MODEL FOR THE APPORTIONMENT OF THE TOTAL VOLTAGE DROP IN COMBINED MEDIUM AND LOW VOLTAGE DISTRIBUTION FEEDERS

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Abstract: The maximum allowable voltage variation is a major and often primary constraint in the planning and design of distribution networks. In South Africa the apportionment of the allowable voltage drop between the MV and LV networks is not standardised and often not managed. The best voltage apportionment depends on network and load characteristics, including distribution transformer tap settings. A model is developed to calculate MV and LV voltage and voltage drop limits based on selected network and load characteristics. Comparing the results of the model with load flow simulations show the model to be suitably accurate for application to feeder calculations.

Key words: Voltage regulation, voltage drop apportionment, voltage limits, distribution planning.

1. INTRODUCTION

Medium and low voltage (MV and LV) electricity distribution networks should supply customers at voltages within ranges that allow the efficient and economic operation of equipment and appliances. The permitted voltage variation is usually defined in regulations. Voltage variation is a key constraint in electrically weak networks, and voltage management is applied to compensate for the voltage drop in the impedance of the distribution feeders through improving the load power factor or changing the effective ratio of transformers and voltage regulators. The planning, design and operation of distribution networks is based on limits adopted for the voltage drop in the MV and LV systems, but the limits for each level are mostly selected and applied separately. This paper presents an investigation of the allocation of the voltage drop in combined MV and LV systems with voltage variation management.

2. DISTRIBUTION VOLTAGE MANAGEMENT

Although ‘voltage regulation’ is a term often used to describe the variation of voltage this paper uses ‘voltage variation’ to avoid confusion with the government regulations regarding voltage. The main components of voltage variation management in distribution systems are [1]:

- Selection of technology, nominal voltage and the conductor size. Technologies include three-phase, phase-phase, single-phase and neutral, dual-phase, and single wire earth return (SWER). The conductor thermal rating and the feeder voltage drop both limit the loads that a feeder can supply.
- Fixed and switched shunt capacitor banks improve the load power factor, reducing current magnitude, voltage drop and energy losses. Shunt capacitors on MV systems can typically only increase the minimum voltage by 3% to 5%.
- MV busbar voltages at HV/MV substations are kept relatively constant despite variations in the HV and MV networks by automatic control of HV/MV on-load tap change (OLTC) transformers. Busbar voltages vary slightly due to the tap step size, voltage controller bandwidth and the use of line drop compensation.
- Line voltage regulators are used to compensate for unacceptably large voltage drop. They do not reduce reactive power demand or losses (as shunt capacitor banks do), but can usually vary the voltage over a range of 10 to 15%.
- Many MV/LV distribution transformers are fitted with low cost tap switches or tappings brought out to separate terminals, which allow the ratio of the transformer to be changed by up to 6%. As the ratio can only be changed with the transformer off, they are referred to as de-energised tap switches (DETS). The DETS setting is affected by two conflicting requirements; the maximum tap boost increases the lowest voltage received by customers when the feeder load is high, but the maximum LV voltage at low feeder load must not be unacceptably high.

The result of the voltage variation management should be to maintain the voltages at customer terminals on both the MV and LV systems within an acceptable range of the nominal voltage, usually defined by supply contracts and government regulations [2]. The planner/designer of a future network assumes the network will be operated in a reasonable manner (voltage control and tap settings, balanced loads and appropriate configuration of normally open points), and apportions the allowable voltage variation between the MV and LV networks [3, 4]. Typically, experience-based rules, which vary considerably between utilities, regions and individuals, are used to plan, design and manage the voltage drop limits for
Figure 1: Major components of a typical distribution network [1]

2.1 Approaches to voltage control

There are three main approaches to voltage control on distribution feeders [3]:

- **MV boosting**: The MV sending voltage at the source substation is increased to relatively high levels (for example 11kV +10% = 12.1kV) such that, with the MV/LV transformers on their nominal ratio, the LV voltage is at the maximum LV limit allowed.

