IMPACT OF PV AND LOAD PENETRATION ON LV NETWORK VOLTAGES AND UNBALANCE AND POTENTIAL SOLUTIONS

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ABSTRACT

This paper presents the impact of increasing amounts of PV and load penetration on LV network voltages and unbalance, and assesses the feasibility of potential mitigation solutions.

INTRODUCTION

Distribution systems were traditionally designed to supply loads with electrical power generated from a centralized generation system that was either connected directly to the distribution system or via a transmission system. With the effect of electricity market deregulation, government incentives in promoting a low carbon future, decreasing cost of power electronics, PVs, etc., there has been a steady growth and penetration of small scale Distributed Generation (DG), especially considerable amount of PV penetration into LV networks [1]-[3].

Existing utility LV loads are predominately single-phase connections supplying typical household loads, with a few balanced three-phase connections for small scale business owners, and to larger LV customers. Although efforts are made by utilities at the design stage to maintain a fair distribution of single-phase loads among phases [3], a certain level of load unbalance still exists due to consumer consumption habits, physical connection constraints, etc. In addition, new single-phase DGs are often connected to existing load phase connection points that are allocated to enable fairly equal load distribution among phases, but not generation. This adds to further unbalance in the network.

The paper presents a study undertaken on an actual LV network in the UK. The level of voltage drop/rise and unbalance across the network is investigated for both normal and assumed extreme operating conditions of existing load/generation levels and grid operating conditions. The investigation into assessing the effectiveness of various mitigation options in regulating LV voltages and unbalance is presented.

STUDY NETWORK

A four-wire model of the sample network was developed in DIgSILENT PowerFactory software, as given in Figure 1, based on the actual geographic layout of the network. The network consisted of four three-phase LV feeders supplying approximately 240 individual domestic single-phase connections, 25 three-phase domestic connections (supplying a single or several properties), one three-phase connection to a local school, 77 street lights, and 38 domestic PV connections. The data and assumptions used in the study are summarised in the subsections following.

Figure 1 – Sample LV Network

Network Equipment Data

500kVA supply transformer, 11/0.433kV, DYn11, Z=0.0047+j0.016Ω referred to the LV side, Y side solidly earthed, 5 taps with 2.5% per tap; UK LV utility feeder configurations with lengths according to geographic layout in Figure 1. Typical values are assumed for cable impedances. The following assumptions were made: fixed domestic and non-domestic loads are 1kW and 18kW respectively, at 0.95 lag power factor; fixed street lighting loads are 0.1kW at 0.9 lag power factor and PV units range between 1.7kW to 3kW in output, at unity power factor.

Network Operational Data

UK statutory LV voltage magnitudes of +10% and -6% of 230V nominal line to ground, and voltage unbalance factor of 1.3%; 11kV supply voltage extremes magnitudes of ±6% of nominal were selected; LV transformer at nominal tap; UKREC [4] typical load profiles with either Domestic Unrestricted or Domestic Economy 7 type per simulation, and Non-domestic load was Non-Domestic Maximum Demand with Load Factor 20-30%; normalised typical average half-hourly PV generation; normalised typical average half-hourly street lighting load.

Network Performance Indices

The following indices were used to assess the LV network performance for various considered voltage magnitude and unbalance mitigation solutions.

Network Voltage Performance Index ($V_{PNetIdx}$)

$$V_{PNetIdx} = \frac{\sum_{n=0.1}^{n=0.9}[percentile(V_{P2Idx}, n)\cdot(1-n)]}{\sum_{n=0.1}^{n=0.9} n}.$$

Where, $0 \le V_{PNetIdx} \le 1$, $V_{P2Idx} = \begin{vmatrix}[1-abs(1-V_{a1})]^2 \\ \vdots \\ [1-abs(1-V_{an})]^2\end{vmatrix}$,

'P' is Phase A, B, or C, and 'n' is the total number of network nodes or buses under consideration. Voltage performance is best when the $V_{PNetIdx}$ value approaches 1 and worst when it approaches 0.

Network Maximum Voltage Unbalance (VUF_{Max})

$VUF_{Max} = \mathrm{Max}[V_x]$. Where, $V_x = \begin{vmatrix}[u_{21}/u_{11}] \times 100 \\ \vdots \\ [u_{2n}/u_{1n}] \times 100\end{vmatrix}$, and x is the total number of network nodes or buses under consideration.

Network Loss Performance Indices (L_{PIL}, L_{PIG})

L_{PIL} = [Total Losses / Total Load] x 100 %; L_{PIG} = [Total Losses / Total Generation] x 100 %. Where, total generation is the sum of network's distributed generation and external network/grid supply.

