; \quad \forall i \in I, \quad \forall i' \in I, \quad \forall t \in T \tag{11}$$

The range of deployable load curtailment associated with nonresponsive and responsive loads are declared as follows

$$0 \le PC^{\text{NR}}_{i,t} \le PD^{\text{NR}}_{i,t}; \quad \forall i \in I, \quad \forall t \in T \tag{12}$$

$$0 \le PC^{R,a}_{i,t} \le PD^{R,a}_{i,t}; \quad \forall i \in I, \quad \forall a \in A, \quad \forall t \in T \tag{13}$$

The following set of expressions cap the amount of shifted load by the associated limit. As can be seen, the limit is equal to the responsive demand of active customers at respective bus and time

$$0 \le \sum_{t'} PS^{R,a}_{i,t,t'} \le PL_i PD^{R,a}_{i,t}; \quad \forall i \in I, \quad \forall a \in A, \quad \forall t \in T \tag{14}$$

The next set of equations is taken into account to ensure that no responsive load is shifted to an earlier time

$$PS^{R,a}_{i,t,t'} = 0; \quad \forall i \in I, \quad \forall a \in A, \quad \forall t' < t \tag{15}$$

The above problem is established and solved for those contingencies in which at least a violation in operating conditions is occurred. The value of curtailed and shifted loads constitutes the problem outputs.

3.2 Reliability indices

The set of reliability indices calculated and given in this study includes system average interruption frequency index (SAIFI), system average interruption duration index (SAIDI), expected energy not served (EENS), and expected interruption cost (EIC). Interested readers are referred to [20] for the mathematical formula of the above indices.

Finally, although DR capabilities are effective in reducing the needs for load shedding, interrupting or postponing the operation of a responsive load is also undesirable from the reliability perspective. In fact, a distribution network whose

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responsive loads are usually postponed to mitigate capacity and/or voltage violations has a poor reliability level. Accordingly, in order to represent the service quality for responsive loads, expected interruption frequency (EIF), expected interruption duration (EID) and expected postponed energy (EPE) for the interruption of responsive loads are calculated as well. EIF denotes the average interruption rate of responsive loads. EID shows the average interruption duration of deferred loads. EPE represents the expected energy of deferred loads.

4 Numerical results

In this section, DR capabilities and the respective assumptions extracted from the metered and the survey data are applied to a distribution network. After introducing the network under study, a number of contingencies are discussed in detail. Then, system and load point oriented reliability indices are given. A sensitivity analysis on key parameters is the last study of this section. Two different case studies designated as base case and DR enabled case are conducted and the results are compared. Needless to say, DR potentials are not enabled in the base case, whereas the DR enabled case utilises available DR potentials to improve the service reliability.

4.1 Network introduction

An urban Finnish distribution network is studied here. The network, as shown in Fig. 9, feeds 61 distribution substations (20/0.4 kV) through two radial feeders with a normally open tie-line between them. The normally open tie-line can be closed when the network reliability is jeopardised. The network technical data are accessible online at [21].

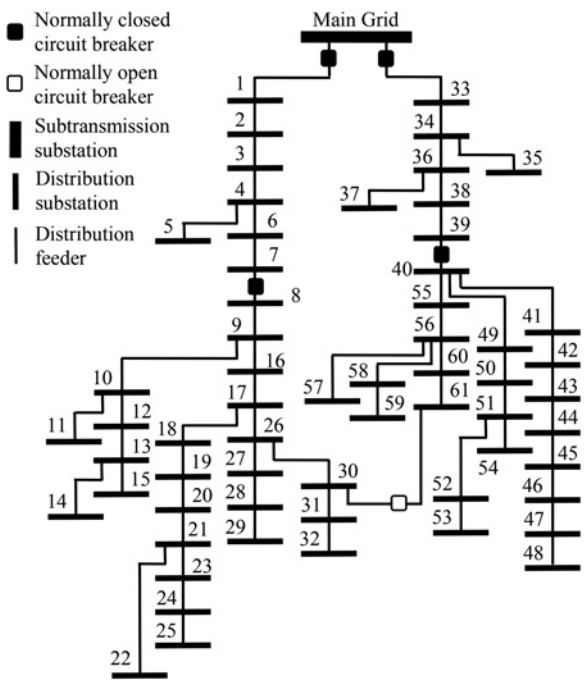

Fig. 9 *Single line diagram of Finnish distribution network under study*

4.2 Some illustrative cases

This section simulates a number of likely contingencies to illustrate the effectiveness of the DR. It should be noted that these contingencies are selected such that the impact of enabling the DR potentials is demonstrated clearly.