- **LV boosting**: The transformation ratio of MV/LV transformers are such that for a nominal MV voltage the output LV voltage is the maximum rated service voltage (for example an 11kV to 400V + 10% = 440V transformer). The MV sending voltage at the source substation is not increased above nominal voltage.

- **MV and LV boosting**: A combination of MV automatic voltage control, line drop compensation and voltage compounding, and MV/LV transformer DETS tap settings.

The IEC 38 [5] and national regulatory standards in South Africa [2] only specify the voltage limits that must be met at a customer’s service point, without specifying or guiding the apportionment of voltage drop between the MV and LV networks. ANSI C84.1-1995 [6] provides recommended voltage limits for different North American distribution voltage levels (e.g. 13.8kV and 110V), but the basis for the limits is unclear. Furthermore the voltage limits are unlikely to be suitable for application in Southern Africa due to the

MV and LV networks separately, with little attention to the relation between the MV and LV network levels.

Voltage drop guidelines adopted by a utility are usually documented in internal directives, standards and policies and are not easily reviewed or referenced. Where voltage drop limits are standardised within a utility, the methodology and assumptions for the calculation of the limits are seldom specified and may not be applicable to other utilities or different networks, customers and regulatory obligations.

As shown in figure 1, the voltage conditions on the MV and LV feeders are closely related. Customers at the LV service level experience the combined effect of the voltage drops and voltage management in both the MV and LV feeder levels. The way the network is operated determines the effective voltage variation.

The system depicted in figure 1 is typical of distribution systems in Southern Africa and many other developing countries using extensive LV feeders. However, it is less typical of North American systems in which most of the distribution is at MV with very short LV feeders.

Voltage variation management in distribution systems differs fundamentally from that of transmission and sub-transmission networks due to the comparatively low X/R ratio, connection of loads at intermediate points along feeders, and use of fixed tap (DETS) transformers.

2.2 Urban and rural networks

Most urban networks in Southern African, illustrated in figure 2, are characterised by short (<5 km) MV feeders usually operated at 11kV, with “large” (200-1000 kVA) three-phase distribution transformers supplying typically up to 100 LV customers. Most of the voltage drop occurs in the LV network.

In contrast, traditional rural networks (figure 3) comprise long (20-100 km) feeders, typically operating at 11, 22 or 33 kV, supplying individual or small groups of customers through small (16-200kVA) distribution transformers. Most LV feeders are short (<100 m) relative to the MV feeders, and most of the voltage drop occurs in the MV network.

However, many Southern African rural electrification networks combine the characteristics of both urban and traditional rural networks, where they supply several villages of low-income domestic customers. The LV network from a distribution transformer can be extensive, supplying numerous customers, and similar percentage voltage drop occurs in the MV and LV networks.

A survey of present planning and design practices [1] indicated that the adoption of standardised voltage apportionment limits would reduce the costs of rural electrification, such as implemented by the Eskom Distribution Division.

2.3 Distribution transformer tap settings

Voltage boosting on the MV/LV transformers can be used to increase feeder capacity, as illustrated in figure 4. The maximum level of tap boosting depends on the voltage control in the MV system. Increasing the tap boost increases the allowable voltage drop in the MV and/or LV feeders.

2.4 Voltage limits and voltage drop

Voltage limits are the maximum and minimum voltages that must not be exceeded (a and b in figure 4). Voltage drop limits are the maximum allocated voltage drop (c for LV and d for MV in figure 4) and depend on the voltage limits, load, network topology, and voltage control. The limits and voltage drops refer to steady state values and voltage variation (e in figure 4) occurs because of changes in load and active voltage control.
The calculation of expected voltage drops is well described and incorporated into commercial and utility loadflow packages [7].

The network planner/designer must ensure that the expected voltages and voltage drops do not exceed acceptable limits. This is achieved by feeder load flow analysis, and comparison of the steady state simulation results with utility standards for voltage limits and voltage drop limits. Load flow results also need to be interpreted by system operators because they are responsible for the settings on DETS transformers and line voltage regulators.

