INTRODUCTION

A developed methodology for design of low voltage networks with small generators is described in this paper by presenting the design stages/tasks, applied methods and the developed procedures. The main focus is on compliance with statutory planning limits such as voltage regulation, voltage unbalance and fault levels. Installation of a simple on-load tap-changer on distribution transformers is envisaged as a possibility to resolve the voltage rise/drop problem.

BACKGROUND

Following the setting of UK targets to increase electricity generated by renewable and combined heat and power (CHP) sources, it is expected that the number of small scale embedded generators (SSEGs) connected to the low voltage (LV) network will increase dramatically over the coming years. The extensive international work has identified several areas that need elaboration [1]–[5], and among them, voltage regulation, voltage unbalance and fault levels play the dominant role when considering design of LV networks [6].

National work within UK industry has followed rapid developments in this field and the main focus was placed on solutions and guidelines for connecting distributed generators to the network [6]–[8]. Technical terms and conditions for connecting SSEGs to LV networks were recently published in Engineering Recommendation G83/1 [9]. This has indicated that the traditional planning of LV networks within utilities needs to be revised, and that the new codes of practices for designing LV networks that can accommodate large penetrations of SSEGs need to be developed.

In this paper, we present a developed methodology for design of LV networks with SSEGs. The main stages are the determination of the cross-sectional areas of the LV distributors and services and checking the LV network design to ensure that voltage unbalance and fault levels are within prescribed limits. Three algorithms are developed to integrate the design stages into a new LV network design procedure. The green-field development (GD) procedure is applied where a new substation is necessary to supply new premises with SSEGs. The green-field/brown-field development (GBD) procedure is used where the existing LV substation has sufficient spare capacity for the new premises with SSEGs. Finally, the Brownfield development (BD) procedure is applied in cases where a number of existing customers have purchased SSEGs. The presented methodology is supported by a worked-through illustrative example.

DESIGN STAGES AND TASKS

The main stages required to design LV networks are:-
1. Determination of the number of new LV substations.
2. Design of the LV distributors including interconnections.
3. Checking of fault levels against the prescribed limits.
4. Checking of voltage unbalance against the statutory limits.
5. Ensuring that voltage fluctuations do not give rise to voltage flicker.

The first two stages can further be classified into a number of tasks. When considering design of a LV network with SSEGs, following tasks will usually be required:-
1. Assessment of the load supplied to new domestic premises with SSEGs and of the load delivered to existing premises in the maximum regime. The maximum regime is the operating regime where the difference between the total demand and generation is maximal (conventional power flow).
2. Assessment of load supplied to new and existing premises in the minimum regime. The minimum regime is the operating regime where the difference between the total generation and demand is maximal (reverse power flow).
3. Determination of the volume of micro generation to be connected to the LV network.
4. Assessment of the unused conventional and reverse capacities of the existing LV network and, possibly, of the HV system.
5. Determination of the number and sites of new LV substations (if any).
6. Selection of the procedure for design of the LV system.
7. Sizing of the LV distributors and services. Cross sectional areas will be determined by considering the voltage drop in the maximum regime, the voltage rise in the minimum regime and the electrical loadings in both regimes.
8. Determination of the correct fusing to protect all LV distributors.

LOW VOLTAGE NETWORK DESIGN TASKS

A brief description of the tasks, models and tools used for design of LV networks with SSEGs is given in the following subsections.
Load Supplied in the Maximum and Minimum Regimes

Assessment of the load delivered in the maximum regime is done where there are new premises with SSEGs (GD and GBD procedures). All loads are calculated using the after diversity maximum demand (ADMD) method [10].

The load in the minimum regime is determined from the total number of new and existing customers and the minimum average demand (MAD) per customer in kW. MAD per customer is dependent on the type of domestic premises and type of generation installed. For example, average winter daily profiles are considered for domestic CHP (DCHP), fuel cell CHP (FC CHP) and micro-hydro (μH), average summer and winter daily profiles for FC and micro-wind (μW), while photovoltaics (PV) require analysis of daylight windows of the average summer daily profiles. The indicative values of the MAD per customer are given in Table 1.

