IET Generation, Transmission & Distribution

Research Article

ISSN 1751-8687
Received on 01st May 2018
Revised 04th June 2018
Accepted on 02nd July 2018
doi: 10.1049/iet-gtd.2018.5415
www.ietdl.org

Demand side flexibility schemes for facilitating the high penetration of residential distributed energy resources

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Abstract: Presently, the penetration of residential distributed energy resources (DER) that produce (photovoltaics, wind generators) or consume (electric heat pumps, electric vehicles) electric power, is continuously increasing in an uncoordinated fashion. If the appropriate steps are not taken to ensure their smooth integration, issues such as violations of voltage and thermal limits occur, especially at higher DER penetrations. This study investigates the impact of each DER on low-voltage (LV) networks, and subsequently, multiple large-scale demand side flexibility (DSF) schemes are proposed per DER type, based on the cooperation of system operator and residential customer, to combat said issues and to significantly increase DER penetration. A rule-based approach is used for each DSF scheme, to highlight their effectiveness in 'raw' form, and to assess whether they merit further practical consideration. Using data on real LV feeders and real DER profiles, through a Monte Carlo simulation framework considering the stochastic behaviour of the various network elements, DER impact and DSF performance are measured. The results include a major improvement in delivered power quality, highly increased DER accommodation capacity, a thorough comparison of the technical performance of each DSF scheme, and a conclusion on the effectiveness of each DSF scheme.

1 Introduction

Distributed energy resources (DERs) are gradually becoming part of daily life at the residential level, supported by policies seeking for efficient low carbon solutions. With DER capital costs decreasing, end-customers are encouraged to utilise DER and take advantage of their multiple benefits. Recent surveys indicate a significant penetration of DER in low-voltage (LV) networks. About 753,000 electric vehicles (EVs) were sold worldwide in 2016, 60% of which are pure EVs [1]. In Australia, 16% of homes use photovoltaic (PV) rooftop systems as of 2016 [2]. The American wind energy association estimates that due to a 40% per annum growth, residential wind generators (WGs) could contribute 3% of U.S. production by 2020 [3]. The global market is being introduced to domestic, energy storage systems (ESSs), intended for domestic purposes, like solar power exploitation, and backup power. DER-based energy is eco-friendly, promoted by governments and power industries to meet de-carbonisation and emissions targets.

1.1 Motivation

High amounts of uncontrolled DER operation can create technical problems in LV networks. Shifting weather conditions cause random fluctuations in the power output of PVs and WGs, while high heat demand in the winter increases the use of electric heat pumps (EHPs), and thus the overall power demand. In addition, uncoordinated charging of EVs might create unexpected peaks in the daily load profile. Common problems arising from the aforementioned situations include voltage drops and rises across the LV feeders, as well as thermal overloads of MV/LV transformers, all of which have been highlighted and investigated during the last years [4–13].

Increasing DER penetration is a major goal for future power systems, and thus DER-related technical issues at high DER penetrations are an important concern. Power engineers and DSOs should investigate the DER penetration levels, up to which the LV networks operate problem-free and propose schemes (either on the demand side or on the distribution network side) to increase the feasible penetration levels of DERs.

1.2 Literature survey

Several studies focus on the impact of different DER technologies in LV networks [4–7]. The impact of EHPs in residential LV networks is investigated in [4] and the probability of EHP-related problems occurrence is addressed for different penetration levels. Using a similar approach, the work [5] assesses the impact of EVs in LV networks in a worst-case scenario (single load level). The impact of EVs is also assessed in [6] after data acquisition and definition of EVs' charging patterns. The work of Navarro-Espinosa and Ochoa [7] addresses the technical issues that occur for different penetration levels considering four different DERs: PVs, EVs, EHPs, and micro combined heat and power (μCHP). The probabilistic impact of each DER is investigated separately through a Monte Carlo simulation (MCS).

Research papers have proposed several demand side flexibility (DSF) schemes to manage DER-related problems. In [8], electrical energy storage systems and demand side response techniques are combined to combat voltage drops caused by EVs and EHPs. In [9], two demand response (DR) models are proposed based on price elasticity and tested in an Irish suburban residential LV feeder, using a 24-hour winter time-varying load. Malík and Havel [10] introduce a demand-side management (DSM) system to centrally and optimally control the residential area's electric water heaters to facilitate a high PV penetration. The developed system is tested on a pilot installation in the Czech Republic. To mitigate voltage/thermal problems and increase PV and EHP penetration in residential LV networks, the meshed operation of a UK LV network is investigated in [11]. In [12], the EVs' charging is managed by a centralised control algorithm, applied in nine UK LV networks. In [13], the operation of domestic ESSs is used to manage the demand in response to energy price incentives and to mitigate network problems. This operation strategy is examined without considering the impact of other DERs.

From the literature review, it is concluded that more schemes are needed, either new or re-invented, for combating DER-related technical issues (thus significantly increasing their penetration) along with a practical comparative analysis for each case. Diversifying the end-users' demand habits, managing DER behaviour, or simultaneously combining the appropriate DERs

Table 1 Contributions and main features of the reviewed papers and the proposed work

Ref.	DER impact assess.	DER				MPL[a]	DSF PSS[b]					ESS
		PV	WG	EHP	EV		LS	RLS	SLG	SC	FL	
[4]	√			√		√						
[5]	√				√	√						
[6]	√				√							
[7]	√	√		√	√	√						
[8]				√	√	√	√					√
[9]										√	√	
[10]		√					√					
[11]	√	√		√		√						
[12]	√				√	√				√		
[13]							√				√	√
proposed	√	√	√	√	√	√	√	√	√	√	√	√

[a]MPL = multiple penetration levels.
[b]PSS = proposed strategy/scheme.

have proven to be the suitable means to operate LV networks with high DER penetration. This is primarily achieved through DSM, an all-encompassing term, which, depending on the timing and the impact, can be categorised as energy efficiency (EE), time of use (TOU), spinning reserve (SR), or DR [14]. Special mention is given to DR, as it is the most commonly employed tool of DSM. DR can be market-based or physical [14] depending on the policy and the decisions made by distribution system operators (DSOs). A decentralised DR framework under which the end-users adapt their demand profile in response to control signals broadcasted by the system operator is introduced in [15]. A load scheduling learning algorithm for multiple domestic customers in response to real-time price feedback is proposed in [16]. A comprehensive review of DR potentials, benefits and needed infrastructure can be found in [17].

1.3 Contributions

This paper uses the term DSF, as a wider term than DSM, encompassing additional tools not available in DSO practices. For instance, for some of the DSF schemes, direct control of customer-owned DER can be given to the DSO, an approach not included currently in the DSM.

This paper investigates five practical DSF methods based on total demand increase, total demand decrease, and total demand redistribution. The methods utilised are

i. load shifting (LS), redistributing total demand maintaining the total energy per time period,
ii. reverse LS (RLS), redistributing total supply maintaining the total energy per time period,
iii. strategic load growth (SLG), increasing total demand and thus total energy,
iv. strategic conservation (SC), decreasing total demand and thus total energy,
v. flexible load (FL), re-shaping demand on a per-case basis.

The application of these DSF schemes in mitigating the technical problems created by the increased penetration of DER is examined. Table 1 summarises the contributions and features of the reviewed papers and our proposed work.

This paper's main contributions are summarised as follows:

- Using a combination of new (SLG, RLS) and old (FL, SC, LS) DSF methods, both network-wide and fully customer-based (all DSF tools actually belong to the customers), under conditions ranging from normal to extremely severe, it investigates the ‘brute force’ (no optimisation) potential of these DSF methods in ameliorating the impact of DERs in LV networks. Moreover, the most viable DSF method per DER is identified.
- Through a simplified, yet realistic scheme, for each DSF method, it achieves a substantial increase in DER penetration. Most importantly, this is achieved through the almost full cooperation of consumers, as based on a survey, conducted in the context of this paper, showing that most consumers (>91%) would accept to adopt such schemes.
- It demonstrates that that for the largest network studied, thanks to the proposed DSF schemes, on average an amelioration of about 70 and 34% is achieved in terms of voltage and overload problems, respectively, while in many cases, overloading fully disappears, even at a DER penetration of 100%. This shows that regardless of the studied DER, an additional 50% of existing customers can now operate their loads problem-free and that the previously unacceptable thermal stressing is now fully eliminated.