RESULTS, DISCUSSION, AND FINDINGS

Fixed Time Load and PV Generation

Voltage profile results from the network unbalance load flow calculations at a single point in time for the following cases are given in Figure 2 and Figure 3 respectively: Maximum load, no PV generation, low 11kV supply voltage; low load, maximum PV generation, and high 11kV supply voltage. These studies were also repeated for nominal 11kV supply voltage.

Although significant efforts are made by the utilities in equal distribution of loads and DGs where possible, it's not always possible to maintain a complete symmetry of load and generation among network phases, even when all the loads and generation connected may be of the same capacity. This is due to variation in feeder section distances due to geographic asymmetry, unequal distribution of load and PV connections between phases, and practical difficulties in making or knowing phase notation of physical connections, especially when they were possibly laid and connected several decades ago. These characteristics are seen in both Figure 2 and Figure 3. In Figure 2, the red phase is more loaded (and therefore greater voltage drop along the feeders) in Feeders 2, 3, and 4, while the Feeders 4 and 5 are more loaded compared to the other two feeders. Similarly in Figure 3, there is more PV generation and voltage unbalance in Feeders 2 and 4 compared to the other two feeders.

A general trend of deviation of voltage magnitude and voltage unbalance from their nominal values was observed along the feeders, especially with feeders supplying greater distances, loads, PV generation, and their unequal connection between phases. Under nominal 11kV supply conditions and extreme conditions of network loading and PV generation, the LV network voltage magnitudes and unbalance factors were within statutory voltage limits. At the extremes of supply voltage, voltage magnitudes exceeded statuary limits, and unbalance factors approached limits. In practise, the 11kV node voltages are typically regulated by the primary substation transformers, maintaining them close to nominal values.

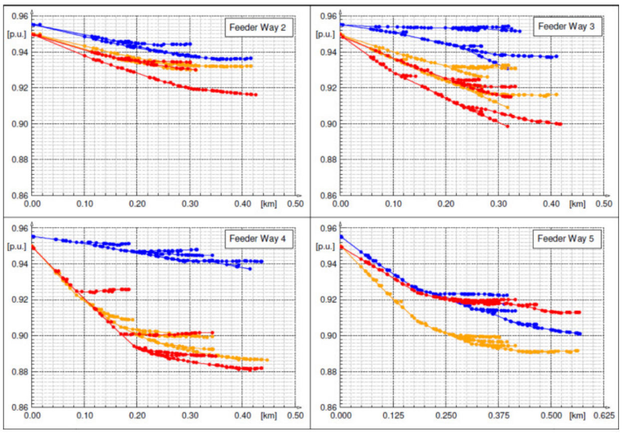

Figure 2 – High Load Voltage-Distance Plots (V_{Grid}=0.94p.u)

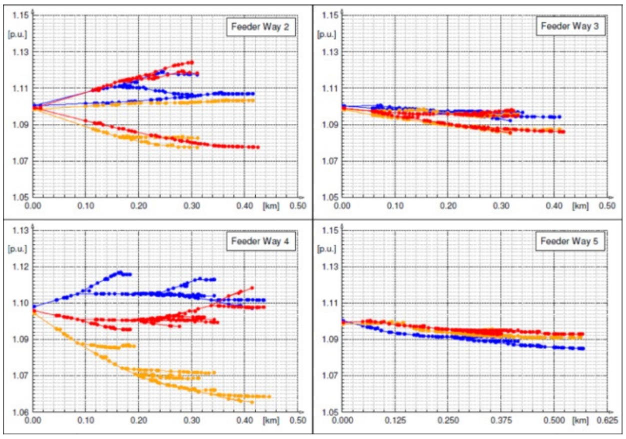

Figure 3 – High Generation Voltage-Distance Plots (V_{Grid}=1.06p.u)

Time Dependent Load and PV Generation

Although assumed worst case fixed load and generation conditions can be used for network design purposes, any voltage magnitude and unbalance improvement solution should, in addition, account for the trends identified using the voltage-time characteristics at various nodes in the network. This will greatly help the solution designers to ascertain the type of mitigation solution needed, and if the solution needs to be in operation only during specific times of the day or seasons of the years.

Accordingly, 24hr time dependent unbalance load flow studies were undertaken for both normal and extremes of

11kV supply voltage, and time dependant load and PV generation that vary with time of day, and seasons of the year. These simulations were repeated for two types of domestic load, considering one type per 24hr simulation, and applied to all LV network loads in Figure 1. The worst case network voltage-time characteristics observed during these simulations are given in Figure 4 and Figure 5. In these figures, the voltage-time plots at the LV substation are given in the top left hand corner, while the remaining are at the farthest ends of the feeder spurs.