Contingency 1: A fault on line 26–30 (see Fig. 9) at 10 am on a summer weekday is followed by the operation of the upstream circuit breaker which leads to the isolation of load points 8–32. The load points will remain isolated for the switching time (here, it is set to 1 h), that is, the faulted line is opened and the opened breaker and the normally open tie-line are closed. Once the switching actions are done, load points 8–29 are fed through the main feeder while load points 30–32 are fed through the neighbouring feeder. The new operating point is consistent since there is not any overloads or under voltages. In the base case, the whole electricity demand of the customers connected to the isolated load points should be curtailed for the switching time. However, in the DR enabled case, the amount of curtailed loads can be reduced by deferring the operation of responsive loads to a time after the service restoration. This can lead to a significant reliability enhancement. Table 2 compares the reliability aspects of the discussed contingency for the two cases. As can be seen, the energy not served and the associated costs are reduced by 36% if the DR potentials are enabled. The point deserving emphasis is that enabling the DR has no impact on the number of the affected load points and the duration of the interruption since the interrupted load points become isolated when the fault occurs and their nonresponsive loads should be curtailed inevitably. It is worthy to mention that the above reliability benefits are achieved by postponing 290.73 kWh responsive load about 0.69 h in average.

Contingency 2: Line 8–9 goes out because of a fault at 7 pm on a winter weekday, the upstream circuit breaker operates, and load points 8–32 are isolated. In the base case, even after the switching time, only few isolated load points can be fed through the neighbouring feeder to avoid an overload condition. In the DR enabled case, before the switching time, the demand flexibility can be used to reduce the amount of load shedding. After the switching time, also, more load points can be fed through the neighbouring feeder if flexibility of the responsive appliances is utilised to mitigate the overload condition. The reliability aspects of the two cases during the discussed contingency are given in Table 3. As can be seen, significant reductions in the interruption duration, the energy not served, and the associated damage cost is achieved when the DR is enabled. The energy not served and the associated cost are reduced by 82 and 79%, respectively. However, the number of affected load points is the same for the two cases since the nonresponsive loads of the isolated load points are curtailed. The reliability benefits

Table 2 Service reliability improvements realised by DR: Contingency 1

Index	Base case	DR enabled
number of affected load points	25	25
average interruption duration, h	1	1
energy not served, kWh	799.55	508.82
damage cost, €	18 025.63	11 471.27

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Table 3 Service reliability improvements realised by DR: Contingency 2

Index	Base case	DR enabled
affected load points	25	25
average interruption duration, h	2.68	1
energy not served, kWh	8310.19	1499.30
damage cost, €	163 496.39	33 801.33

are obtained by deferring 11880.81 kWh responsive load for about 1.55 h in average.

Contingency 3: A fault on Line 21–23 at 1 pm on a spring weekday is followed by operation of the upstream circuit breaker which leads to the isolation of load points 8–32. After the switching time, once the faulted line is opened, the service to load points 8–22 and 26–32 is restored by closing the opened circuit breaker while customers connected to load points 23–25 remain isolated till the end of the repair process of the faulted line. For those customers whose service is restored by the switching actions, the DR can be useful in reducing the amount of energy not served and as such the associated damage cost will reduce. However, the flexibility of the responsive appliances connected to load points 23–25 is not useful anymore since the operation of them cannot be deferred to a time when the repair process is finished. In fact, the ADT value for the responsive appliances is much less than the repair time of the faulted line, that is, 6 h. Table 4 compares the reliability aspects of the discussed contingency for the two cases. Owing to the results, the energy not served and the associated costs are reduced by 29 and 31% when the DR potentials are enabled. These improvements are realised by postponing 563.48 kWh responsive load about 0.85 h in average.