1.4 Organisation of manuscript

The paper is organised as follows. Section 2 outlines the load profiles and the DERs’ power curves under consideration. Section 3 describes the investigated DSF schemes. Section 4 presents the assessment framework of the DSF schemes. The DSF schemes proposed are applied to real UK LV networks and the obtained results are presented and discussed in Section 5. Conclusions are drawn in Section 6.

2 Loads and DER under consideration

To fully study DERs’ impact on LV distribution networks, their corresponding time-series profiles are utilised. This work includes the profiles of residential loads, EHPs, EVs, PVs, available in [16], while WGs profiles were generated according to the method of Section 2.4.

The daily profiles have 5-minute resolutions (288 5-min intervals each). The average daily profiles of the residential loads (summer and winter) and of DER are depicted in Fig. 1. Excruciating detail is necessary to ensure that voltage-related issues are properly captured according to the European Standard EN 50160 requiring, 10-min rms averages [18].

As in [7], each DER is studied during the periods where they present the most intensive ‘usage’. Thus, WG and EHP profiles correspond to winter conditions, PV profiles correspond to summer conditions, and EV profiles correspond to both winter and summer conditions [7]. This is the first reason why each DER is examined separately. The second reason is that we want to examine the individual DER's potential.

2.1 Residential loads profiles

The random 100 individual residential load profiles used in [19] are also used in this work (the creation method is explained in [20]). The number of profiles is artificially augmented from 100 to 2000 by considering that residential loads’ behaviour largely follows the normal distribution in any distinct period [21]. The process is the same for both winter and summer conditions. The daily average load curve of the resulting profiles is presented in Fig. 1 and minimally differs from the profiles of [19]. Considering

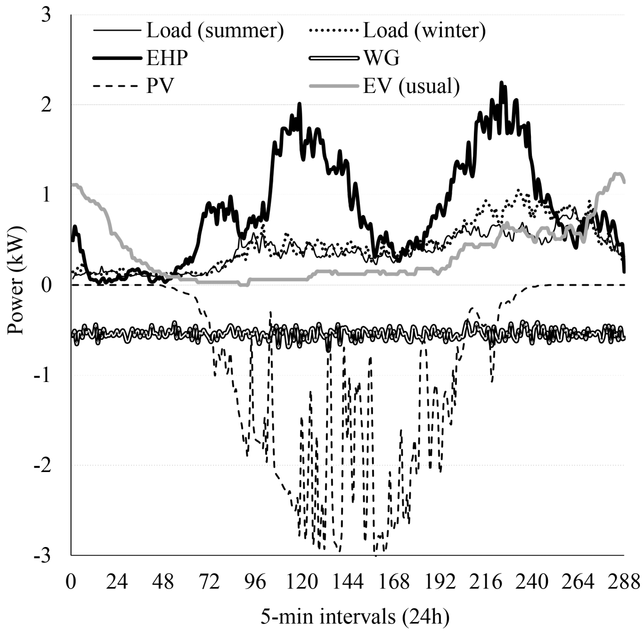


Fig. 1 *Average profiles of load and DERs under investigation*

the average of the resulting 2000 profiles for winter, the average peak demand is just over 1.0 kW, whereas, for summer, the corresponding value is around 0.8 kW. In terms of energy consumption, the values are around 10.44 and 9.03 kWh, for winter and summer, respectively.

2.2 PV profiles

The 100 individual PV profiles used in [19] are also used in this work (data on sun irradiance, the efficiency of energy conversion, and PV inverter are, respectively, acquired from [22, 23]). The number of profiles is artificially augmented from 100 to 2000 by considering that PVs' behaviour follows the Weibull distribution in any distinct period [24]. The daily average PV power curve of the resulting profiles is presented in Fig. 1, differing slightly from the profiles that are presented in [19] (the difference is attributed to the higher randomness in modelling sun irradiance). Thus, considering the average of the resulting 2000 profiles, the average peak power generation (presented as a negative, being power injection) is a little over 3 kW. In terms of energy production, the average profile corresponds to a daily energy production of about 20.66 kWh.

2.3 EHP profiles

The 100 individual air source EHP profiles used in [19] are also used in this work. The number of profiles is artificially augmented from 100 to 2000 by considering that EHPs follow the same behavioural patterns as residential loads. The daily average EHP profile is presented in Fig. 1 and differs to a small degree from the profile presented in [19]. The replication suffers due to deviations in the usage of EHPs, the error factor, however, is relatively small. Thus, considering the average of the resulting 2000 profiles, the average peak demand is just over 2.2 kW, corresponding to an energy consumption of about 19.8 kWh.

2.4 WG profiles

The WG profiles are obtained by the methodology presented in [24], considering a WG of 2 kW nominal power. A cut-in wind speed of 4 m/s was assumed, whereas nominal wind speed and wind disconnection speed were assumed as 15 and 25 m/s, respectively. By taking into account that wind speed follows the Weibull distribution [24] and the wind speed data that were collected for the three windiest months of 2016 in the UK [25], 2000 profiles were artificially created. The resulting profiles' average WG power curve is presented in Fig. 1. While each individual WG profile greatly resembles a real WG's operation, the 2000-profile average is generally steady throughout the day, as expected. Thus, considering the average of the resulting 2000 profiles, the average peak production (presented as a negative power injection) is just under 0.75 kW. In terms of energy production, the average profile corresponds to a daily energy production of just about 13 kWh.

2.5 EV profiles

The EV profiles are the same as in [7]. An EV charging load is different from traditional loads due to its binary nature. Thus, the generation of a typical profile, the probability distribution of connection times and the required energy absorption are used to create 2000 daily charging profiles [7]. It should be noted that this method considers a single charging per day, while the statistical analysis that is used is the one presented in [6]. The 2000-average profile is presented in Fig. 1 and differs very little from the one presented in [7]. Thus, considering the average of the resulting 2000 profiles, the average peak demand is just under 1.25 kW, corresponding to an energy consumption of about 8.5 kWh.

3 DSF schemes

Five different DSF schemes (SLG, LS, RLS, SC, and FL) are applied, briefly presented in Fig. 2. SLG and RLS aim at solving overvoltage, while LS and SC undervoltage problems and FL aims at eliminating both problems. Each scheme is designed as a rule-based approach, i.e. its application is an intuitive manual act and is based on the appropriate intervention tool shown in Fig. 2. This is a key strength of the paper, as for each scheme, its effectiveness is simply estimated, before applying more sophisticated optimisation methods. For the realistic implementation of each scheme, the response of consumers for each scheme is modelled based on the survey of Table 2.

For some of the intervention tools (FL and SC), there is some optimisation involved in their construction. However, this is done at the customer level; there is no network-wide optimisation involved. All intervention 'tools' have the same penetration as corresponding DER, the only exception being SC, assumed to always have a 100% penetration. This is a key assumption in this paper. If DER penetration is to grow in a coordinated way, then any scheme-related expansion must work in complete unison with the DER expansion plan, no less, no more. One should note that each DSF scheme focuses on combating the issues created by a single DER. If more than one DER were used, the response would be an appropriate combination of DSF schemes. It should be noted that each DSF scheme has different investment and operational costs. However, the ultimate goal of each scheme is to achieve a 100% penetration of DER. While each DSF scheme has different costs, those that are more efficient on a technical level are more desirable operationally. Besides, the costs of each DSF scheme may be highly variable in the future, and thus their financial comparison may change throughout time. The technical comparison is an absolute comparison, not subject to future change. In addition, this paper makes two additional assumptions. Firstly, just like the DERs are already part of the network, the necessary DSF tools are also assumed to be already part of the network and readily available to be utilised. Thus, DSF installation costs can be largely ignored. Secondly, it is assumed that the customer reimbursement costs and the network costs (due to network voltage and thermal issues) are far higher than each DSF scheme's operational costs. Thus, since the financial benefits of ameliorating the network issues are much higher than the financial costs of their implementation, our paper is focused on the technical performance of DSF schemes.

