INCREASING NETWORK CAPACITY BY OPTIMISING VOLTAGE REGULATION ON MEDIUM AND LOW VOLTAGE FEEDERS

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INTRODUCTION

The maximum allowable voltage variation is a major and often primary constraint in the planning and design of distribution networks. Assumed or assigned volt drop limits affect the capital and lifetime costs of the networks. This paper describes recent research directed to:

• reducing the costs of extending and strengthening MV and LV networks,
• improving voltage regulation on existing networks, and
• standardising the maximum voltage drop limits used for planning, designing and operating MV and LV networks, taking into account the characteristics of urban and rural networks.

VOLTAGE REGULATION

Reliability constraints and economic objectives aside, the purpose of the distribution network is to provide customers with power at voltage levels for which appliances and equipment will operate with acceptable levels of performance and efficiency [1]. Customers taking supply at the low voltage service level (LV, typically 3-phase 230/400V or dual phase 230/460V) experience the combined effect of the voltage drops in both the medium voltage (MV, typically 11 or 22 kV) and LV networks. The allowable total voltage drop must be apportioned between the MV and LV network levels [2,3]. In a typical distribution network the voltages supplied to LV customers depend on:

• the type and settings of voltage control (line drop compensation, voltage compounding and fixed voltage) at the MV source;
• the MV/LV distribution transformer nominal secondary voltage and tap setting (if installed); and
• the voltage drop in each of the MV network, distribution transformer and LV network.

The distribution transformer nominal secondary voltage and tap setting influence the recommended maximum MV and LV voltage drops. The larger the tap boost, the greater the allowable voltage drops before the minimum voltage limits are exceeded at the customer’s supply point. The manner in which the distribution network is operated (voltage control settings, methodologies and distribution transformer tap settings) directly impacts the recommended voltage drop limits and apportionment for network planning and design. Standardised voltage drop and apportionment limits need to take network operating practices into consideration.

Engineers in Eskom (the national electricity utility in South Africa) have used experience-based rules, which vary considerably between individuals and regions, for the voltage drop limits for MV and LV network planning and design, with little understanding of the relation between the MV and LV network levels. National regulatory standards in South Africa only specify the voltage limits that must be met at the customer’s service point, without specifying or guiding the apportionment of voltage drop between the MV and LV networks. Preliminary studies indicated that the adoption of standardised voltage regulation and apportionment limits would benefit the Eskom Distribution Division.

CONSIDERATIONS

The following factors needed to be considered in establishing voltage regulation and apportionment standards.

National Regulatory Requirements

Regulator standards allow LV service voltage regulation of ±10% of the nominal voltage at the service point (meter) [4]. The voltage drop within the customer’s LV network (beyond the service point) is limited to 5% [5].

Customer Equipment and Appliances

In 1990 South Africa adopted a LV service voltage of 230/400V, but many customers still operate equipment rated for 220/380V. Some 220/380V equipment may experience problems (either failure to operate or reduced efficiency and/or life span) when operated at the higher voltage limit allowed by the present standard [6].

Even equipment rated for the standard LV voltage of 230/400V may not be compatible with the maximum voltage variations allowed. Three phase LV motors in South Africa have historically been designed for a maximum continual voltage variation of ±5% [7], and need to be de-rated in order to operate at ±10% [6].

Distribution Transformers

The characteristics and specifications of transformers vary significantly as a result of the changes to standard purchasing specifications in response to changes in electricity regulations. Eskom’s distribution transformers have a wide range of nominal secondary voltages including 380V, 400V, 415V and 420V three phase, and 220V, 230V, 240V and 242V single phase. Furthermore the location of the tap switch (primary or secondary), the step-size (2.5%, 3% or 5%) and number of steps (3 or 5) vary depending on the nominal secondary voltage and technology (single, three and
dual-phase).

Compatibility

The application of new apportionment limits to new and existing networks should increase, rather than reduce, their capacities, and not require network strengthening or modifications to achieve compliance with the regulations.

Network and Load Types

Distribution networks are largely influenced by the magnitude (load per customer) and density (customers per unit of area) of the load they supply [1].

Most urban networks are characterised by short (<5km) 11kV feeders supplying numerous LV customers through “large” (200-1000kVA) three phase distribution transformers. The LV transformer zones are relatively large (radius >200m), and most of the voltage drop is in the LV network.