Contingency 4: A fault is occurred on line 6–7 at 10 pm on an autumn weekday, the upstream circuit breaker operates, and load points 1–32 are isolated. By some appropriate switching actions, load points 8–32 are transferred to the neighbouring feeder. In the base case, the loads connected to load points 1–7 are curtailed for the switching time during which the faulted line is opened and the opened breaker is closed. Also, a portion of the loads transferred to the neighbouring feeder should be curtailed to avoid an overload condition. However, in the DR enabled case, operation of the responsive loads in load points 1–7 is postponed to reduce the amount of load curtailment. Also, flexibility of the responsive appliances is utilised to alleviate the overload and hence, to reduce the load curtailments in load points 8–32. Reliability indices associated with the two cases are given in Table 5. As can be seen, a significant improvement in reliability performance of the network is achieved when the DR is enabled. The energy not served and the associated damage costs are reduced by 91 and 87%, respectively. Note that the number of the affected load points is improved since some load points among 8–32 only experience a momentary interruption which is not considered as an interruption. The reliability benefits are achieved by deferring 3414.73 kWh responsive load for about 1.37 h in average.

Table 4 Service reliability improvements realised by DR: Contingency 3

Index	Base case	DR enabled
affected load points	25	25
average interruption duration, h	1.60	1.60
energy not served, kWh	1919.00	1355.52
damage cost, €	39 736.03	27 336.51

Table 5 Service reliability improvements realised by DR: Contingency 4

Index	Base case	DR enabled
affected load points	19	7
average interruption duration, h	1.16	1
energy not served, kWh	2387.92	221.00
damage cost, €	43 502.88	5499.09

4.3 General results

Reliability benefits of the DR during few individual contingencies were demonstrated in the previous section. As observed, value of the benefits varies dramatically from a contingency to another. This section aims to investigate the impacts of the DR on the overall performance of the network. For doing so, all credible contingencies are analysed and the obtained results are combined to estimate the load point and the system oriented reliability indices. Fig. 10 shows the EENS for all individual distribution substations of the under study network. As can be seen, the service reliability in all of the distribution substations is improved and the amount of the improvement in different substations is almost the same. This is because of the fact that a portion of demand in each load point is responsive. Table 6 gives the system oriented reliability indices. The results indicate the great impacts of enabling DR potentials on reliability performance of the network.

According to the results, enabling the DR potentials can provide great reliability enhancements. However, as discussed earlier, a network whose connected responsive loads are usually deferred in order to keep it working is not an ideal network from the reliability perspective. In fact, although responsive loads are flexible, interrupting or shifting their operation is not desirable. Table 7 provides information on the invoked DR potentials in the DR enabled case. As can be seen, significant reliability improvements are achieved by deferring operation of the responsive loads in each load point by less than 2 h in 0.17 times a year. In other words, the reliability benefits can be achieved by interrupting the responsive loads only for a few minutes a year. Another key observation is that nearly 861 kWh responsive load should be postponed in order to reduce the EENS by 583 kWh. This is because of the limited ADT values for the responsive loads.

To provide more detailed information on how DR potentials are utilised, probability density function of the delay time in operation of the invoked responsive loads is shown in Fig. 11. As can be seen, almost all of the invoked responsive loads are operated with a delay time of less than 2 h. Also, close to 60% of the deferred loads are operated with a delay time less than 1 h. This observation can mitigate the existing concern about customers comfort when DR is enabled.

4.4 Sensitivity analysis

Active customer penetration level would significantly affect the capability of DR and consequent reliability benefits.

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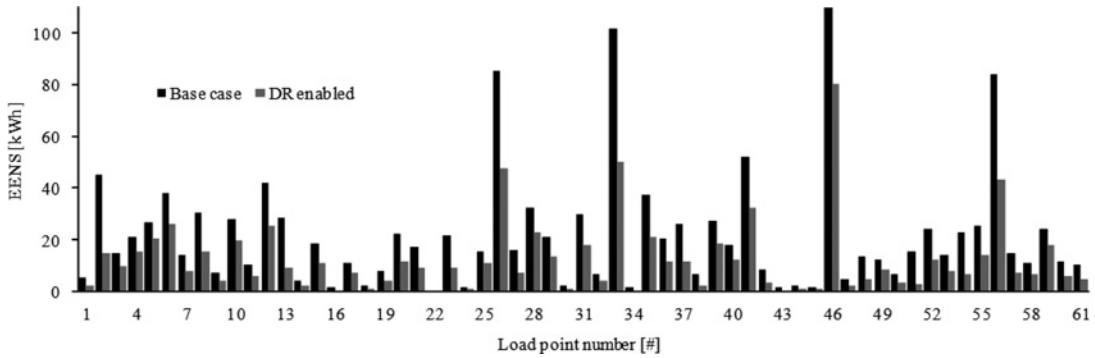