3. VOLTAGE DROP APPORTIONMENT MODEL

3.1 Constraint analysis

Voltage drop limits in the MV and LV systems depend on combinations of:
- voltage control settings;
- distribution transformer specifications including nominal secondary voltage, impedance, tap step and tap range;
- transformer maximum flux levels;
- distribution transformer and feeder loading levels and voltage drops;
- regulatory or contract obligations at the service point (voltage limits);
- voltage drops within the customers’ LV networks to the equipment or appliances, and their voltage compatibility limits.

The MV and LV voltage drop limits can be calculated for any combination of these factors [1]. The result is the maximum, but not necessarily optimal, limits for the voltage and voltage drop in both the MV and LV networks. The effect of various combinations of control techniques and distribution transformer tap positions can be analysed.

The constraint analysis is illustrated in figure 5. The minimum voltage on the MV feeder is dictated by the requirement for a distribution transformer with a nominal secondary voltage of 380 V to be able to supply a 400 V motor with acceptable voltage, assuming that the motor is relatively close to the distribution transformer, shown as (a). The further the motor is from the transformer the higher the minimum MV voltage would have to be. With the minimum MV voltage established by this constraint, the maximum LV voltage drop is calculated for each of the combinations of a 380 V transformer supplying 230 V domestic loads, a 400 V transformer supplying a 400 V motor and a 400 V transformer supplying 230 V domestic loads, at (b), (c) and (d) respectively. The maximum voltage limit of the 380 V motor constrains the 400 V transformer tap setting at (e).

The MV voltage limits are based on a particular combination of transformer, load and LV network (the most limiting combination is termed the critical constraint). The LV voltage drop limits are calculated for other combinations of transformers, loads and voltage limits so that the LV voltage drop limit can be maximised for each application. Networks with different loads, transformers and contractual obligations have different constraining combinations, and the MV and LV voltage drop apportionment vary. Practical distribution networks consist of a diverse range of distribution transformers and appliances/loads.

For network planning, design and operational purposes it is not practical to analyse all possible constraining combinations for each network study. Even if utility databases contain detailed network models, information on customer networks and appliance voltage requirements are generally unknown. Hence, it is desirable to standardise voltage limits based on typical constraining combinations.

The voltage and voltage drop limits established via the constraint analysis are applicable to steady state network studies. Additional requirements may apply for motor starting and other dynamic studies, but are not described here.

3.2 Voltage relationships and equations

As illustrated in figure 6, the minimum MV voltage limit depends on the level of distribution transformer tap boosting, which in turn depends on the maximum MV voltage. In order to establish the minimum MV voltage limit, the maximum MV voltage must be included in the analysis.

The practical tap boost range is limited by the maximum voltage drop and relationship between maximum and minimum loads.
Annex A contains the equations for the calculation of:

- the optimal tap ratio as a function of the maximum MV voltage and LV load and network characteristic;
- the minimum and maximum MV voltage limits as a function of the tap ratio and LV load and network characteristic;
- the maximum MV voltage as a function of the minimum MV voltage and load characteristic;
- the LV voltages at service points and appliances as a function of the tap ratio, maximum and minimum MV voltages and LV load and network characteristic; and
- the maximum LV voltage drop limits for different target service voltages.

3.3 Model inputs, methodology and outputs

The constraint analysis, incorporating the voltage relationships and equations, is implemented in a Microsoft EXCEL spreadsheet. The model is simple enough to execute in a spreadsheet, but could be implemented in another programming language.

The model inputs, functions and outputs are described as a series of steps and illustrated in figure 7.

*Step 1: Model library:* A database of parameters, many of which are utility specific, includes:
- Rated voltage and variation range for typical appliances
- Standard and limit voltages at the service point, defined by regulations, customer service agreements or contracts
- The specifications of distribution transformers, including nominal voltage, design flux limit, impedance, tap range and step size
- Maximum and minimum distribution transformer loading levels and associated load power factor

*Step 2: Combinations:* Specify the combinations of particular appliances, service voltage agreements, distribution transformers, distribution transformer loading levels and LV voltage drops that are to be applied for a particular network. The EXCEL model allows for up to ten combinations.