3.1 SLG scheme

This method refers to the augmentation of customer demand across the day [26]. In this paper, the scheme uses EV charging, to counter the problems arising from surplus DER-produced power. Since EV charging patterns are of stochastic nature, two charging profiles, average daily usual EV profile and daily average desired EV profile, are considered to create the daily average final EV profile of the proposed SLG scheme. By considering that people need to regularly use EVs during weekdays, the proposed scheme separates

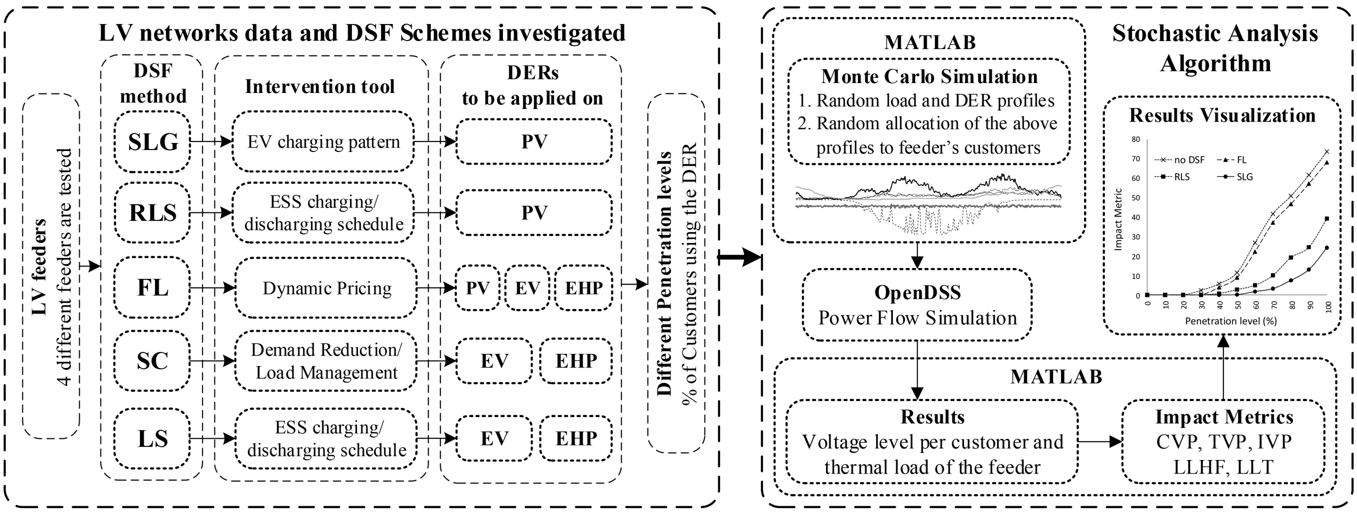


Fig. 2 *DSF schemes proposed and schematic overview of the assessment methodology*

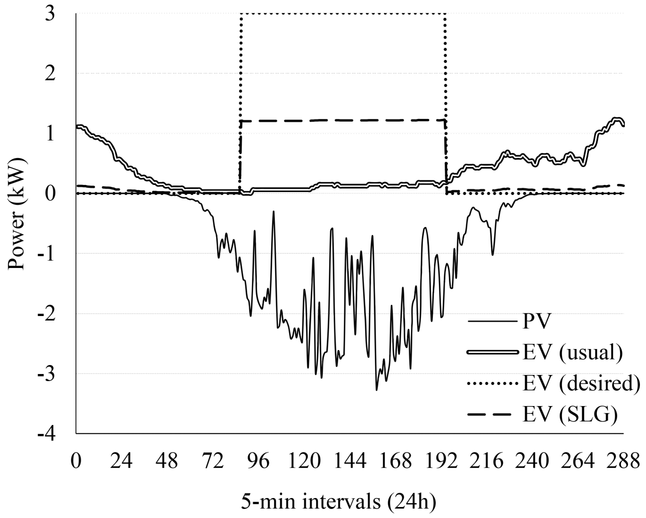


Fig. 3 *EV charging patterns and PV daily profile for SLG*

weekdays' participants into five equal groups, each applying the desired charging plan during a different weekday (i.e. group 1 on Monday, group 2 on Tuesday and so on). During the weekend, it is assumed that all willing participants follow the desired charging scheme. Thus, according to Table 2, on an average daily basis of a 7-day week, 39.5% of users fully adopt the desired charging profile, 8% of users follow their own charging schedule as presented in [19], while the remaining 48.8% of users do not charge their EVs at all. All three daily EV profiles in question (usual, desired, and SLG) are presented in Fig. 3. The EV profile considered to apply the SLG scheme demonstrates an average peak demand of about 1.2 kW, with a daily energy consumption corresponding to 11.7 kWh.

3.2 LS/RLS scheme

This method focuses on shifting surplus load-consumed or DER-produced (reverse) power to less demanding time periods throughout the day, to mitigate the corresponding issues that would normally occur [26]. This is achieved by using residential ESSs with a per-case custom charging schedule. Commercial ESSs with a capacity of 13.5 kWh and nominal power of 5 kW are used (i.e. Tesla Powerwall 2). Based on the research conducted (Table 2) the charging/discharging schedule for this use of the ESSs is assumed to have a response rate of 100%. A key constraint that was considered when designing this scheme was that the initial ESSs state of charge (SoC) should be equal to the final SoC over the scheduling horizon and one cycle of charging/discharging should occur during a day. This constraint can ensure a longer lifetime for the ESSs. Thus, considering both SoC and the application of the

Table 2 Electricity consumers response rate to DSF schemes

Question	'Would you accept the proposed DSF scheme if offered adequate financial incentive'?			
Answers	760 answers, ages 17–70, average age 51.4 years			
DSF scheme	intervention tool	'yes' (%)	'no' (%)	'not sure' (%)
SLG	EV (weekdays)	85.3	11.1	3.6
	EV (weekend)	95.6	0.8	3.6
LS, RLS	ESS	97.5	1.5	1.0
SC	demand reduction	5.0	94.5	0.5
	load management	98.5	1.0	0.5
FL	dynamic pricing	81.0	11.0	8.0

ESSs, Fig. 4*a* and Table 3 indicate that when used together with EHPs, ESSs demonstrate a peak power (positive or negative, depending on SoC) of 1.0 kW corresponding to an energy profile (absorption or production, depending on SoC) of 8 kWh. When used in combination with EVs, as shown in Table 3 and Fig. 4*b*, ESSs demonstrate a peak power of 0.375 kW while charging and 0.75 kW while discharging, both corresponding to an energy profile of 15 kWh. Finally, Table 3 and Fig. 4*c* indicate that when used in combination with PVs, ESSs demonstrate a peak charging power of 1.1 kW and a peak discharging power of 0.9 kW, corresponding, respectively, to an energy absorption and production of 12.1 kWh. Like EV penetration in SLG, ESS penetration always corresponds to PV, EV and EHP penetration, accordingly, for demonstrating the LS and RLS schemes.