In contrast, Eskom’s rural networks mostly comprise relatively long (20 - 100km) 11kV or 22kV feeders supplying individual customers through relatively “small” (16-200kVA) distribution transformers. Technologies include three phase, single phase, bi phase and single wire earth return. Most transformers are close to the customers and LV feeders are relatively short (<50m). Most of the voltage drop occurs in the MV network.

Many networks exhibit the characteristics of both urban and rural networks. This is especially the case with rural electrification, where low-income domestic load densities and settlement patterns are such that long (20 to 100km) MV feeders supply LV customers in large distribution transformer zones (radius >300m).

Network and Load Data Constraints

Eskom Distribution’s MV data is relatively well recorded, and simulations can be performed easily at the MV network level. However, LV load and network data records are generally incomplete, so simulations of existing LV networks require considerable data capturing activities. Apportionment processes and limits that requires detailed simulations of existing LV networks will have limited use.

Resources and Processes

The same individual does not necessarily perform the MV and LV plans and designs, and in some cases the responsibility for the different network levels is divided between different sections.

STRATEGIC ALTERNATIVES

There are two basic approaches to determining the maximum voltage drops and apportionment.

Customised voltage apportionment: The optimum MV and LV voltage drops can be determined for every feeder using actual network data, load forecasts and expected future changes. Detailed MV and LV network studies must be performed for each network expansion and strengthening project to establish the optimal voltage drop limits for the network. Values must be assumed or assigned for several variables, including loading, to which the outcomes are sensitive. The assumptions and the limits adopted must be recorded for future use for each network.

Standardised voltage apportionment: The allowable MV and LV voltage drops can be standardised for a limited set of broad network categories adequate for most applications. Customisation is performed to the extent that the most suitable Network Class is identified for a particular network or network section, and only the class needs to be recorded for each network section.

The standardised approach is preferred in the present situation because it:

• requires less data for the initial analysis, and less to be recorded for future use;
• allows parameters to be established by identifying an appropriate class for each network; and
• requires a lower level of knowledge of feeder performance and modelling, and therefore less staff training.

Ultimately once resources, network data and systems evolve to the required levels, customised apportionment may be feasible, but this is not presently the case.

NETWORK CLASSES

The maximum allowable voltage drops in both the MV and LV networks were calculated based on the:

• common distribution transformer specifications including nominal secondary voltage, tap step and tap range;
• transformer maximum flux levels;
• typical distribution transformer loading levels and internal voltage drops;
• regulatory obligations at the service point;
• typical voltage drops within the customers LV network;
• desired point of utilisation voltage regulation for customers with significant (≥7.5kW) three phase motor loads i.e. voltage regulation at the motor terminals.

The consideration of the different combinations of distribution equipment and voltage regulation limits in Eskom Distribution resulted in four natural groupings (classes) of allowable maximum MV and LV network voltage drops.

Each distribution feeder, or section of feeder, is classified as one of four Network Classes (C1, C2, C3 and C4), representing the voltage drop apportionment between the MV and LV network levels. The voltage apportionment is illustrated in figure 1.
Classes C1 and C2 will typically be used in urban networks where the MV network voltage drop is relatively small and the LV voltage drop can be large. Classes C3 and C4 will typically be used in rural networks, where the LV network voltage drop is relatively small and the MV voltage drop can be large. The classification process is performed taking into consideration the networks, distribution transformers, customers and load forecasts.

### Medium Voltage Constraints

Each Network Class has a set of upper and lower voltages within which the MV network must be planned and designed to operate. The highest value of MV voltage is constrained by transformer fluxing, and the minimum MV voltage depends on the transformer Tap Zone (the Tap Zone concept is described below). Additional constraints are placed on the MV voltage regulation limits for distribution feeders supplying customers directly at MV (these are not included in this paper).

Two MV voltage drop ranges are provided for each Network Class: “normal” and “abnormal”. The “normal” limits will ensure that, provided the LV networks are designed in accordance with requirements, all customers will receive service voltages within the national regulatory limits. Many customers will experience voltage regulation far better than the minimum requirements. During network contingencies the “abnormal” MV limits can be utilised. The “abnormal” limits may result in isolated cases where service voltages do not comply with the national standards, and may only be used as short term emergency operating conditions.

