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Theme 1: Integrating New Flexibility Tools and Principles for Planning

Flexibility from multi-vector systems: beyond low-voltage network modelling

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Matthew Deakin ✉, *Sara Walker*, *Phil C. Taylor*

Department of Engineering, Newcastle University, Newcastle upon Tyne, UK
✉ *E-mail: matthew.deakin@newcastle.ac.uk*

Abstract: The relative size of energy demands from domestic water and space heating make them ideally suited for providing demand-side flexibility services. However, co-ordinated operation of flexible devices results in coincident changes in demand on adjacent low-voltage (LV) networks, and can therefore lead to a coupling of voltages between circuits. In this work, water heating temporal flexibility and space heating vector flexibility (from hybrid gas–electric heat pumps) are enabled across a network service area, and the voltage changes measured using the proposed 'flexibility voltage modulation' index. It is demonstrated that integrated medium-voltage (MV)–LV modelling increases the mean voltage modulation threefold and the variance of the voltage modulation by 70% when compared to results from an isolated LV model. The work, therefore, demonstrates the crucial role of MV networks in LV circuit simulation.

1 Introduction

Integrating zero-carbon heating and transportation demands in power systems represents a significant opportunity to improve whole energy system performance, with the change inspiring the challenge of the legacy 'fit-and-forget' power system design philosophy by engineers and academics alike. Demand-side flexibility is known to have enormous value in power systems, as it can allow for the deferral of asset upgrades or the avoidance of the purchase of expensive peaking capacity. To maximise the value to the whole system, many proposed future scenarios assume flexibilities in domestic-scale demands, so that the full potential of demand-side flexibilities can be harnessed. This has the complementary benefit of empowering consumers so that they can actively support the decarbonisation of whole energy systems.

In distribution systems, flexibilities can ameliorate peak load (thermal) constraints and voltage constraints. In the case of peak load, only those elements which are downstream of a given thermal constraint make a significant impact in radially operated systems. On the other hand, voltages on adjacent low-voltage (LV) circuits are coupled by the medium-voltage (MV) primary feeder in a European-style system; voltages are decoupled from sub-transmission via the tap changer at the primary substation.

Previous works on European-style distribution systems often neglect the primary (MV) feeder when modelling domestic-scale distributed energy resources. For example, in [1], the authors study the impact of low carbon technologies (such as electric vehicles and heat pumps) on 128 feeders, with the head of each LV feeder set to a constant voltage. Similarly, in [2], the authors consider the use of energy storage for controlling LVs, considering only the allowable voltage drop in the LV network. Sometimes, the primary circuits are modelled using a Thévenin equivalent impedance, as in [3]; again, the challenge here is that other circuits on the primary (MV) feeders will cause additional voltage drops if flexibilities are called upon in all LV circuits. If there is only one LV circuit with flexibility capabilities, these methods are justified; in a high-penetration scenario, however, this is not realistic.

Some works do consider the impacts of the coupling between circuits explicitly. In [4], the authors study a similar problem to that described here using an integrated MV–LV system, although the authors do not consider system flexibilities and a linearised load flow is used (so some error will be introduced in system voltage calculations). In [5] an LV circuit is modelled alongside the MV feeder for the purpose of ensuring that the number of tap changes is kept to a minimum. To the best of our knowledge, there are no works that study the impact of flexibilities on voltages in a European-style MV–LV network, with a deep penetration of domestic scale loads on all LV circuits, with each load providing flexibility services.

This work proposes an enhanced method for studying the impact of domestic-scale flexibility on distribution network voltages. A UK-based scenario is considered with a significant penetration of electrified space- and water-heating demand (these demands are currently met by gas). It is proposed that the MV distribution circuit should be explicitly modelled in its entirety, *without* aggregating LV loads, so that the full impacts of the flexibility on voltages can be calculated. The proposed 'flexibility voltage modulation', accounting for increased voltages due to reduced or shifted demand, is studied to determine the impact of the improved modelling method.

2 Methodology

As outlined in the introduction, previous works only consider the impact of domestic-scale flexibility on individual LV circuits (as shown in Fig. 1). The main purpose of this paper is to illustrate this modelling of distribution network service areas using decoupled LV circuit models can lead to the under-valuing of domestic-scale flexibilities (with respect to the sensitivity of the system to voltages).

The traditional and proposed methods for evaluating the benefits of flexibilities are termed the *isolated* LV model (Fig. 1) and the *integrated* MV–LV system model (Fig. 2). The characteristics of these models can be summarised as follows:

- The Isolated model uses a Thévenin impedance to model the MV primary feeder, connecting the MV bus at the MV–LV (secondary) substation transformer to the primary substation. Each LV circuit is modelled in isolation.
- The Integrated model uses the full MV system model, with all LV circuits in the network service area simulated concurrently.