3.3 FL scheme

According to this method, the demand profile at each given moment may be subject to change (increase, decrease, or no change). The total daily demand profile is thus increased, decreased, or re-distributed (remains the same), according to the network's needs on a case-by-case basis. This is achieved through financial incentives, such as dynamic pricing [26]. FL aims at creating a smoother demand profile, by changing energy prices throughout the day, which in turn affects customer behaviour; e.g. if customers knew that energy prices were to drop, they would be incentivised to consume more electricity. This is supported by multiple studies, such as [27, 28]. This is usually applied on an hourly basis, to better supervise and control the power system. In short, when demand is high, prices are raised to discourage consumption and vice versa. The FL scheme is applied in a PV-only, an EHP-only, and an EV-only environment, with the corresponding effects on the demand profile presented in Section 5. Additionally, due to the inflexibility of the EVs between their two states (either charging or not charging, no in-between load is possible), and because they must have a full single charge per day, it is assumed that while the FL scheme is applied based on total required energy, EV charging profiles remain unaffected. The method used is adopted straight from [27] although executed only at the customer level. In the daily simulations, the hourly energy prices used for winter and summer are the per-hour winter-average and summer-average wholesale UK energy price for 2016. The application of this scheme requires the grid to be equipped with online smart metering devices, to allow two-way communication between customers and electricity utility.

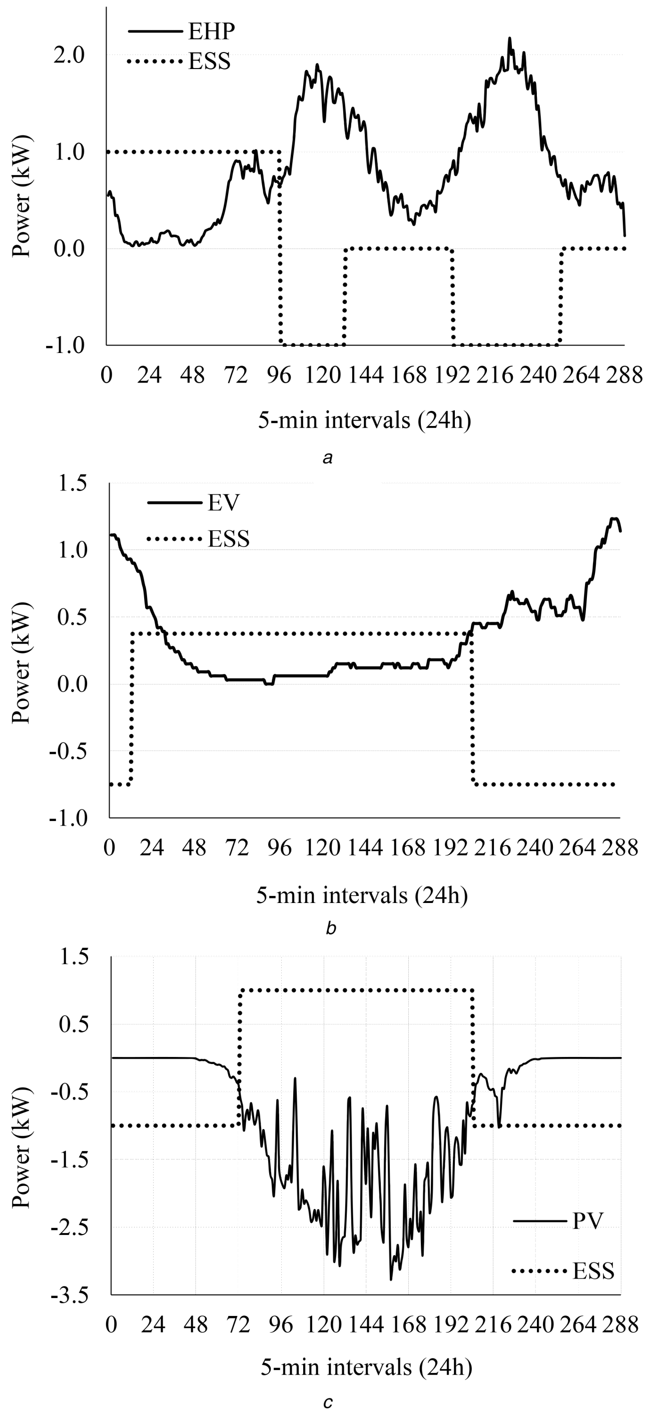


Fig. 4 *ESS charging/discharging schedule for*
(a) EHP average daily profile (winter day), ***(b)*** EV average profile, ***(c)*** PV average profile (summer day)

3.4 SC scheme

The strategic conservation method refers to a combination of intentional reduction of energy demand (e.g. on grounds of environmental sensibility [26]) and efficient energy use, achieved by financial incentives. This paper's scheme includes demand reduction and better load management through several conservation strategies, such as pre-cooling, zonal temperature set up, or chilled water loop. Based on Table 2, however, load reduction without any palpable motivation seems unlikely (marginally 5% of customers are willing participants). On the other hand, customers are more willing to better manage their energy demand (this includes the incorporation of energy efficient appliances and better energy redistribution), if offered adequate financial incentives. The application and the corresponding effects of several conservation strategies are examined through the Demand Response Quick Assessment Tool (DRQAT) of the U.C. Berkeley Lab [29]. After the application of all measures, (at a customer level, assuming each customer will always follow one to five of the strategies) the new total 3-month power profile is calculated. It remains largely unchanged in form, albeit with total demand reduced. The new profile is then converted to its corresponding daily profile. Therefore, the total behavioural profile is the same as before, while total demand is reduced throughout the day. When SC is applied to an EHP-only environment (EHPs are affected by this scheme), the reduction ranges at any given moment between 5 and 15% (Fig. 5). When the scheme is applied in an EV-only environment, their charging profile remains unaffected, although the winter load is reduced between 5 and 15%. Thus, the total actual reduction is minimal during EV charging periods (1−6%).

4 Impact assessment methodology

4.1 Assessment methodology without DSF

The probabilistic assessment framework used in this paper is the same as the one presented in [7], designed to consider all types of uncertainties concerning loads and DERs, such as location or behaviour, by employing a Monte Carlo simulation. Different penetration levels, from 0 to 100%, (steps of 10%), are investigated. The penetration level is defined as the percentage of customers using a type of DER [7]. 100 such simulations were executed, since the results obtained after performing 100, 500, 1000, and 2000 Monte Carlo simulations were virtually the same [7]. The stochastic analysis algorithm (SAA) used is briefly depicted in Fig. 2 and its pseudo algorithm is as follows (note that SAA is executed for all DER penetration levels, from 0 to 100%, in steps of 10%)

i. Define the feeder and the DER to be studied.
ii. Set n = [number of customers of the chosen feeder].
iii. Set p = [DER penetration level (%)].
iv. For each MCS iteration (100 in total):

   a. Randomly allocate n load profiles to n customers.
   b. Randomly allocate $n \times p$ DER profiles to $n \times p$ random customers.

Table 3 ESS characteristics for DSF schemes

DER	DSF Scheme	CR[a], %	DCR[b], %	ESS charging period	ESS discharging period
PV	RLS	22.0	18.6	06:00–17:00	17:00–06:00
EHP	LS	20.0	20.0	00:00–08:00	08:00–11:00 16:00–21:00
EV	LS	7.5	15.0	17:00–01:00	01:00–17:00

[a]CR = charging rate.
[b]DCR = discharging rate.

c. Execute the power flow analysis.
v. Extract and analyse the MCS results.

Concerning the totality of load profiles, not only the realistic distribution of the number of people per household is considered, but also the coincidence between electricity and heat consumption, as the real electricity consumption data associated with each house, are used [7].

Concerning the totality of DER profiles, the uncertainties associated with their size and behaviour are also considered, as described in Section 2.

The three-phase asymmetrical power flow analysis (daily time-series power flow) is executed using the OpenDSS tool [30], storing voltages, currents and powers for the impact assessment [7].

The DER phase connection is always that of the corresponding house (connections' distribution presented in Table 4) [7]. Since the DERs are residential, their installation follows any random allocation, following the actual distribution of customers among the phases [7]. Thus, while some of these DER allocations could be such that the imbalances created to result in larger voltage rises [31, 32], or drops [5], the potential unbalance is a realistic scenario.