*Step 3: MV voltage control settings:* Specify the MV voltage control settings including set-point, bandwidth and voltage compound adjustment (the desired/allowable change in MV source voltage from zero to peak load).

*Step 4: MV load ratio (ratio of low to peak load):* The load ratio is used to calculate the maximum MV voltage and thereby establish if a multiple tap zone (additional transformer tap boosting at feeder extremities) can be applied. The worst-case assumption is a load ratio of zero.

*Step 5: Transformer tap optimisation:* The highest distribution transformer tap ratio allows the maximum MV and LV voltage drop limits. Initially it is assumed that the maximum MV voltage is the maximum MV set-point voltage. For each combination the distribution transformer tap ratios are optimised (Annex A, Eq 2, 3, 4 and 5) to provide the maximum level of boosting allowed while still complying with maximum service voltage limits (compulsory), maximum transformer flux levels (optional) and maximum appliance voltage limits (optional). Transformer taps can be set manually to establish the...
impact of non-optimal settings and operational decisions, such as operating all transformers on nominal tap regardless of rated secondary voltage, service agreement or appliance specifications.

**Step 6: Minimum MV voltage calculation**: Based on the transformer tap ratios, the minimum limit of the MV voltage is calculated for each combination (Annex A, Eq 6, 7 and 8). The highest minimum MV voltage is the most restrictive (the MV voltage must not fall below this value in order to meet the voltage limits of a combination), and is retained as the minimum MV voltage limit.

**Step 7: Maximum MV voltage calculation**: The expected maximum MV voltage is calculated using the minimum MV voltage limit, load ratio and MV voltage control settings (Annex A, Eq 9 and 10).

**Step 8: MV voltage feedback**: The calculated maximum MV voltage is fed back into step 5 and the transformer tap ratios are revised (the minimum and maximum MV voltage limits are related via the DETS tap setting). This is an iterative calculation that converges on the optimal tap ratio. The maximum number of iterations required for convergence is the number of transformer taps (typically 5). The SOLVER function in EXCEL is used to perform the iterative solution (see Annex B).

**Step 9: Combination results**: Using the maximum and minimum MV voltages and associated tap ratios, the maximum and minimum LV voltages at the service point and appliance are calculated (Annex A, Eq 11, 12, 13 and 14) for each combination.

**Step 10: Summary results**:• optimal tap ratio (Eq 2, 3, 4 and 5);• minimum MV voltage limit (Eq 6, 7 and 8);• maximum MV voltage limit (Eq 15, 16 and 17);• expected MV voltage variation (Eq 18);• maximum MV voltage drop limit (Eq 9); and• LV voltage drop limits (maximum LV network voltage drop limit for each transformer for different service agreements and appliances, Eq 19).

By analysing multiple combinations, trends are established manually in an iterative process such that the critical combinations are identified, verified for validity, and refined. The voltage limits adopted by a utility may not necessarily be compatible with all possible combinations, but rather the majority of combinations.

### 3.4 Example application

The method is used to establish the MV and LV voltage and voltage drop limits for a network supplying 400 V and 380 V motors with the characteristics in Table 1, with the MV network parameters shown in Table 2.