### TABLE 1 – MAD per customer for different load & generation categories

<table>
<thead>
<tr>
<th>Load Category</th>
<th>MAD per customer (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic Unrestricted</td>
<td>0.17 0.16 0.31</td>
</tr>
<tr>
<td>Domestic Economy 7</td>
<td>0.45 0.23 0.23</td>
</tr>
</tbody>
</table>

Volume of Micro Generation and Unused Capacities

Generator nameplate data are used to find total nominal active (kW) and reactive generations (kVAR). It is assumed that the SSEGs operate at full output in the maximum regime.

Unused conventional capacity of the LV system is determined where new domestic premises are connected to the network, while unused reverse capacity is assessed in all cases. The unused conventional and reverse capacities of the LV network are determined as the minimum values of the unused conventional and reverse capacities of the individual LV network components. The latter are the MVA (or MW) margins between the component conventional/reverse capacity and the conventional/reverse power flow in the maximum/minimum regime. These quantities are used to determine whether new LV substations are required for the new premises.

In some cases it is beneficial to assess the unused conventional and reverse capacities of the HV system. The unused conventional capacity is found by considering conventional capacities of HV components, voltage regulation and reliability indicators. On the other hand, the reverse unused capacity is based on the reverse capacities of HV components, voltage regulation and protection settings. It should be noted that some types of tap-changers on primary transformers can have reduced reverse power flow capability.

Checking and sizing of LV distributors

Voltage drop. Permissible voltage drops on LV distributors and services are given in [11]. Calculation of the actual voltage drops in the maximum regime is done using either a manual approach or the dedicated software tool [11].

Permissible voltage rise. The maximum permissible voltage at any point of the LV network is 230 V + 10%. The permissible voltage rise from the substation low-voltage busbar to any customer’s cut-out is the difference between this limit value and the low-voltage busbar voltage:

\[ \Delta v^w = [110 - v_{HV}(1+b_k)] \% \]

where \( \Delta v^w \) is permissible voltage rise (%), \( v_{HV} \) is voltage magnitude (%) at the high voltage busbar of the distribution substation possibly modified by the voltage rise/drop on the transformer impedance and \( b_k \) is distribution transformer voltage boost (pu) that is dependent on tap position \( k \). The transformer boost is calculated using the formula:

\[ b_k = \left[ \frac{V_{2n}^r}{V_{2n}} \cdot \frac{1}{1 + v_k/100} - 1 \right] \text{ pu} , \]

where \( V_{2n}^r \) is nominal voltage (V) of the distribution transformer secondary (typically 433 V), \( V_{2n} \) is nominal voltage (V) of the LV network (230-3 V) and \( v_k \) is percentage voltage increase/decrease (%) of the distribution transformer voltage at the HV side that is dependent on the tap position \( k \). Values of voltage boost \( b_k \) for a distribution transformer with ±2x2.5% taps are given in the Table 2 (\( V_{2n}^r =433 \text{ V} \); \( V_{2n}=230-3 \text{ V} \)), and the permissible voltage rises are presented in Table 3.

### TABLE 2 – Voltage boost for different tap settings

<table>
<thead>
<tr>
<th>Voltage change ( v_k(%) )</th>
<th>+5</th>
<th>+2.5</th>
<th>0</th>
<th>-2.5</th>
<th>-5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage boost ( b_k(\text{pu}) )</td>
<td>0.0351</td>
<td>0.0604</td>
<td>0.0869</td>
<td>0.1148</td>
<td>0.1441</td>
</tr>
</tbody>
</table>

### TABLE 3 – Permissible voltage rise \( \Delta v^w \)

<table>
<thead>
<tr>
<th>HV voltage ( v_{HV}(%) )</th>
<th>97</th>
<th>98</th>
<th>99</th>
<th>100</th>
<th>101</th>
<th>102</th>
<th>103</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permissible rise ( \Delta v^w(%) ) (nominal tap)</td>
<td>4.6</td>
<td>3.5</td>
<td>2.4</td>
<td>1.3</td>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permissible rise ( \Delta v^w(%) ) (lowest tap)</td>
<td>9.6</td>
<td>8.5</td>
<td>7.5</td>
<td>6.5</td>
<td>5.4</td>
<td>4.4</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Voltage at the high-voltage busbar. Voltage \( v_{HV} \) should be assessed in the minimum regime as accurately as possible. Where the LV transformer is supplied from a meshed HV system, the simplest approach is to use a dedicated software tool. Manual calculation is suitable for radial HV systems. Here, further simplifications can be introduced. For example,

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1 Based on load research undertaken by Electricity Association
where the distribution transformer is close to the primary substation, voltage set-point of the tap-changer on the primary transformer can be used.