4.2 Impact metrics

Due to the time-varying nature of DERs and household demand, technical impacts change throughout the day. In quantifying any arising issues, seven (7) metrics are adopted (three from [7] and four original):

(a) *Customers with voltage problems (CVPs):* It expresses the number of customers not supplied with power according to the EN 50160 standard over a day. The CVP, here a percentage, is the average of all problematic customers divided by the total number of customers in the feeder [7]. It is the main indicator of customer satisfaction.
(b) *Loading level at head of the feeder (LLHF) and loading level of the transformer (LLT):* They express the thermal 'stressing' of the feeder and the substation transformer, respectively. They are estimated as the percentages of the maximum head of feeder ampacity and the transformer's rated power, respectively [7].
(c) *Time with voltage problems (TVPs) and instances of voltage problems (IVPs):* They provide a global estimation of the feeder supply quality. TVP expresses the estimated time duration with voltage violations over a day, while IVP is the number of voltage violations (overvoltages and undervoltages) in the feeder over a day. The TVP, expressed as a percentage, is the average of all problematic 5-min time-intervals divided by the number of 5-min time-intervals over a day (i.e. 288), while IVP is expressed as a pure number.
(d) *Voltage elasticity (VE) and thermal elasticity (TE):* These economics-inspired metrics measure the 'elasticities' of voltage and thermal problems, respectively, per percentage increase of DER penetration. They are expressed as pure numbers. Overall, they express how much the network is stressed (in terms of voltage and thermally) as DER penetration increases, starting from the penetration level that issues first start being noticed. They are calculated as the average changes in CVP and the average change in LLHF per percentage change in DER penetration, from the point that issues start being noted. For instance, a VE of 2.5 means that after issues are first observed, an increase in DER penetration by 1% worsens the CVP by 2.5%. Note that if no issues are observed (ideal case), the elasticity is not calculated, because there is no problem-accompanying stressing of the network.

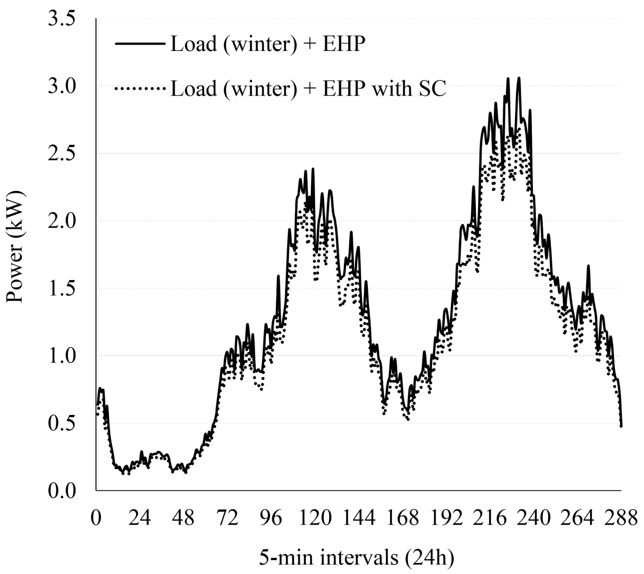


Fig. 5 *Load reduction due to strategic conservation*

4.3 Assessment methodology with DSF

The impact assessment methodology is largely the same as the five-step SAA of Section 4.1, albeit with minor differences per scheme:

i. *SLG:* The SAA (Section 4.1) is implemented, though after step 4a, $n \times p$ random consumers are chosen as EV hosts, with the predefined SLG EV profiles, as depicted in Fig. 3.
ii. *LS:* Same as SLG. EVs are now replaced by ESSs; their operation profile is available in Table 3.
iii. *RLS:* Same as LS. ESSs' charging/discharging schedule now changes according to Table 3.
iv. *SC:* The SAA (Section 4.1) is implemented after the new SC load profiles are defined in step 4a.
v. *FL:* The SAA (Section 4.1) is implemented after the new FL load profiles are defined in step 4a.

5 Case study and results

5.1 Case study description

To compare the performance of the proposed DSF schemes, four real UK LV feeders of different sizes were selected. The data of LV feeders used for the demonstration are available in [19]. The main characteristics per feeder are briefly presented in Table 4, showing the feeder length and the customers hosted. The loads are supplied by an MV/LV 11/0.4 kV, 750 kVA transformer. All LV feeders operate at 230-V nominal phase voltage. All loads, power consumption DERs (EHPs and EVs) and power production DERs (PVs and WGs) are considered with lagging power factor of 0.95.

For the case study, the EN50160 standard is followed, according to which [18], the rms voltage value across the feeder must never exceed the upper limit of 1.1 per unit (pu) and the lower limit of 0.85 pu. Simultaneously, voltage drops under 0.9 pu are accepted with a strict tolerance of 5% of the time over a 24-

Table 4 Main characteristics of LV feeders

LV feeder	Length, m	Residential customers	Winter peak load, kW	Summer peak load, kW	Winter min load, kW	Summer min load, kW	Distribution of connections, %		
							Phase A	Phase B	Phase C
N2F5	734.9	23	24.3	19.7	2.1	1.5	39.13	34.78	26.09
N1F1	1437.8	55	58.1	47.1	5.0	3.6	38.18	34.55	27.27
N2F3	2763.6	112	118.3	95.9	10.2	7.4	37.50	30.36	32.14
N2F1	5205.6	175	184.9	149.9	16.0	11.6	34.86	34.28	30.86

hour period. To overcome extreme voltage drops during days with high demand, the LV side of the MV/LV transformer is set at 1.05 pu, i.e. 241.5 V phase voltage.

The customers of the considered LV feeders use EVs and ESSs; their operational characteristics are described in Section 3. The load profiles, the EHP profiles, along with the power generation curve of PVs and WGs are described in Section 2. The case study is executed both with and without DSF.

5.2 DER impact assessment without DSF

The assessment methodology is applied per DER without applying any DSF scheme. DER-related problems proportionally increase with the size of LV feeder. Considering the same penetration level, the larger the feeder, the poorer the delivered power quality. The following analysis focuses on the largest feeder (N2F1), as it presents the more appreciable results, and because the two smaller feeders present no issues. However, the results of all feeders are presented in Table 5.

Q1 During summer days (only PVs studied), overvoltages firstly occur when over 30% of the end-customers utilise a PV on their premises, as Fig. 6*a* shows. From that point, a 1% penetration increase worsens the voltage issues by about 1%. Accordingly, during winter days undervoltage issues can be observed when a percentage of 30% of the end-customers use either an EHP for domestic heating (Fig. 6) or charge their EV (Fig. 6*c*). VE has values of about 0.7 for EHP, and 0.2 for EV (Table 5). WGs are found to have no influence on the normal operation of any LV feeder, and thus DSF measures are not needed.

High heat demand during winter days causes increased power injection to the feeder. The MV/LV transformer is overloaded if over 20% of customers use an EHP. Additionally, it presents a high TE, of almost 2. PVs overload the transformer with reverse power flow during summer days, if over 80% of the customers use a PV system, with the TE being similar to the EHP case. Overloading is also possible if about 35% of households have an EV, however, EVs are much less damaging, having a TE of <0.2. It should be noted that while a simultaneous EV and PV analysis would have been possible, it holds little merit to do so; as it can be seen in Fig. 1, the PVs' main operation is when the EVs are largely inactive and vice versa.