In both instances, the tap changer between the sub-transmission and MV systems is modelled as a perfect regulator (i.e. the regulated bus is modelled as a voltage source). Likewise, all LV

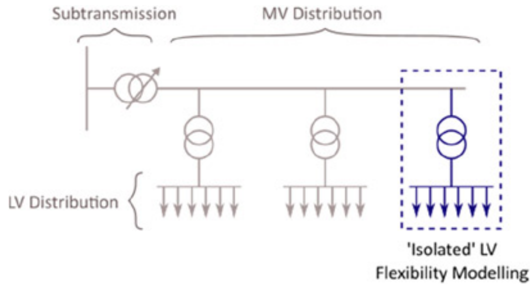

Fig. 1 *Isolated LV flexibility modelling does not consider the coupling of voltages that occurs on MV distribution lines (although a Thévenin impedance models the impedance of the MV distribution circuit to an individual feeder)*

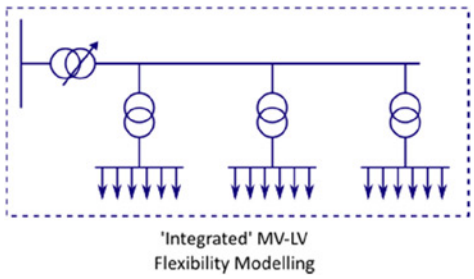

Fig. 2 *Integrated MV–LV flexibility modelling explicitly models all coupled circuits, to calculate the full realisable benefits of flexibility actions on voltage magnitudes*

feeders are connected to a common busbar downstream of the MV–LV transformer. The integrated model does have additional computational requirements compared to the isolated model, but no special computing resources were required for any calculations (the load flow calculations are carried out in OpenDSS on a desktop Windows PC).

2.1 Circuit model

The 33 Bus circuit of [6] is utilised with this work, with LV circuits models taken from [7]. Networks are chosen from the latter such that the peak load power matches the individual loads of the 33 Bus, so the MV profile of the circuit does not change.

Although all load buses have an LV circuit connected, for clarity the circuit at Load 31 (located at Bus 32) is chosen for study. This is towards the end of the primary feeder, and has Network 1 from [7]

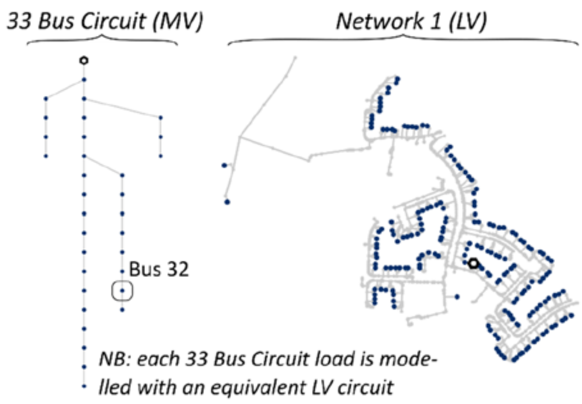

Fig. 3 *33-Bus circuit of [6] (left) is coupled with 32 LV networks from [7], with Network 1 (right) connected to Bus 32*

connected. Single-line diagrams of the MV system and the Network 1 LV circuit are plotted in Fig. 3.

2.2 Demand modelling

Synthetic data from the Centre for Renewable Energy Systems Technology (CREST) thermal–electric demand model [8] are obtained for electricity and heat demand. A cold winter's day is assumed, with an average outdoor temperature of 0°C, with an assumed heat pump coefficient of performance of 2.0. A total of 4019 domestic demand profiles are created for each load from the 32 LV circuits, with 20% of them having electric space and water heating. A profile for each load is created at a 1-min resolution, which is downsampled to a 10-min resolution (to match steady-state voltage violation requirements).

2.3 Types of flexibilities

Two types of flexibilities are considered in this work: flexibilities within *time*, and flexibilities within *vectors*. Flexibilities in time include most traditional demand-side response methods (electric vehicle smart charging, using thermal storage), whilst flexibilities within vectors imply there are multiple vectors that can meet a particular energy demand (e.g. hybrid heat pumps or hybrid electric vehicles). Flexibilities in time, therefore, represent demand that must be met later, which is not the case for demands shifted by vector.