**Actual voltage rise on the LV system.** Actual voltage rise shall be assessed in the minimum regime and compared against the permissible limit values (Table 3). Where a software tool is used, the HV and the LV systems should be studied as an integral entity. Manual calculation can be applied to analyse balanced, radial systems where loads and generations are balanced. The actual voltage rise on the j-th section of the LV distributor can be found as:

$$\Delta v_j = \{(0.5 \cdot D_{j} + T_{D}) \cdot P_{nom} \cdot (0.5 \cdot D_{j} + T_{D}) \cdot P_{cus} \} \cdot L_{j} \cdot v_j \cdot \% \tag{3}$$

where $\Delta v_j$ is percentage voltage rise ($\Delta v_j>0$) or drop ($\Delta v_j<0$) on section $j$, $D_0$ is number of “distributed” customers with SSEGs in section $j$, $T_0$ is number of “through” customers with SSEGs fed by section $j$, $P_{nom}$ is rated active power (kW) of a SSEG, $D_0$ is number of “distributed” demand customers in section $j$, $T_0$ is number of “through” demand customers fed by section $j$, $P_{cus}$ is the MAD per customer (kW) in the minimum regime, $L_j$ is length (km) of section $j$ and $v_j$ is specific voltage drop (%/kW/km) equal to $r_j \cdot \tan \theta \cdot \frac{1}{V_{nom}^2}$, $r_j$ is specific resistance and reactance ($\Omega$/km); tan$\theta$ is ratio of reactive and active powers in section $j$; $V_{nom}$ is nominal voltage (kV). A similar expression can be used to find the voltage rise on the LV service, where the only difference is that factor of 0.6 is used rather than 0.1 to calculate the specific voltage drop $v$ for single-phase arrangements.

**Graphical approach.** The main parameters needed for the voltage rise calculation are permissible voltage rise, number and type of demand customers, number, size and type of generators, cable size and the feeding distance. We can further define the relative number of generators with respect to the number of demand customers’ houses. Bearing in mind that the generation and demand types uniquely define the MAD per customer, we can produce a set of two-dimensional graphs, one for each generation-demand type. Each graph will have the generator and cable sizes as parameters and would display a set of curves describing the relationship between the number of houses multiplied by the feeding distance and the relative number of generators. Each curve will be drawn for a pre-specified voltage rise. These curves are used either to calculate the voltage rise given the data on generation and demand customers, or to find the maximum number (and size) of generators that can be connected when the maximum permissible voltage rise is known.

**Checking of Voltage Unbalance and Fault Levels**

Statutory limit for the voltage unbalance, which is defined as the maximum allowable percentage difference between the average of all three voltages and the individual phase voltages, is currently set to 1.3 % [12]. Dedicated software capable of calculating three-phase load flows can be used to find unbalanced voltages. Alternatively, the worst-case scenario by which all generation is connected at the given point to a single phase of the radial system with the neutral can be assessed with the aid of the following expressions:

$$U_{A} = U_{A} + \{(R + R_{A}) \cdot \cos \theta + (X + X_{A}) \cdot \sin \theta \} \cdot I_{A};$$

$$U_{B} = \{(U_{B})^{2} + I_{B} \cdot (R_{B} + X_{B}) - 2U_{B} \cdot I_{B} \cdot Z_{N} \cdot \cos \theta \}^{\frac{1}{2}};$$

$$U_{C} = \{(U_{C})^{2} + I_{C} \cdot (R_{C} + X_{C}) - 2U_{C} \cdot I_{C} \cdot Z_{N} \cdot \cos \theta \}^{\frac{1}{2}};$$