5.3 Production DER impact assessment with DSF

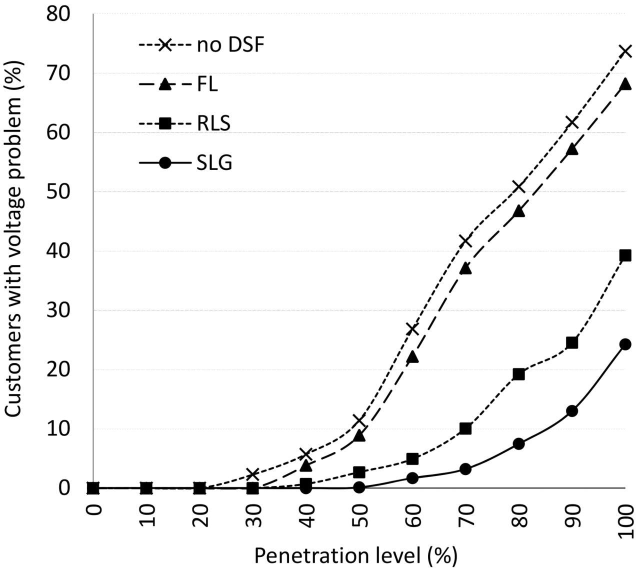
5.3.1 Strategic load growth: The results of this scheme are impressive as shown in Figs. 6*a*, 7*b* and Table 5. A significant decrease of the TVP and IVP metrics is observed, while the quality of power supplied is improved per penetration level. Assuming full penetration of PVs, the number of customers with voltage problems is decreased by about 65%, while feeder and transformer thermal issues are fully eliminated (loading below 100%). VE is reduced by >50%, and TE is no longer a concern. Another important benefit is that the PV-related problems firstly occur at the penetration of 60% (30% without DSF). It is worth to be

Table 5 Comparative overview of the impact metrics for all networks

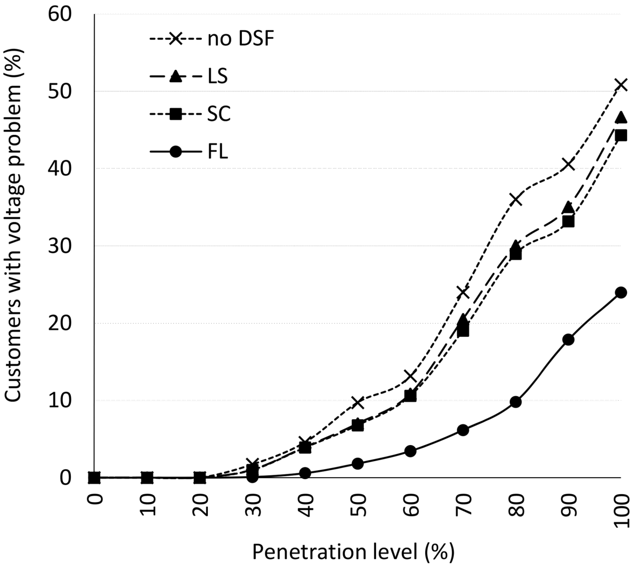
Feeder	DER tested	DSF scheme[a]	Maximum DER penetration (%) without violation of			Elasticities[b]		Values of impact metrics at DER penetration level of 100%				
			Voltage limits	Thermal limits of transformer	Thermal limits of feeder	VE	TE	CVP, %	TVP, %	IVP, %	LLHF, %	LLT, %
N2F5	WG	N/A	100	100	100	N/A	N/A	0	0	0	<70	49.6
	PV	N/A	100	100	100	N/A	N/A	0	0	0	<70	131.1
	EHP	N/A	100	100	100	N/A	N/A	0	0	0	<70	258.8
	EV	N/A	100	100	100	N/A	N/A	0	0	0	<70	152.4
N1F1	WG	N/A	100	100	100	N/A	N/A	0	0	0	<70	49.6
	PV	N/A	100	100	100	N/A	N/A	0	0	0	<70	131.1
	EHP	N/A	100	100	100	N/A	N/A	0	0	0	<70	258.8
	EV	N/A	100	100	100	N/A	N/A	0	0	0	<70	152.4
N2F3	WG	N/A	100	100	100	N/A	N/A	0	0	0	<70	49.6
	PV	SLG	80	100	100	0.324	N/A	7	0.27	0.79	<70	98.2
		RLS	70	100	100	0.358	N/A	9	0.34	0.99	<70	114.6
		FL	60	90	90	0.482	1.551	20	0.75	2.16	<70	125.4
		no DSF	60	90	90	0.539	1.627	23	0.90	2.59	<70	131.1
	EHP	LS	80	30	60	0.178	1.407	5	0.45	0.78	154.9	232.9
		SC	80	30	70	0.203	1.252	4	0.35	1.02	145.3	217.4
		FL	90	70	100	0.080	1.032	2	0.27	1.29	108.2	167.1
		no DSF	80	20	50	0.223	1.534	6	0.66	1.90	161.1	258.8
	EV	N/A	100	40	100	N/A	N/A	0	0	0	108.4	152.4
N2F1	WG	N/A	100	100	100	N/A	N/A	0	0	0	<70	49.6
	PV	SLG	60	100	100	0.482	N/A	25	0.4	1.09	93.3	98.2
		RLS	50	100	100	0.643	N/A	40	0.6	1.76	104.2	114.6
		FL	40	90	90	0.919	1.592	69	2.3	6.49	114.1	125.4
		no DSF	30	90	90	1.02	1.687	74	2.9	8.28	119.3	131.1
	EHP	LS	30	30	60	0.652	1.534	47	4.6	4.64	221.8	232.9
		SC	30	30	70	0.619	1.499	45	4.2	4.20	207.1	217.4
		FL	40	70	100	0.341	1.382	24	2.5	2.49	159.1	167.1
		no DSF	30	20	50	0.702	1.868	51	5.2	5.32	246.5	258.8
	EV	LS	70	100	100	0.032	N/A	1	0.2	0.57	82.7	86.1
		SC	40	40	50	0.168	0.657	12	0.5	1.62	141.6	149.9
		FL	40	90	100	0.106	N/A	7	0.3	0.89	100.0	104.1
		no DSF	30	40	40	0.175	0.723	13	0.5	1.71	146.4	152.4

[a]N/A means that no scheme was applied.

[b]N/A means that a calculation is not possible, because there was no violation observed.



a



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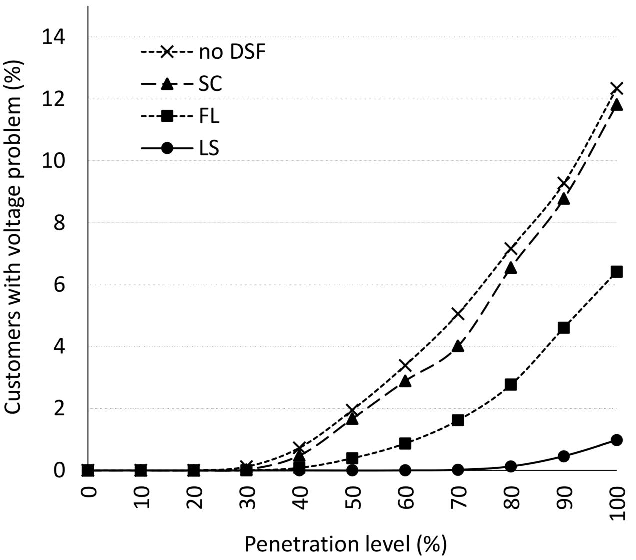

c

Fig. 6 *CVP impact metric per DSF scheme*
(a) PV case, ***(b)*** EHP case, ***(c)*** EV case

mentioned that despite the additional load, owing to some customers that charge their EVs during the night, there is no voltage drop.

5.3.2 Reverse LS: In comparison with SLG, by applying RLS, the essential voltage problems are firstly observed when over 50% of customers have a PV, essentially reducing the voltage limits. While TE is again eliminated, VE is about 40% higher than on SLG. Generally, the scheme applied for RLS implementation is 35% less efficient. Even though the utilisation of ESSs allocates the residential energy consumption better than EVs do, this allocation does not perform optimally.