### Table 1: LV network and load parameters

<table>
<thead>
<tr>
<th>LV network and load parameters</th>
<th>400V motor</th>
<th>380V motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor rated voltage (ARV)</td>
<td>400V</td>
<td>380V</td>
</tr>
<tr>
<td>Motor voltage regulation range (ARR)</td>
<td>±5%</td>
<td>±10%</td>
</tr>
<tr>
<td>Nominal service voltage (SCV)</td>
<td>400V</td>
<td></td>
</tr>
<tr>
<td>Service voltage regulation range (SRH, SRL)</td>
<td>+10% -10%</td>
<td></td>
</tr>
<tr>
<td>Distribution transformer: Rated secondary voltage (TRV)</td>
<td>415V</td>
<td></td>
</tr>
<tr>
<td>Distribution transformer: Tap range</td>
<td>-6% -3% 0%</td>
<td>+3% +6%</td>
</tr>
<tr>
<td>Distribution transformer: Maximum rated flux limit (TFL)</td>
<td>105%</td>
<td></td>
</tr>
<tr>
<td>Max and min internal voltage drop (TDP, TDL)</td>
<td>2.85% 0.84%</td>
<td></td>
</tr>
<tr>
<td>Max and min LV voltage drop between dist. transformer and service point (TSP, TSL)</td>
<td>2% 0.5%</td>
<td></td>
</tr>
<tr>
<td>Max and min LV voltage drop between service point and motor (SAP, SAL)</td>
<td>2.5% 0.5%</td>
<td></td>
</tr>
<tr>
<td>Non motor load: Nominal LV service voltage (LVN)</td>
<td>230/400V</td>
<td></td>
</tr>
<tr>
<td>Non motor load: Minimum LV service voltage regulation range (LVSMax)</td>
<td>-10%</td>
<td></td>
</tr>
</tbody>
</table>

TDP and TDL are based on a transformer impedance of 4%, X/R ratio of 2, and maximum and minimum loadings of 90% (PF=0.90) and 30% (PF=0.95) respectively.

### Table 2: MV network and load parameters

<table>
<thead>
<tr>
<th>MV network and load parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV source voltage (MVSP, MVSL)</td>
<td>102% 102%</td>
</tr>
<tr>
<td>MV load ratio (MVLR)</td>
<td>30%</td>
</tr>
</tbody>
</table>

Table 3 compares the results of the model with results from a commercial load flow package (ReticMaster©) using constant current (Const I) and constant power (Const P) load types. Constant current load types are considered the most appropriate for distribution network steady state analysis [8] and are commonly used, but some analysts use constant power load types. The largest difference between the proposed model and constant current load flow simulation is in the voltage drop across the transformer, which is expected as the errors in Eq 1 increase for predominately reactive impedances.

### Table 3: Model summary results. Values in brackets are differences relative to the model

<table>
<thead>
<tr>
<th>Model results</th>
<th>Model</th>
<th>Const I</th>
<th>Const P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimal tap ratio (TAP) of 415V transformer</td>
<td>1,00</td>
<td>1,00 (0%)</td>
<td>1,00 (0%)</td>
</tr>
<tr>
<td>Minimum MV voltage limit (MVMin)</td>
<td>98.76%</td>
<td>98.75% (-0.01%)</td>
<td>98.99% (0.24%)</td>
</tr>
<tr>
<td>Maximum MV voltage limit (MVMax)</td>
<td>102.51%</td>
<td>102.54% (0.03%)</td>
<td>102.43% (-0.08%)</td>
</tr>
<tr>
<td>Expected maximum MV voltage variation (MVEVR)</td>
<td>2.27%</td>
<td>2.27% (0.03%)</td>
<td>2.36% (3.93%)</td>
</tr>
<tr>
<td>Maximum MV voltage drop limit (MVDMax)</td>
<td>3.24%</td>
<td>3.25% (0.19%)</td>
<td>3.01% (-7.21%)</td>
</tr>
<tr>
<td>Maximum MV/LV transformer voltage drop</td>
<td>2.85%</td>
<td>3.00% (5.17%)</td>
<td>3.03% (6.22%)</td>
</tr>
<tr>
<td>LV voltage drop limit for non motor loads (LVSDMax)</td>
<td>9.50%</td>
<td>9.50% (0.00%)</td>
<td>9.71% (2.21%)</td>
</tr>
<tr>
<td>Maximum total voltage drop to service point</td>
<td>15.60%</td>
<td>15.75% (0.98%)</td>
<td>15.75% (0.98%)</td>
</tr>
</tbody>
</table>

The purpose of the model is to analyse various combinations of load and network characteristics for the standardisation of voltage and voltage drop limits. The
small additional accuracy of the more complex load flow simulations is not justified given the uncertainties in the model input parameters.