$$Z_{N} = (R_{N} + X_{N})^{\frac{1}{2}}, \quad \theta = \arctg \left( \frac{X_{N}}{R_{N}} \right).$$

where $U_{A}, U_{B}, U_{C}$ are phase-to-neutral voltages (V) following connection of generation of magnitude $I_{A}$ (A) and power factor angle $\theta$, $U_{A}$ is balanced voltage (V) prior to generation connection, $R$ and $X$ are resistance and reactance ($\Omega$) of the phase conductor and $R_{N}$ and $X_{N}$ are resistance and reactance ($\Omega$) of the neutral.

Calculation of fault levels should be done in accordance with Engineering Recommendation G74 [13]. Contribution of rotating SSEGs to the fault level is calculated as the product of a coefficient and the rated power.

**DESIGN PROCEDURES**

A simplified flowchart of design of a new LV distributor connected to a new distribution substation (GD procedure) is depicted in Fig. 1. Where voltage rise in the minimum regime is the limiting factor, then possibilities of using either the non-nominal taps of the off-load tap-changer or a simple on-load tap-changing mechanism are envisaged. In the former case, it is necessary to reconsider both the maximum and the minimum regimes. In the latter case, the minimum regime is only analysed and it is envisaged that the on-load tap-changer can change the taps twice a day via a timer or other simple trigger. In the case where any of the LV distributors has been designed using a lowered tap position, further analysis is required. It is necessary to check whether the distributors that were designed using the nominal tap setting meet the voltage constraints in the minimum and the maximum regimes. If this is not the case, a cost-effective solution is required. Firstly, the cost increase of replacing these distributors with “thicker” ones is found. This should be compared with the costs of replacing the distributors designed using a lowered tap position with the distributors whose cross sectional areas are based on the standard voltage rise/drop. The lesser of the two cost increases should determine the final distributor design.

The GBD procedure is applied in the case where existing distribution transformer has sufficient capacity for new connections. Each customer group is considered in turn and is tested as to whether it can be connected to an existing distributor. If this is not possible, the procedure given in Fig. 1 is used to design a new LV distributor. Where new premises can be connected to an existing distributor, voltage drop/rise and loadings in both regimes are calculated, and where all constraints are met, the existing distributor is used. If this is
not the case, two additional remedies are envisaged. These are transferring customers between existing LV distributors and overlaying part or the entire distributor. In the case where voltage rise is the only problem remaining, application of the on-load/off-load tap-changer is again envisaged. However, use of the lowered tap settings is only permitted if it does not adversely affect other existing LV distributors and this must be specifically checked.

In the case where existing customers have purchased SSEGs, the GD procedure, which is similar to the GBD procedure, is used. The main differences are that the minimum regime is only analysed and that overlaying the entire LV distributor rather than constructing a new distributor should be used as the last resort to solve the problem of violated constraints.

### Consider the next LV distributor:
1. Find cross-section 1 based on voltage drop.
2. Find cross-section 2 based on voltage rise.
3. Find electrical loadings in both regimes.

**ILLUSTRATIVE EXAMPLE**

A test LV system (Fig. 2) is supplied from node A and it comprises 4 sections whose lengths are AB=75 m, BC=25 m, CD=360 m and BE=300 m. Section AB supplies 30 non-electric non-detached homes, section CD 60 non-electric detached homes where 40 homes have DCHPs, while 60 non-electric detached homes and 10 with DCHP are connected to section BE. All domestic premises belong to the domestic unrestricted load category, such that the ADMD per customer is 1.0 kW (non-electric, non-detached) and 1.4 kW (non-electric, detached) [11], and the MAD per customer is 0.17 kW for all domestic premises (Table 1). All SSEGs are identical having a rated active power of 1.5 kW, while three options in respect of reactive power output are envisaged. The nominal power factor is either 0.95 lagging ($Q_G$ is produced), or 0.95 leading ($Q_G$ is absorbed), or 1.0 (no $Q_G$).