5.3.3 Flexible load: This scheme offers a slight improvement over the no-DSF situation as shown in Fig. 6*a* and Table 5. All limits are slightly increased and all metrics show a small decrease. However, the power production of PVs significantly remains higher than the residential power demand during summer days, because power demand is inelastic in price fluctuations. As a result, FL seems to be the least efficient to combat PV-related problems.

5.4 Consumption DER impact assessment with DSF

5.4.1 Load shifting: Concerning EHPs, an overall improvement of the initial results by 15% is achieved for TVP, IVP and CVP. VE and TE also show a small improvement. This low performance is owing to the ESS's weakness to better allocate constantly excessive EHP demand. In contrast, LS has the most effective performance in combating EV-related problems. TE has been eliminated, meaning there are no observable thermal issues, while even at maximum penetration, only 1% of houses are estimated not to be supplied according to EN 50160 standard (VE is almost reduced to zero), proving ESSs are a truly effective strategy.

5.4.2 Strategic conservation: Concerning EHPs, SC presents about 10% better results than LS in all evaluation metrics. The energy conservation schedule described in Section 3 results in about 10% energy savings, translated to an equivalent proportion of EHP-related problems reduction. SC seems to be the least effective among the proposed schemes for eliminating EV-related problems, with feeder's operation slightly improving for penetration levels above 30%. Additionally, it is the only scheme that still allows for thermal issues. This is due to SC's intervention profile, as it reduces residential load demand, while EV charging pattern, however, remains the same.

5.4.3 Flexible load: Compared to this scheme's application for combating PV-related problems, FL is significantly more efficient in combating EHP-related problems (Figs. 6 and 7). Compared to the initial situation, TVP, IVP and CVP metrics are reduced by about 55%, while the transformer normally operates with EHP penetration up to 60% (15% higher than no DSF scheme), as shown in Fig. 7*b*. Additionally, VE and TE have been reduced by approximately 60%. Concerning the EVs, FL reduces the CVP metric by about 52%, at a penetration level of 100%, permitting 10% more consumers to use an EV with no technical issue occurrence across the feeder (Fig. 6*c*). As far as the thermal issues are concerned, the feeder operates problem-free even when all consumers use an EV. However, this scheme's practical application, for both DERs, would involve some additional infrastructure investment costs.

5.5 Discussion about general applicability

The work of this paper is split into two parts. The first part studies the voltage and overloading problems associated with the uncoordinated and high-level penetration of several DER in LV networks, and the second part proposes different DSF schemes to ameliorate voltage and overload problems of LV networks. For both parts, the same general probabilistic assessment methodology is employed, which has been extensively used to evaluate various DER, such as EHP, EV, PV, and μCHP [4, 7, 11].

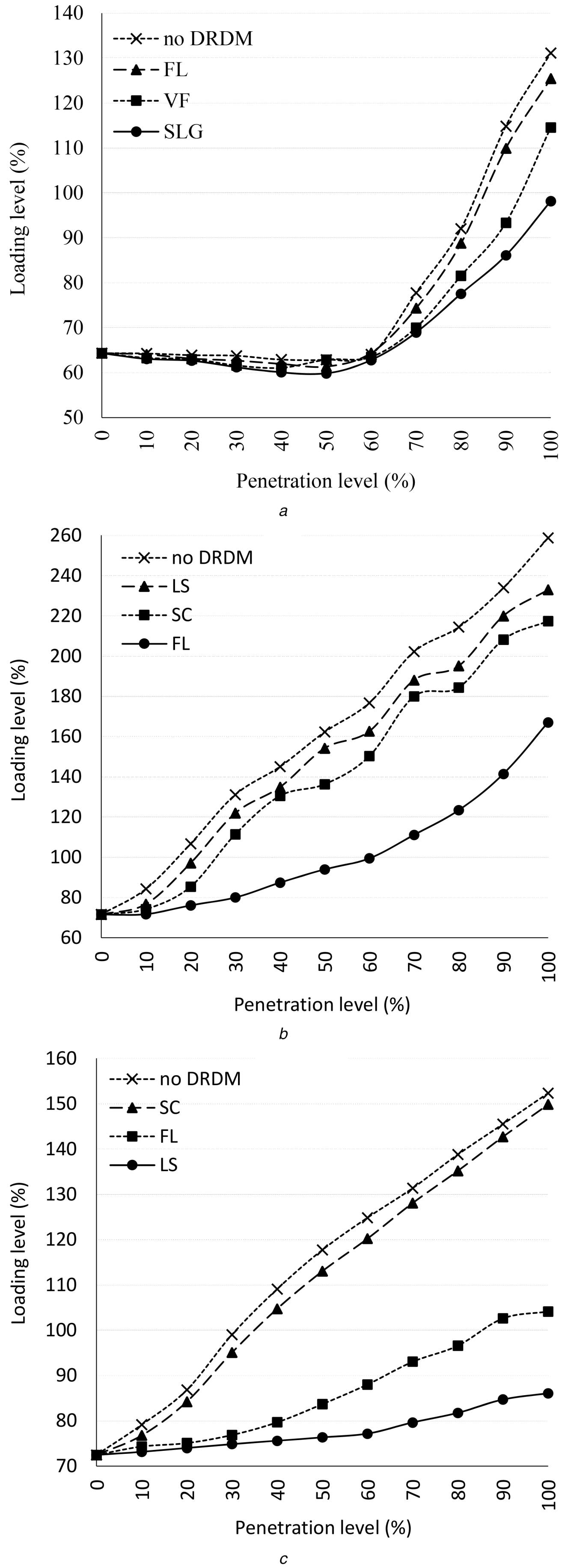

Fig. 7 *LLT impact metric per DSF scheme*
(a) PV case, ***(b)*** EHP case, ***(c)*** EV case

The results of this paper are expandable because of the following three reasons:

(i) Our study was conducted on four different real-life feeders of varying sizes to capture the impact of DER under many different scenarios. As was expected, the bigger the network and the higher the DER penetration, the more problems appeared. Thus, size-related consistency can indeed be claimed.
(ii) Our study was conducted using fully realistic tools and resources, meaning that they are currently installed at the residential level and are fully representative of what can be found at LV networks, as the parameters and profiles have resulted from real measurements. The results show that the higher the size and use of DER technology, the higher the DER penetration and the more network problems appeared. Thus, characteristics-related consistency can also be claimed.
(iii) The solution of network problems was realised using DSF schemes that were 100% customer-owned, meaning the DSO has no real authority over their operation, and that optimisation, while theoretically feasible, may find great obstacles in customers not willing to allow interventions. The rule-based approach (and seeming crudeness) of each DSF scheme was one of the most important goals of our paper because its simplicity made it easily understandable to the customers, who mostly accepted each proposal (Table 2). The fact that the survey was on every single DER and DSF scheme, and that the sample examined was quite big only adds to this claim. This is an approach built solely on cooperation and simple coordination and manages to balance social welfare and 'reality constraints' in a good way. The fact that it is fully acceptable and readily applicable means that realism-related consistency can finally be claimed.

In summing up, the representative feeders studied were real and size-varying, the loads, DER and DSF tools used were real and pre-installed, and the DSF schemes utilised, in full cooperation with the customers, were simple and always the same (in other words, realistic). Each DSF scheme, while custom-made, was applied in the same way on representative feeders of a real-world LV distribution network. The performance ranking was the same in every case. All of the above, combined with the consistency of the results on every single metric, and past bibliography, means that the conclusion drawn can be, in general, expanded to the corresponding population of LV feeders. Moreover, the probabilistic assessment methodology of Section 4 is generally applicable to other LV distribution network cases and scenarios.