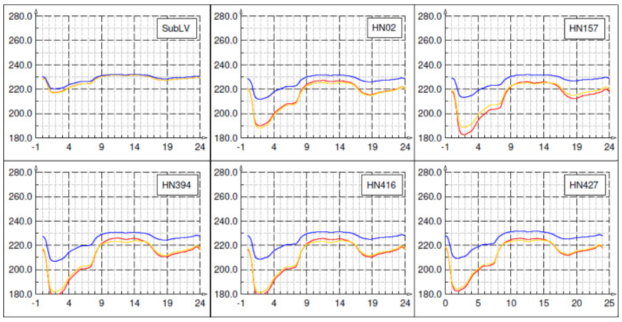

Figure 4 – High Load V-T Plots (Feeder Way 4, Winter, Domestic Economy 7 Load, V_{Grid}= 0.94p.u)

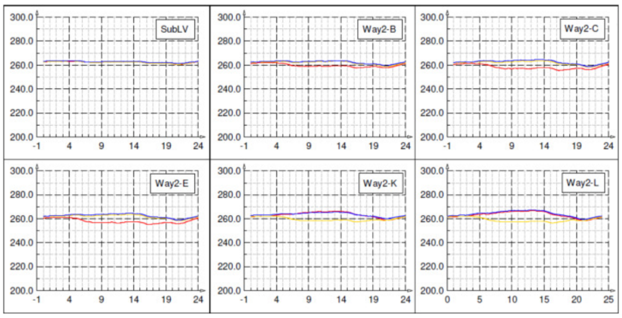

Figure 5 – High PV Gen. V-T Plots (Feeder Way 2, Summer, Domestic Unrestricted Load, V_{Grid}= 1.06p.u)

General trends identified using the fixed time simulations, such as pronounced voltage magnitude deviation and increase in voltage unbalance with feeder distance, concentration of load and PV generation on some feeders to others, etc. were also found to apply to time dependent load and PV generation variation simulations. In addition, the load and PV generation levels were found to be higher in certain times of the day and months and season, and therefore the level of network voltage magnitude deviation from nominal and voltage unbalance. For example, the studies found that severe magnitude deviations from nominal and voltage unbalance were found during the winter and spring months, at some LV nodes exceeding statutory limits.

Among the LV feeders, the lowest network voltages and severe unbalance were found to be on the Way 4 and Way 5 feeders (due to high load penetration, and loading during spring and winter months), while the highest voltages and severe unbalance were on the Way 2 and Way 4 feeders (due to light load, and high PV generation during the summer months). For the same network conditions, density of a certain load type (e.g. domestic load type) was found to affect the network voltages and unbalances significantly compared to other load types.

Results in Figure 4 and Figure 5 also show that the voltage magnitude and unbalance severity are a function of load and generation levels in time. Therefore, depending on the time of day, season, network loading and generation, the voltage magnitudes and unbalance experienced in the network may vary with feeder to feeder, and even nodes adjacent to each other on the same feeder to some degree.

Impact of Transformer Taps and PQ Injections

Table 1 shows the balanced load flow sensitivity results for a selected feeder (Way 2), the sensitivities of nodes (along the feeder) voltages to active (P) and reactive (Q) power injections, and transformer tap change across the feeder. Results in Table 1 also indicate the distance of nodes along the feeder or its spur from the LV substation.

Table 1 –Feeder Way 2 Load Flow Sensitivity Results

Bus Name	Dist. from LV Sub. (m)	ΔV/ΔP (p.u/MW)	ΔV/ΔQ (p.u/MVAr)	ΔV/ΔTap (p.u/Step)
Bus X	0	0.03	0.08	0.03
Bus A	4	0.03	0.09	0.03
Bus B	193	0.57	0.23	0.03
Bus E	425	0.67	0.26	0.03
Bus V	299	0.64	0.21	0.03

The LV voltage sensitivities to both active and reactive power node injections, i.e. ΔV/ΔP and ΔV/ΔQ, increase with nodes along the feeder with distance. In addition, the X/R ratios along the feeder are also expected to decrease with length, and therefore the LV voltages, especially at the feeder spur end nodes, are likely to be more sensitive to active power injection than the reactive power injection, and vice-versa when close to the LV substation.

The voltage sensitivity to transformer taps was fixed throughout the feeder, and was generally smaller than that of active and reactive power injections (at least in the Figure 1 sample network).

In addition, the crossover point where ΔV/ΔP > ΔV/ΔQ was found to be at nodes following the feeder's large initial sections, where the cable resistance was smaller in comparison to the remainder of the feeder cable sections. The voltage magnitudes at nodes before the crossover point were found to be more effectively regulated by the supply transformer taps, and nodes after the crossover point by the active and reactive power injections, and nodes farthest node with active power injection alone. This suggested that a PQ injection type equipment in LV network could continue operating in desired mode, while switching to most effective P or Q injection mode during emergencies (e.g. voltage limit excursions), helping bring back the entire/local LV network voltage close to its normal or LV equipment tolerance levels.