In addition to the Network Class, each distribution feeder (or section of feeder) is assigned one of three Tap Zones (TZ). The Tap Zone dictates the required tap setting of the MV/LV distribution transformer (TZ1 – minimum boosting, TZ2 - moderate boosting, TZ3 – maximum boosting). The application of Tap Zones improves the voltage performance of the network and ensures compliance with regulatory requirements while maximising allowable voltage drops. The Tap Zone influences the recommended maximum MV network voltage drop for a particular Network Class. If the MV network voltage control methodologies, settings and load characteristics are such that increased boosting of distribution transformer taps can be performed then the maximum MV network voltage drop can be increased accordingly for that particular network.

The maximum MV voltage at each point on the network dictates the required Tap Zone. The maximum MV voltages associated with each of the three Tap Zones, and their impact on the recommended maximum MV network voltage drops are shown in table 1. The voltage drop limits are based on the maximum MV operating voltage under normal and abnormal operation (see table 2), and will need to be reduced accordingly if the actual MV source voltage is less than the specified maximum.

<table>
<thead>
<tr>
<th>Tap Zone</th>
<th>Maximum MV voltage %</th>
<th>C1 Normal</th>
<th>C1 Abnormal</th>
<th>C2 Normal</th>
<th>C2 Abnormal</th>
<th>C3 Normal</th>
<th>C3 Abnormal</th>
<th>C4 Normal</th>
<th>C4 Abnormal</th>
</tr>
</thead>
<tbody>
<tr>
<td>TZ1</td>
<td>103&lt;V&lt;106</td>
<td>2,5%</td>
<td>6,5%</td>
<td>7%</td>
<td>10,5%</td>
<td>9,5%</td>
<td>13%</td>
<td>12,5%</td>
<td>16%</td>
</tr>
<tr>
<td>TZ2</td>
<td>100&lt;V&lt;103</td>
<td>4,5%</td>
<td>8%</td>
<td>9,5%</td>
<td>12,5%</td>
<td>12%</td>
<td>15%</td>
<td>12,5%</td>
<td>16%</td>
</tr>
<tr>
<td>TZ3</td>
<td>V&lt;100</td>
<td>7%</td>
<td>11,5%</td>
<td>11,5%</td>
<td>15%</td>
<td>14%</td>
<td>17,5%</td>
<td>17,5%</td>
<td>21%</td>
</tr>
</tbody>
</table>

**TABLE 1**: Upper limit of allowable voltage drop in MV network as a function of the Tap Zone (maximum MV voltage) and based on the minimum acceptable MV voltage

<table>
<thead>
<tr>
<th>Network Class</th>
<th>Maximum MV Voltage %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>104%</td>
</tr>
<tr>
<td>C2, C3 &amp; C4</td>
<td>105%</td>
</tr>
</tbody>
</table>

**TABLE 2**: Maximum MV network operating voltages for normal and abnormal network states

<table>
<thead>
<tr>
<th>Distribution Transformer</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>240/415V and 242/420V</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>230/400V</td>
<td>✔</td>
<td>N/A</td>
</tr>
<tr>
<td>220/380V</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**TABLE 3**: Distribution transformer nominal secondary voltage restrictions
Referring to table 1, the “normal” MV voltage drop limits on C3 and C4 networks vary between 9.5% and 17.5%. These large voltage drops can only be supported if the distribution transformers used are restricted to ones with nominal secondary voltages shown in table 3 (N/A = Not Allowed).

**Low Voltage Constraints**

Standardised LV voltage drop limits are used for LV network planning, design and operation. Referring to table 4, the maximum LV voltage drop is a function of the:
- Network Class (C1, C2, C3 or C4); and

<table>
<thead>
<tr>
<th>Distribution Transformer</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
</tr>
</thead>
<tbody>
<tr>
<td>240/415V and 242/420V</td>
<td>11%</td>
<td>7.5%</td>
<td>5%</td>
<td>3.5%</td>
</tr>
<tr>
<td>230/400V</td>
<td>8.5%</td>
<td>5%</td>
<td>2.5%</td>
<td>N/A</td>
</tr>
<tr>
<td>220/380V</td>
<td>5%</td>
<td>2.5%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

TABLE 4 - Maximum LV network voltage drop (excludes MV/LV distribution transformer internal voltage drop)

Detailed MV load flow studies are not needed to establish the allowable LV network voltage drops for every case. Instead, a simple look-up table is used to establish the maximum LV voltage drop for a particular network based on its Network Class and the distribution transformer characteristics.

The standard distribution transformer tap settings associated with each of the Tap Zones limits the maximum LV service voltage to 107.5% of nominal (230/400V). This approach:
- enables the MV network to be operated at slightly higher voltages during abnormal network states without exceeding the maximum service voltage restriction (110% of 230/400V); and
- results in acceptable maximum voltages for most 220/380V equipment.