6 Conclusions

This paper examines the voltage and overloading problems associated with the uncoordinated, high-level penetration of several DER in LV networks, and in turn, proposes different DSF schemes (the performances of which are also compared to each other) to combat said technical problems. It is demonstrated that the proposed DSF schemes offer distinct advantages, such as power quality improvement and energy cost savings through increased DER use. As can be seen in Table 5, almost all DSF schemes increase the maximum problem-free DER penetration level between 10 and 40% and cause a significant reduction in voltage violations (in quantity and in affected customers) and thermal violations (at the feeder and at the substation). In terms of effectiveness, the PV-induced problems during summer days are tackled most effectively by the SLG scheme, which, even at the highest level of penetration, eliminates all thermal issues and alleviates the voltage issues of >50% of customers. In winter time, the LS scheme more than doubles the acceptable EV penetration, while at the highest levels the LS scheme eliminates all thermal issues and exhibits virtually no voltage issues. EHP-related issues are drastically combated by the FL scheme, which, while only slightly increases the maximum penetration level, it effectively halves all impact metrics. On average, at a 100% DER penetration, the most effective DSF schemes achieve an average (overall) customer satisfaction improvement (CVP improvement) of about 70% and a thermal stressing reduction of about 34%. It should be noted that although the various DSF schemes are studied in a heuristic way, the results obtained can be used to screen which DSF schemes are more effective/ineffective for each DER. It must be further stressed that all schemes are simple (heuristic), realistic (no excessive additional infrastructure investment) and fully applicable (Table 2), also considering customer participation, meaning they are in theory immediately realisable. Based on the first level analysis performed by this paper, it can be decided which DSF schemes are worth exploring further. In conclusion, since it is now known which DSF scheme is most effective for each DER, there are two important suggestions for future research on the field: an optimisation study (assuming public acceptance), to discover the peak performance/limitations of each scheme, as well as a techno-economical study, to examine the applicability of each scheme.

Q2 7 References

[1] International Energy Agency (IEA): 'Tracking clean energy progress 2017', June 2017

[2] Renewable Energy Policy Network for the 21st century (REN21): 'Renewables 2016, Global Status Report', 2016

[3] American Wind Energy Association (AWEA): 'The U.S. Small Wind Turbine Industry – roadmap, a 20-year industry plan for small wind turbine technology', June 2002

[4] Navarro-Espinosa, A., Mancarella, P.: 'Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks', *Appl. Energy*, 2014, **127**, pp. 249–266

[5] Richardson, P., Flynn, D., Keane, A.: 'Impact assessment of varying penetrations of electric vehicles on low voltage distribution systems'. Proc. IEEE Power and Energy Society General Meeting, 2010, pp. 1–6

Q3 [6] Richardson, P., Taylor, J.: 'Impact of electric vehicle charging on residential distribution networks: an Irish demonstration initiative'. Proc. Int. Conf. Electricity Distribution, 2013, pp. 1–4

[7] Navarro-Espinosa, A., Ochoa, L.F.: 'Probabilistic impact assessment of low carbon technologies in LV distribution systems', *IEEE Trans. Power Syst.*, 2016, **31**, (3), pp. 2192–2203

[8] Yi, J., Wang, P., Taylor, P.C., *et al.*: 'Distribution network voltage control using energy storage and demand side response'. Proc. 3rd IEEE PES Innovative Smart Grid Technologies Conf. Europe (ISGT Europe), Berlin, Germany, 2012

[9] McKenna, K., Keane, A.: 'Residential load modeling of price-based demand response for network impact studies', *IEEE Trans. Smart Grid*, 2016, **7**, (5), pp. 2285–2294

[10] Malík, O., Havel, P.: 'Active demand-side management system to facilitate integration of RES in low-voltage distribution networks', *IEEE Trans. Sustain. Energy*, 2014, **5**, (2), pp. 673–681

[11] Navarro-Espinosa, A., Ochoa, L.F., Randles, D.: 'Assessing the benefits of meshed operation of LV feeders with low carbon technologies'. Proc. IEEE PES Innovative Smart Grid Technologies Conf. (ISGT), February 2014

[12] Quirós-Tortós, J., Ochoa, L.F., Alnaser, S.W., *et al.*: 'Control of EV charging points for thermal and voltage management of LV networks', *IEEE Trans. Power Syst.*, 2016, **31**, (4), pp. 3028–3039

[13] Wang, Z., Gu, C., Li, F., *et al.*: 'Active demand response using shared energy storage for household energy management', *IEEE Trans. Smart Grid*, 2013, **4**, (4), pp. 1888–1897

[14] Palensky, P., Dietrich, D.: 'Demand side management: demand response, intelligent energy systems, and smart loads', *IEEE Trans. Ind. Inf.*, 2011, **7**, (3), pp. 381–388

[15] Bahrami, S., Amini, M.H., Shafie-khah, M., *et al.*: 'A decentralized electricity market scheme enabling demand response deployment', *IEEE Trans. Power Syst.*, article in press

Q4 [16] Bahrami, S., Wong, V.W.S., Huang, J.: 'An online learning algorithm for demand response in smart grid', *IEEE Trans. Smart Grid*, article in press

[17] Siano, P.: 'Demand response and smart grids – a survey', *Renew. Sustain. Energy Rev.*, 2014, **30**, pp. 461–478

[18] EN 50160: 'Voltage characteristics of electricity supplied by public distribution systems', 2007

[19] ENWL: 'Dissemination document – low voltage networks models and low carbon technology profiles', June 2015. Available at https://www.enwl.co.uk/globalassets/innovation/lvns/lvns-academic/summary-report.pdf, accessed 28 May 2018

[20] Richardson, I., Thomson, M., Infield, D., *et al.*: 'Domestic electricity use: a high-resolution energy demand model', *Energy Build.*, 2010, **42**, (10), pp. 1878–1887

[21] Paatero, J.V., Lund, P.D.: 'A model for generating household electricity load profiles', *Int. J. Energy Res.*, 2006, **30**, (5), pp. 273–290

[22] 'The University of Manchester, The Whitworth Meteorological Observatory'. Available at http://www.cas.manchester.ac.uk/re-stools/whitworth, accessed 20 May 2016

[23] 'EvoEnergy, Solar cell efficiency 2014'. Available at http://www.evoenergy.co.uk/solar-panels/our-technology/pv-cell-comparison/, accessed 28 May 2018

[24] Evangelopoulos, V.A., Georgilakis, P.S.: 'Optimal distributed generation placement under uncertainties based on point estimate method embedded genetic algorithm', *IET Gener. Transm. Distrib.*, 2014, **8**, (3), pp. 389–400

[25] 'Wind & Sun Co, Info on the UK Windspeed Database'. Available at http://www.windandsun.co.uk, accessed 28 May 2018

[26] Gellings, C.W.: 'The concept of demand-side management for electric utilities', *Proc. IEEE*, 1985, **73**, (10), pp. 1468–1470

[27] Conejo, A.J., Morales, J.M., Baringo, L.: 'Real-time demand response model', *IEEE Trans. Smart Grid*, 2010, **1**, (3), pp. 236–242

[28] Logenthiran, T., Srinivasan, D., Shun, T.Z.: 'Demand side management in smart grid using heuristic optimization', *IEEE Trans. Smart Grid*, 2012, **3**, (3), pp. 1244–1252

[29] 'Demand response research center – demand response quick assessment tool'. Available at https://drrc.lbl.gov/tools/, accessed 28 May 2018

[30] Dugan, R., Mcdermott, T.: 'An open source platform for collaborating on smart grid research'. Proc. IEEE Power and Energy Society General Meeting, 2013, pp. 1–7

[31] Jaeger, E., Du Bois, A., Martin, B.: 'Hosting capacity of LV distribution grids for small distributed generation units, referring to voltage level and unbalance'. Proc. 22nd Int. Conf. Electricity Distribution (CIRED 2013), Stockholm, Sweden, June 2013, pp. 1–4

[32] Bletterie, B., Kadam, S., Stifter, M., *et al.*: 'Optimization of LV networks with high photovoltaic penetration—balancing the grid with smart meters'. Proc. IEEE Grenoble PowerTech 2013, Grenoble, France, June 2013, pp. 1–6

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