![Fig. 1 – Design of a LV distributor (GD procedure)](image)

First for the maximum regime an economical design of the LV system is undertaken by imposing constraints on the voltage drop and the electrical loading. The following cable sizes are obtained: section AB = 185 mm$^2$; section BC = 95 mm$^2$; section CD = 95 mm$^2$ and section BE = 95 mm$^2$. The total voltage drop on section AD is $v_{AD}$=5.71 % and on section AE is $v_{AE}$=4.7 %.

Next the minimum regime is analysed and the greatest voltage rise is found at point D. Three alternative distributor designs for route AD give the following voltage rises:

- **I**) $AB=185$ mm$^2$ and $BD=95$ mm$^2$: $\Delta v_{AD}=3.36$ % ($Q$ produced); $\Delta v_{AD}=2.82$ % ($Q$ absorbed); $\Delta v_{AD}=3.09$ % (no $Q$).
- **II**) $AD=185$ mm$^2$: $\Delta v_{AD}=2.13$ % ($Q$ produced); $\Delta v_{AD}=1.58$ % ($Q$ absorbed); $\Delta v_{AD}=1.86$ % (no $Q$).
- **III**) $AD=300$ mm$^2$: $\Delta v_{AD}=1.43$ % ($Q$ produced); $\Delta v_{AD}=0.9$ % ($Q$ absorbed); $\Delta v_{AD}=1.17$ % (no $Q$).

These voltage rises should be compared against the permissible voltage rises from Table 3. Assuming that the HV voltage in the minimum regime is 100 %, the permissible voltage rise $\Delta v_{\text{nom}}$ is 1.3 % for the nominal tap setting, 4 % for the $+2.5$ % position and 6.5 % for the $+5$ % setting.

The first solution to the voltage rise problem implies an increase of the distributor sizes along the ABCD route while maintaining the nominal tap setting. The solution where a 300 mm$^2$ distributor is laid in all sections (Scenario III) shows that the voltage rise constraint is satisfied when SSEGs either absorb reactive power or operate at unity power factor. However, if SSEGs produce reactive power, actual voltage rise $\Delta v_{AD}=1.43$ % is slightly greater than the limit of 1.3 %.

The second alternative is application of the on-load tap changer, which maintains the tapping on nominal tap in the maximum regime and taps down in the minimum regime. In this way, the
voltage drops stay unaffected, but the maximum allowable voltage rise becomes 6.5 % if the +5 % setting is applied. The most economical design of the LV system (Scenario I: AB=185 mm$^2$; BD=95 mm$^2$) satisfies the newly imposed voltage rise limit such that no increase of the distributor sizes is required.

The third option is to change the tap position on the off-load tap-changer, which affects the maximum and the minimum regimes. If the tap setting of +2.5 % is applied, the maximum allowable voltage drop of 7 % reduces to (7-(8.69-6.04))= 4.35 %. Since the actual voltage drops are $\Delta V_{AD}$=5.17 % and $\Delta V_{AE}$=4.7 %, it is necessary to re-design the overall LV system. Selecting the 185 mm$^2$ for all LV sections (Scenario II) gives the satisfactory voltage drops of $\Delta V_{AD}$=3.96 % and $\Delta V_{AE}$=3.4 %. The minimum regime, where the permissible voltage rise is 4 %, is studied next and it is found that the actual voltage rises are well below that limit (Scenario II).

**CONCLUSIONS**

In this paper we have presented the developed methodology for design of LV networks with small generators. We have decomposed the overall procedure into a number of tasks and stressed that it is necessary to study two operating regimes, namely the maximum and the minimum regime. We have shown that there is a correlation between the types of the small generators and the demand data used. We have presented the developed method for voltage rise calculation which accounts for non-nominal tap setting on the tap-changer. The individual design tasks were integrated into three different design procedures that can be used for network design on both green-field and brown-field sites. Finally, we have shown that application of an on-load tap changer on distribution transformers can be beneficial because the sizes of distributors can significantly be reduced.

**REFERENCES**


[9] Electricity Association, 2003, Recommendations for Connection of Small-Scale Embedded Generators (up to 16A per phase) in Parallel with Public Low Voltage Networks, Engineering Recommendation ER G83/1, UK.