Conventional Mitigation Solutions

The following case studies were selected from a utility's perspective in assessing the effectiveness of conventional solutions in regulating LV network voltages and reducing voltage unbalance based on full utilization of existing equipment in the network, solution numbers, location, implementation, cost, and their impact on network losses.

A. Base case - Based on network equipment data, operational data, and layout given in the STUDY NETWORK section of this paper.
B. Case A with inclusion of an on-load tap changer on the existing LV supply transformer.
C. Case A with both individual feeder-spurs paralleling, and paralleling of feeders with high load and distributed generation at their closest connection points.
D. Case A with feeder mid-sections supplied completely by new additional cables.

Table 2 – Effectiveness of Conventional Solutions

Case #	$V_{PNetIdx}$ Max. of Phases	VUF_{Max} (%)	L_{PIL} (%)	L_{PIG} (%)
High load and nominal 11kV supply voltage				
A	0.95	0.87	0.052	0.050
B	0.95	0.87	0.052	0.050
C	0.95	0.71	0.050	0.047
D	0.95	0.78	0.048	0.046
High load and low 11kV supply voltage				
A	0.83	0.94	0.056	0.053
B	0.93	0.88	0.053	0.050
C	0.83	0.77	0.053	0.050
D	0.83	0.84	0.051	0.048
High PV and nominal 11kV supply voltage				
A	0.94	0.43	0.021	0.020
B	0.98	0.44	0.021	0.020
C	0.94	0.34	0.016	0.016
D	0.94	0.42	0.021	0.021
High PV and high 11kV supply voltage				
A	0.82	0.41	0.020	0.020
B	0.92	0.43	0.020	0.020
C	0.83	0.32	0.016	0.016
D	0.82	0.40	0.021	0.020

Among the above considered list of solutions (results given in Table 2), the case with a tap changer (Case B) on the supply transformer was found to be the most effective solution option in improving the network's voltage performance, especially when the 11kV supply voltage deviates significantly from 1p.u. On the other hand, reinforcement of existing feeder-sections closest to the substation using new additional cables (Case D) was found to be the most effective solution in reducing the network losses and maintaining low voltage unbalance in the network.

Studies undertaken on the sample network have shown that conventional mitigation solutions may offer partial improvement in reducing voltage magnitude and unbalance. Their effect was found to be rather broad than the much needed local mitigation of the voltage magnitude deviation and unbalance problem, applying to the larger part or the entire network supplied by a LV particular substation.

Modern Mitigation Solutions

Use of custom power devices [3][5][6], such as STATCOMs, DVRs, etc., to LV networks that offer continuous voltage regulation as their sole purpose, and/or use of installed DGs, energy storage, etc. offering partial or complete continuous voltage regulation as part of their ancillary service, are currently being explored and studied around the world. These solutions often require significant field testing and capital investment. A few of these technologies, with LV voltage regulation in part, are currently investigated in the US, EU, etc. as part of pilot projects with public and/or private funding to modernize their respective national and/or local grids.

CONCLUSIONS

With integration of new loads and DGs in LV networks, the voltage magnitude deviation and unbalance levels are expected to rise from the current acceptable levels, requiring new design strategies to enable LV networks as a sustained platform for electrical energy transfer. These strategies should be based on techno-economic factors providing the best service to the network users, while maintaining minimum asset and operational costs.

REFERENCES

[1] UK Department of Energy & Climate Change (DECC), "The UK Low Carbon Transition Plan: National Strategy for Climate and Energy", ISBN: 9780108508394, Jul. 2009.
[2] Blaabjerg, F.; Zhe Chen; Kjaer, S.B.; "Power electronics as efficient interface in dispersed power generation systems," *IEEE Transactions on Power Electronics*, vol.19, no.5, pp. 1184-1194, Sep. 2004.
[3] Shahnia, F.; Ghosh, A.; Ledwich, G.; Zare, F., "Voltage Correction in Low Voltage Distribution Networks with Rooftop PVs using Custom Power Devices," *IECON 2011 - 37th Annual Conference on IEEE Industrial Electronics Society*, vol., no., pp.991-996, 7-10 Nov. 2011.
[4] UK Energy Research Centre (UKERC), "Electricity User Load Profiles (daily) by Profile Class", 1997.
[5] Chua, K.H.; Lim, Y.S.; Wong, J.; Taylor, P; Morris, E; Morris, S., "Voltage Unbalance Mitigation in Low Voltage Distribution Networks with Photovoltaic Systems", *Journal of Electronic Science and Technology*, Vol. 10, NO. 1, Mar. 2012.
[6] Demirok, E.; Sera, D.; Teodorescu, R.; Rodriguez, P.; Borup, U., "Evaluation of the voltage support strategies for the low voltage grid connected PV generators," *IEEE Energy Conversion Congress and Exposition (ECCE)*, vol., no., pp.710-717, 12-16 Sep. 2010.