The results of the model for urban networks generally agree with voltage drop limits historically used by Eskom Distribution planning and design engineers [1]. This builds confidence in the practical validity of the model and its application in the investigation of optimum limits for rural electrification systems.

4. CONCLUSION

In South Africa the apportionment of the voltage drop between the MV and LV network levels is not standardised. Optimum voltage drop apportionment depends on network and load characteristics, regulations and agreements, and distribution transformer tap settings. The consideration of multiple combinations of network/loads is more important than the detailed analysis of a single combination using load flow software. A model has been developed to calculate MV and LV voltage and voltage drop limits based on different network/load combinations. The results of the model are suitably accurate for the calculation of guidelines for optimum voltage drop limits, which work will be reported separately.

5. ACKNOWLEDGEMENTS

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6. REFERENCES


7. AUTHORS

Clinton Carter-Brown graduated with a BSc(Eng) degree in Electrical Engineering from the University of Natal in 1995 and his MSc(Eng) degree from the University of Cape Town in 2002. He is a professional engineer. He joined Eskom Distribution in 1996, where he is involved in the standardisation and optimisation of network planning practices.

Trevor Gaunt is a Professor in the Department of Electrical Engineering at the University of Cape Town.

ANNEX A: VOLTAGE EQUATIONS

Distribution network voltages defined in figure 8 can be calculated from the summation of the voltage drops and transformer tap effects using Eq 1 to 19. Voltage drops are phasor quantities, but can be approximated by scalar values using the following approximation [9], which is valid for a constant current load type:

\[
V_{\text{drop}} = \frac{I}{(R \cdot \cos(\phi) + X \cdot \sin(\phi))}
\]

Where:

- \(V_{\text{drop}}\) Voltage drop [PU]
- \(I\) Load current [amps]
- \(R\) Resistance [ohms]
- \(X\) Reactance [ohms]
- \(\phi\) Load Power Factor
- \(V\) Base voltage [V]

The tap ratio \(TAP\) [ratio] to meet maximum service point and appliance voltage limits and transformer flux limits for a maximum MV voltage \(MV_{\text{Max}}\) [PU] is given by:

\[
TAP = \text{Rounddown} \left(\frac{\text{Min}(TAPS, TAPA, TAPF)}{TAP}\right)
\]

where:

- \(\text{Rounddown}\) is the discrete tap ratio \leq\text{ the calculated ideal tap ratio.}

- \(TAPS\) [ratio] is the tap ratio that results in the upper voltage limit at the service point:
\[ TAPS = \frac{SCV \cdot (1 + SRH + TSL) + TRV \cdot TDL}{TRV \cdot MV_{Max}} \] (3)

**TAPA** [ratio] is the tap ratio that results in the upper voltage limit at the appliance:

\[ TAPA = \frac{AVR \cdot (1 + ARR + SAL) + SCV \cdot TSL + TRV \cdot TDL}{TRV \cdot MV_{Max}} \] (4)

**TAPF** [ratio] is the tap ratio that results in the maximum transformer flux limit:

\[ TAPF = \frac{TFL}{MV_{Max}} \] (5)

The minimum MV voltage MV_{min} [PU] to keep within service point and appliance minimum voltage limits is given by:

\[ MV_{Min} = \text{Max}(MV_{SMin}, MV_{Amin}) \] (6)

where:

**MV_{SMin} [PU]** is the minimum MV voltage to keep within the minimum contracted voltage at the service point:

\[ MV_{SMin} = \frac{SCV \cdot (1 - SRL + TSP) + TDP \cdot TRV}{TRV \cdot TAP} \] (7)

**MV_{Amin} [PU]** is the minimum MV voltage to keep within the appliance design minimum voltage:

\[ MV_{Amin} = \frac{AVR \cdot (1 - ARR + SAP) + SCV \cdot TSP + TDP \cdot TRV}{TRV \cdot TAP} \] (8)

The maximum permissible MV voltage drop MV_{DMax} [PU] is given by:

\[ MV_{DMax} = MV_{SP} - MV_{Min} \] (9)

where:

