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Reliability and risk assessment of post-contingency demand response in smart distribution networks

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ABSTRACT

This paper presents a comprehensive framework for the assessment of reliability and risk implications of post-fault Demand Response (DR) to provide capacity release in smart distribution networks. A direct load control (DLC) scheme is presented to efficiently disconnect DR customers with differentiated reliability levels. The cost of interrupted load is used as a proxy for the value of the differentiated reliability contracts for different customers to prioritize the disconnections. The framework tackles current distribution system operator (DSO)'s corrective actions such as network reconfiguration, emergency ratings and load shedding, also considering the physical payback effects from the DR customers' reconnection. Sequential Monte Carlo simulation (SMCS) is used to quantify the risk borne by the DSO if contracting fewer DR customers than required by deterministic security standards. Numerical results demonstrate the benefits of the proposed DR scheme, when compared to the current DLC scheme applied from the local DSO. In addition, as a key point to boost the commercial implementation of such DR schemes, the results show how the required DR volume could be much lower than initially estimated when properly accounting for the actual risk of interruptions and for the possibility of deploying the asset emergency ratings. The findings of this work support the rationale of moving from the current prescriptive deterministic security standards to a probabilistic reliability assessment and planning approach applied to smart distribution networks, which also involves distributed energy resources such as post-contingency DR for network support.

1. Introduction

Traditionally distribution networks have been designed to comply with prescriptive deterministic standards on the required level of operational redundancy (see for instance the UK Engineering Recommendations P2/6 [1]). In this context, in the UK at 6.6 and 11 kV voltage level, networks are designed in a "ring" configuration but operated radially, with radial feeders that can be interconnected by closing Normally Open Points (NOPs). This configuration guarantees that if a disturbance were to occur, alternative paths exist to supply customers not directly connected to the fault. However, in order to allow this network reconfiguration and reliable customer supply following a fault, distribution feeders are typically underutilized. This also means that in the case of load growth additional asset is needed, even if faults are a relatively rare event, sometimes happening once every few years [2].

Given the new control capabilities enabled by advances on Information and Communication Technologies (ICT), more effective network assets' use could be put forward. In particular, Demand Response (DR) schemes could be enabled deploying increased automation to create self-healing capability. The US Department of Energy defines DR as 'a tariff or program established to motivate changes in electricity use by consumers in response to electricity prices or to give incentive payments to reduce consumption when grid reliability is jeopardized'. DR has been categorized into price-based DR programs (such as Real Time Pricing and Critical Peak Pricing) and incentive based DR programs (such as Emergency DR and Direct Load Control) [3]. In this work, Direct Load Control (DLC) programs will be examined where customers sign up for a contract giving the utility the option to remotely shut down appliances and non-vital loads during high demand periods or power supply emergencies receiving credit for this participation (as implemented by utility [4]). In this respect, a practical scheme has recently been proposed within the '*Capacity To Customers*' (C_2C) project [2] whereby post-fault DR is used along with network automation, as illustrated in [5] with the aim to provide network capacity release. In the literature, several DLC algorithms have been developed. In [6], the DLC algorithm determines the optimal

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Nomenclature

Indices

a	Appliance group index
b	Network buses group index
t	Time group index
i	Interruption group index
c	Cluster group index
j^r	Responsive customers group index
j^n	Normal customers group index
R	Residential customer type
$C\&I$	Commercial and Industrial customer type

Parameters and constants

$VOLL$	Value of lost load
d	Duration of interruption
CL^{DR}	DR capacity level
$\varphi_{b,t}^{DR}$	Binary indicator denoting if the DR action in bus b in hour t has to be initiated
ξ_j	Binary indicator denoting if customer j has been called no more than twice per year
ψ_j	Binary indicator denoting if customer j has been called no more than 8 h in a raw

Variables

$P_{DL_i}^{j}$	Disconnected load of customer j in interruption i
IC_j	Total cost of interrupted load for customer j
IC_c	Total cost of interrupted load for cluster of customers c
$PR_{j_R,b,t}^{a}$	Responsive demand of appliance a of a residential customer j, at bus b and time t
$PR_{j_{C\&I},b,t}$	Responsive demand of commercial or industrial customer j, at bus b, at time t
$P\_DR_{b,t}$	Active responsive demand at bus b, at time t
$P_{DL_j^{n,r}}^{i}$	Disconnected load of customer $j$during interruption i