2.3.1 Flexibilities in time and vector: To demonstrate flexibilities in time, we consider using electric hot water tanks as a thermal store, with the demand schedule brought forward. It is assumed that this does not heavily impact on demands (future works could consider increased demand due to losses).

For considering flexibilities within vectors, we consider a hybrid heat pump. It is assumed that the operation of the heat pump can either be met from electrical or gas vectors.

2.3.2 Impacts of flexibilities: In this work, we are primarily interested in two distribution system quantities: peak load and voltage magnitudes. Assuming that losses are relatively small (electrical losses in the circuit are <5%), peak load can be found by simply adding demand to find the total load. That is, under an assumption of small losses, there is no explicit network model required for modelling peak demands (except for the assignment of loads to substations). Under this model, shifting loads in time or by vector changes peak demands linearly – this is an attractive model by virtue of its parsimony.

In the case of voltages, the isolated and integrated models return very different results. As well as looking at the voltage magnitudes, it is, therefore, necessary to consider how the flexibilities change the voltages. To do so, we define the *flexibility voltage modulation*, ΔV_{Flex}. This is found by taking the difference between the voltage magnitudes at each bus with and without flexibility, at a given time instant t, as

$$\Delta V_{\text{Flex}}(t) = V_{\text{Flex}}(t) - V_{\text{Base}}(t),$$

where the vector V_{Base} collects the voltage magnitudes without flexibilities enabled (the base case) and V_{Flex} collects the voltage magnitudes with the flexibility enabled (the flex case). The Isolated model will be contrasted with the Integrated model by considering this flexibility voltage modulation ΔV_{Flex}.

3 Results

The underlying electricity demand, space heating, water heating and total demand are plotted in Fig. 4 for the whole network both before and after flexibilities are utilised. In the base case, the morning hot water demand peak matches the underlying electricity demand

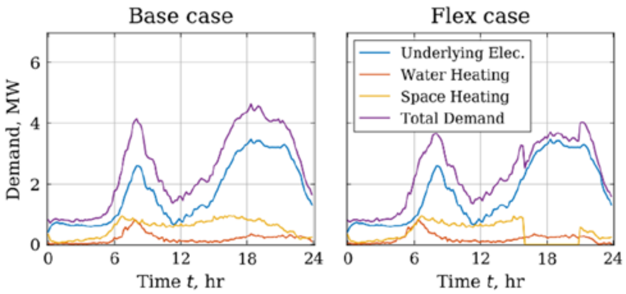

Fig. 4 *By shifting the water heating demand schedule forward by 90 min and using gas for space heating from 16:00 to 21:00 h, the peak demand from the base case (left) is reduced in the flex case in both the morning and the evening (right)*

peak. The space heating demand also peaks around the same time as the underlying electricity demand peak (during the evening peak).

To ameliorate this issue, the flexibility (flex) case has brought forward all water heating demand by 90 min, and switched the space heating vector from electricity to gas between the hours of 16:00 and 21:00. These two actions reduce the daily peak demand by 13%, from 4.62 to 4.03 MW, as shown in Fig. 4 (right). This may represent a worthwhile reduction in peak load, although it is worth highlighting this also leads to 30.2% of the daily space heating demand being met by gas, which may lead to increased carbon intensity of the system.

3.1 Changes in voltages magnitudes and changes in calculated flexibility voltage modulation

As well as impacting the peak demands, the voltages in the circuits will also be affected. We are particularly interested in how these vary between the Isolated and Integrated circuit models. As discussed in Section 2, the former only models the MV distribution network using a Thévenin impedance, whilst the latter models all 32 of the LV circuits explicitly.

The voltages of the MV buses of the circuits are plotted in Fig. 5. The range, interquartile range (IQR) and median voltages are plotted for both the isolated and integrated models, for both the base case and the flex case. The first thing that is notable is that the isolated model shows a much smaller range of voltages, as it is only the source bus and Bus 32 which are explicitly modelled. The other key feature that can be drawn from this figure is that there is a much larger change in the MVs in the integrated than isolated models (around 8 am and 6 pm).