Fig. 10 *EENS for individual load points*

Table 6 System oriented reliability indices

Index	Base case	DR enabled	Improvement, %
SAIFI [int./sub.-year]	0.147203	0.135517	7.94
SAIDI [h/sub.-year]	0.2339	0.2082	10.99
EENS, kWh	1342.49	758.92	43.47
EIC, €	29 224.17	17 169.92	41.25

Table 7 Information on the invoked DR potentials in the DR enabled case

EIF, int./sub.-year	EID, h/int.	EPE, kWh
0.1745	1.79	861.03

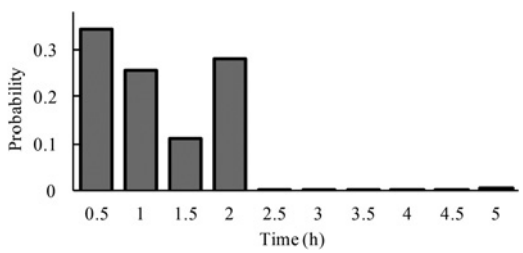

Fig. 11 *Probability density function of delay time in the operation of invoked responsive loads*

The level was assumed to be 100% in the above studies indicating that the entire potential DR is available and the associated customers are participating. This assumption, however, can be too much optimistic since several barriers such as lack of effective automation systems and lack of knowledge among customers about how to respond, prevent the penetration level to be one. This issue is investigated by a set of simulations in which the penetration level of active customers is varied. The obtained results are given in Table 8 from which two major conclusions can be drawn according to the results. The first relates to the fact that reliability benefits realised by enabling the DR potentials increase as the active customer penetration level increases. The second point relates to the declining behaviour of the marginal reliability benefits. In other words, the reliability benefit provided by the first 25% active customers is greater than that of the second 25%, the benefit of the second is greater than that of the third and so on.

Table 8 Reliability indices for different active customer penetration levels

Active customer penetration level	SAIFI, int./sub.-year	SAIDI, h/sub.-year	EENS, kWh	EIC, €
0% (base case)	0.147203	0.2339	1342.49	29 224.18
25%	0.141680	0.2237	1169.18	25 681.76
50%	0.138247	0.2173	1019.51	22 610.31
75%	0.136434	0.2124	882.80	19 789.87
100% (DR enabled)	0.135517	0.2082	758.92	17 169.88

Table 9 Aspects of DR invocation for different active customer penetration levels

Active customer penetration level	EIF, int./sub.-year	EID, h/int.	EPE, kWh
0% (base case)	0	0	0
25%	0.1856	1.94	240.78
50%	0.1785	1.92	461.51
75%	0.1761	1.87	668.25
100% (DR enabled)	0.1745	1.79	861.03

Table 9 compares various aspects of DR invocation for different active customer penetration levels. The surprising observation from the results is that both the frequency of DR invocation and the average interruption time increase as the active customer penetration level is reduced. It means customers discomfort caused by a DR program can be reduced by increasing the number of involved active customers.

5 Conclusion

DR allows network operators to modify the system load profile instead of load shedding when operational limits are violated, thereby improving electricity service reliability. A deep and quantitative study on the benefits that DR can bring for the power industry is a prerequisite for the huge investment needed in the required enabling technologies. This paper provided a comprehensive study on the potential impacts of a DR on major attributes of the service reliability in a residential distribution network. For doing so, hourly metered consumptions and survey data of hundreds of customers from Kainuu, Finland were firstly investigated and the available DR capability in different hours of a day, day types, and seasons was estimated. Then, the obtained DR model was incorporated into the reliability assessment of a Finnish distribution network. Both the load

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point and system oriented reliability indices for two cases, with and without enabling the DR potentials, were compared. The obtained results verify that great reliability benefits can be achieved by enabling DR. It was also shown that the reliability benefits are achieved by negligible adjustments in the operation of responsive loads for only a few minutes a year. The simulations were repeated for different active customer penetration levels and it was demonstrated that the customers' discomfort because of enabling DR can be alleviated by encouraging more customers to become active. The study assumed a balanced network which is an ideal condition and imposes some limitations. This assumption can be released and DR capability in managing the unbalance prevailing should be investigated as a future work. Managing the unbalance would release more capacity in the network contingencies.

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