Reliability indices

CML	Customer Minutes Lost
CI	Customer Interruptions
$EENS$	Expected Energy Not Supplied
$EIC^{n,r}$	Expected Interruption Costs (DSO unreliability costs) for normal/responsive customers
EIC^{n+r}	Expected Interruption Costs (DSO unreliability costs) for all customers
$E[IC_{j^r}]$	Expected total cost of interrupted load for a responsive customer
$E[IC_c]$	Expected total cost of interrupted load for cluster c
$(P(util_{DR}))$	Probability of DR utilization
$(P(DR_{req} > X))$	Probability of DR requirements overriding DR capacity.

control schedules that an aggregator should apply to the controllable devices of a large number of customers in order to optimize load reduction over a specified control period. A building energy simulation tool is employed to model the average behaviour of the thermal loads of each customer type. The controllable customers are operated as a virtual power plant taking part in the electricity market by offering load reduction bids to the system operator. In [7] a DLC scheme of air conditioning loads (ACL) is proposed, aiming to reduce the peak load, scheduling the cycling on/off times of the loads based on their interruption costs. The objective of this DLC is to minimize the overall system operating cost comprising the energy cost, the spinning reserve cost and the compensation to the ACL customers. A novel adaptive control strategy for integrating DLC with interruptible load management to provide instantaneous reserves for ancillary services is presented in [8]. There, a fuzzy dynamic programming is firstly used to pre-schedule the DLC and satisfy the customers' requirements and then the adaptive control strategy further operates the interruptible load to adjust the DLC scheduling in real time.

Effectively, through DLC, DR customers accept a level of '*differentiated reliability*', where the system delivers different levels of reliability to different customers depending on their preferences, which are driven by the willingness to accept lower service quality for economic benefits. A similar concept of differentiated reliability has recently been presented in [9], proposing optimal switch configuration algorithm for customers who pay additional fees for higher reliability. The problem is formulated as an optimization, which is performed off-line (storing optimal switch combinations in a database to be used in real time) with the objective of minimizing utility liability while assuring the supply of power to priority customers. From the above-mentioned DLC references only [7,8] have included the power network constraints into the problem formulation and only [7] has examined the reliability performance of the network including the DLC scheme applying the analytical technique of state enumeration into a transmission network. However, quantifying the reliability and risk profile arising from application of differentiated reliability DR or DLC using probabilistic techniques such as Monte Carlo simulations in current and future distribution networks is a topic broadly unexplored.

Furthermore, the reliability impacts on power networks when implementing demand side management techniques has been already addressed by researchers. DR impacts on bulk system reliability have been researched in [10]. The paper also considers the load forecast uncertainty, while applying load shifting as a demand side management measure. DR impacts on distribution network operation have been discussed in [11] where for the reliability evaluation a limited set of contingency states have been considered. Load profiles for major residential appliances are extracted from metre consumption and also the flexibility of the responsive loads is also taken into account. Impacts of DR programs on short-term reliability assessment of wind integrated power systems is studied in [12] applying Monte Carlo method. The outlined literature aims at quantifying the reliability benefits when DR is activated. However, none of those articles discusses the reliability implications of DR to increase the utilization of the existing network and the potential DR capacity requirements associated with this objective. On the other hand, [13] proposes DR as an option to enhance the utilization of the current distribution network capacity, but without doing any reliability analysis. Therefore, it can be appreciated how little work has been carried out in terms of reliability and risk considerations of DR resources that would accept differentiated reliability contracts, whilst this solution could bring substantial capacity support (and network reinforcement postponement or even avoidance [5]) benefits and is in fact already being trialled, for instance in the aforementioned C_2C project.

On top of that, any load reduction due to the DR scheme would probably need to be recovered at a later time. This process is characterized as energy payback [14] and is a potential side-effect of intentionally reducing consumption. Although this effect has been studied from an operational and a market perspective [8,15], payback effects have been included in [7,16], but to none of the above articles which are more related to distribution network reliability with DR services.

Based on the above and following preliminary work carried out in [17], this paper discusses the implementation of DR in the