The impact of these changes is just as stark on the LVs in Network 1 circuit, as shown in Fig. 6 (for clarity and conciseness, only this LV network is studied explicitly in this work). Again, the range, IQR and MVs are plotted for the isolated and integrated cases; here, however, the key differences are in terms of the depth of the voltage drop in the base case, and then the degree by which the

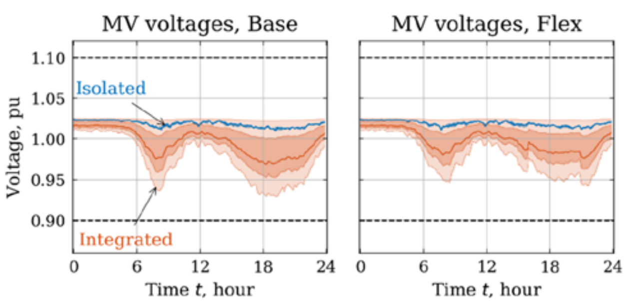

Fig. 5 *Comparing the isolated and integrated models in terms of the range, IQR and median MVs; these are plotted for the base case (left) and flex case (right)*

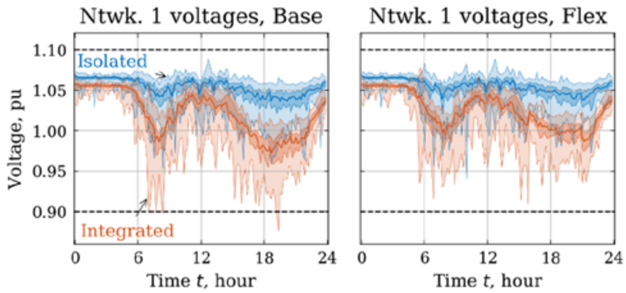

Fig. 6 *Comparing the isolated and integrated models in terms of the range, IQR and median LVs; these are plotted for the base case (left) and flex case (right)*

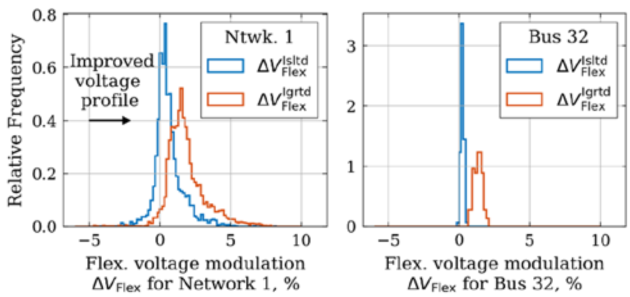

Fig. 7 *Histograms of the flexibility voltage modulation for Network 1 (left) and Bus 32 (right) between the hours of 16:00 and 21:00, comparing the isolated flexibility voltage modulation* $\Delta V_{\text{Flex}}^{\text{Isltd}}$ *against the integrated flexibility voltage modulation* $\Delta V_{\text{Flex}}^{\text{Igrtd}}$

voltages change in the flex case. In fact, from this figure, it can be seen that voltage magnitude violations can be cleared by making use of flexibility measures. If only the isolated model had been used, the voltage violations would not have been identified in the first instance.

This point is further demonstrated by considering the flexibility voltage modulation, ΔV_{Flex}, as described in Section 2.3.3, which is plotted in Fig. 7 for voltages between 16:00 and 21:00 h. In this figure, a histogram of the flexibility voltage modulation is plotted for the LV buses in Network 1 (left). The mean flexibility voltage modulation for Network 1 using the integrated model is 1.86%, whilst it is only 0.609% for the isolated model. Similarly, the variance of the integrated model is 1.89×10^{-4} pu^2, whilst it is only 1.11×10^{-4} pu^2 for the isolated model.

This can be explained by the difference in the voltage at Bus 32 (the MV bus at the head of Network 1): this has a mean flexibility voltage modulation of 1.34% in the integrated model, versus just 0.23% in the isolated model (see Fig. 7, right). It is worth noting that other LV networks with a smaller electrical distance to the primary substation (i.e. closer to the substation in Fig. 3) will likely have less of a difference in the flexibility voltage modulation at the corresponding MV bus.

As previously noted in Section 2.3.2, if peak shaving is the only application, then a network-free model is likely to be sufficient. On the other hand, if voltage modulation is required (or voltage magnitudes are a concern), then these statistics demonstrate clearly the imperative for accurate system-wide network modelling, including a detailed MV network model.

4 Conclusion

This work considers how flexibilities in distributed energy resources such as water and space heating can be used by for peak demand reduction and improving voltage profiles. The study investigates the coupling between LV circuits on a given MV primary feeder via the proposed flexibility voltage modulation index. It is shown that legacy isolated circuit modelling underestimates the mean voltage modulation attributable to flexibility measures by as much as three times on a given LV circuit, with the variance also underestimated by 70%. This is driven by a voltage increase on the MV circuit caused by other LV circuits (each LV circuit is assumed to respond to the same demand-side flexibility signal). It is concluded that distribution network modelling must move beyond Thévenin equivalent models when modelling the impact of pervasive domestic-scale flexibilities on voltages so that services provided to networks can be assessed accurately and incentivised accordingly.

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