Provided the customers’ LV network is reasonably designed, customers located in close proximity to distribution transformers in urban type networks (C1 and C2) will typically be able to supply motor loads with voltages within ±5% of nominal (230/400V).

**General**

The standardised limits are maximum voltage limits within which the network must be planned, designed and operated. Tighter voltage ranges, not reaching the limits, may be implemented where it is economic to reduce the cost of technical losses.

A single feeder may consist of several zones of different Network Classes. This is illustrated in figure 2.

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**FIGURE 2**: Illustration of the concept that a single distribution feeder may have more than one Network Class. For the purposes of simplification a single Tap Zone has been used on the entire feeder.
APPLICATION CONSIDERATIONS

Network planning and design: Standard voltage drop allocation in four classes of network allows planning and design to be simplified, but is flexible enough to plan most networks close to their limits, reducing over-investment.

Network operation: Active management of reticulation networks (voltage control methodologies and settings, including distribution transformer Tap Zones) achieves improved voltage regulation for existing customers, and increased supply capacity for many existing networks without further capital investment. The full-scale implementation of the new approach requires:

- enhancement of the network database to include Network Classes and transformer Tap Zones;
- staff training, resources and business processes for distribution network management and optimisation; and
- management emphasis on the importance of distribution network management (instead of only on sub-transmission).

Progress in respect of these requirements has been made by preparing a technical application standard, including:

- selection of the most appropriate Network Class by considering the MV and LV network characteristics and costs;
- assistance with problem identification when investigating customer voltage complaints;
- selection of distribution transformer tap settings;
- selection of the most appropriate MV voltage control methodology and settings (line drop compensation, voltage compounding and fixed voltage control);
- accountability and process flowcharts for management and operations;
- worked examples; and
- implementing a pilot study.

PILOT STUDY

A pilot study was performed on an 11kV rural feeder. The feeder is 35km long, supplies 115 distribution transformers and has a maximum demand of 1.8MVA. An on-load tap changing (OLTC) 88/11kV transformer regulates the 11kV source. The OLTC operated as fixed voltage control with a set-point of 102% of nominal voltage (11kV). Most distribution transformers were set on minimum boost (effectively a TZ1 Tap Zone). An 11kV voltage regulator was installed along the line, but had failed and was bypassed, resulting in customer voltage complaints.

Plot 1 shows recorded LV voltages at a customer installation at the end of the feeder prior to any optimisation. The mean LV voltages do not exceed 230V and the minimum voltage violates the -10% limit.

The feeder was optimised using the “new” approach:

- There are no 220/380V transformers on the feeder and the LV networks are limited, so the entire feeder was classified as C3. The OLTC voltage control set point was increased from 102% to 104.5% (the recommended maximum “normal” network MV voltage for C3 is 105%); and
- Two Tap Zones (TZ1 and TZ2) were created, resulting in increased tap boosting (TZ2) on 87 distribution transformers.

The measured voltages after optimisation were significantly improved as illustrated in plot 2. The mean voltage varies between +2% and –3% of the standard voltage (230V). The maximum and minimum voltages of +4 –6% are comfortably within the ±10% limits.

Load flow modelling of the feeder indicated that the “normal” capacity (without the voltage regulator in service) had been increased from 0.9 MVA to 1.7 MVA by the optimisation. Since the changes were implemented no further customer voltage complaints have been received. The voltage regulator has not yet been returned to service. Further capacity increase might be possible using voltage compounding or line drop compensation [8].

Plot 1: Recorded LV voltages (10 minute integration) prior to optimisation (line voltage regulator out of service)

Plot 2: Recorded LV voltages (10 minute integration) after optimisation (line voltage regulator out of service)
CONCLUSION

Voltage regulation and apportionment limits are a key constraint in distribution network planning and design. Formal management of voltage control and distribution transformer tap settings can reduce investment and improve the voltages at customers' installations. A new approach, based on Network Classes and transformer Tap Zones, has been developed. Application to a real feeder indicates that the new approach will result in estimated net cost savings of R25m per annum in Eskom Distribution through cancelled or deferred network strengthening no longer needed to increase network capacity.

Research continues to include the effects of load loss costs and variations in revenue due to less than ideal voltage regulation in an optimisation model for MV/LV voltage drop apportionment, which may result in changes to the recommended maximum limits of voltage variation [9].

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REFERENCES


AUTHORS

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