**MV_{SP} [PU]** is the MV source voltage during peak loading.

The expected maximum MV voltage MV_{EMax} [PU] is given by:

\[ MV_{EMax} = MV_{SMin} - MV_{DMax} \cdot MV_{LR} \] (10)

where:

**MV_{SMin} [PU]** is the MV source voltage during low loading.

**MV_{LR}** is the Load Ratio, which is the ratio of the minimum MV load to maximum MV load.

The voltage at the service point during peak loading SVP [V] is given by:

\[ SVP = MV_{Min} \cdot TRV \cdot TAP - TRV \cdot TDP - SCV \cdot TSP \] (11)

The voltage at the service point during low loading SVL [V] is given by:

\[ SVL = MV_{Max} \cdot TRV \cdot TAP - TRV \cdot TDP - SCV \cdot TSL \] (12)

The voltage at the appliance during peak loading AVP [V] is given by:

\[ AVP = SVL - AVR \cdot SAP \] (13)

The voltage at the appliance during low loading AVL [V] is given by:

\[ AVL = SVL - AVR \cdot SAL \] (14)

The maximum MV voltage MV_{Max} [PU] to keep within service point and appliance maximum voltage limits is given by:

\[ MV_{Max} = \text{Min}(MV_{SMax}, MV_{Amax}) \] (15)

where:

**MV_{SMax} [PU]** is the maximum MV voltage to keep within the maximum contracted voltage at the service point:

\[ MV_{SMax} = \frac{SCV \cdot (1 + SRH + TSL) + TDL \cdot TRV}{TRV \cdot TAP} \] (16)

**MV_{Amax} [PU]** is the maximum MV voltage to keep within the appliance design maximum voltage:

\[ MV_{Amax} = \frac{AVR \cdot (1 + ARR + SAL) + SCV \cdot TSL + TDL \cdot TRV}{TRV \cdot TAP} \] (17)

The expected maximum MV voltage variation MV_{EVR} [PU] is given by:

\[ MV_{EVR} = MV_{EMax} - MV_{Min} \] (18)

The maximum permissible LV voltage drop LV_{SDMax} [PU] between the MV/LV transformer and service point is given by:

\[ LV_{SDMax} = \frac{MV_{Min} \cdot TRV \cdot TAP - TRV \cdot TDP - (1 + LV_{Max})}{LVN} \] (19)

where:

**LVN [V]** is the nominal voltage for the voltage drop limit and service voltage.

**LV_{Max} [PU]** is the maximum LV service voltage variation allowed.

**ANNEX B: MICROSOFT EXCEL SOLVER**

The Microsoft Excel Solver tool uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code developed by Leon Lasdon, University of Texas at Austin, and Allan Waren, Cleveland State University.

Linear and integer problems use the simplex method with bounds on the variables, and the branch-and-bound method, implemented by John Watson and Dan Fylstra, Frontline Systems, Inc.
Figure 8: Graphical representation of the equipment, service, and appliance specifications and voltage drops during peak and low load conditions

- **MV/LV transformer with nominal secondary voltage and DETS step sizes and range**
- **LV network between MV/LV transformer and service point**
- **LV network within customer premise**
- **Customer appliance**

**Abbreviations**

- **TRV**: Transformer rated secondary voltage [V]
- **TAP**: Transformer DETS tap ratio [ratio]
- **TDP**: Transformer internal voltage drop during peak load [PU]
- **TDL**: Transformer internal voltage drop during low load [PU]
- **TFL**: Transformer maximum rated flux limit [PU]
- **TSP**: Voltage drop between the transformer and service point during peak load [PU]
- **TSL**: Voltage drop between the transformer and service point during low load [PU]
- **SCV**: Customer contracted nominal voltage [V]
- **SRH**: Customer contracted upper regulation limit [PU]
- **SRL**: Customer contracted lower regulation limit [PU]
- **SAP**: Voltage drop between the service point and appliance during peak load [PU]
- **SAL**: Voltage drop between the service point and appliance during low load [PU]
- **ARV**: Appliance rated nominal voltage [V]
- **ARR**: Appliance rated voltage regulation range [PU]