VOLTAGE CONTROL FOR DISTRIBUTION NETWORKS
and the 230V/400V Standard

by

Alex Baitch **FIEAust, CPEng**
Manager Network Capability, Integral Energy

This paper was presented to the Annual Conference of the Electric Energy Society of Australia held in Canberra 4 – 5 August 2000.

SUMMARY:

This paper discusses some of the issues associated with quality of supply and the procedures associated with voltage control for distribution networks. This includes consideration of the use of voltage control devices to assist with maintenance of acceptable voltages, determination of feeder regulation, the setting of distribution transformer taps and design of low voltage networks.

The impact of the issue of the new Australian Standards AS60038-2000 "Standard Voltages" is considered and conclusions drawn on the actions that need to be taken.

1 INTRODUCTION

The issue of the new Australian Standard AS60038-2000 "Standard Voltages" is an opportune time to review the impact of the new standard on electricity distributors and suppliers. It is also an opportune time to review some of the fundamentals that relate to ensuring that the voltage supplied to customers is maintained within acceptable limits. The original paper by L.A. Chappell (Ref 1) is particularly acknowledged and has been used as a basic source in preparing this paper.

The Distribution Network Service Provider (DNSP) (the term used in the National Electricity Market) is responsible to ensure that the supply provided to electricity consumers within the area that the DNSP supplies is of an acceptable quality. Providing a definition of what constitutes an "acceptable quality" is not a simple task and indeed not a matter about which there is total consensus. There are conflicting pressures between suppliers and consumers as to what constitutes an economically achievable quality of supply.

In essence the consumer seeks to ensure that the power supply is continuous and that the voltage should be within standards acceptable for the electrical equipment connected to the electricity network in terms of voltage, frequency and wave-shape. The objective is to ensure that the electrical equipment and appliances:

- Will operate as designed and can be used to full design capability
- Are at minimal risk of damage when connected to the electricity supply
- Will operate continuously when required, with minimal risk of interruption.

The design and operation issues associated with the maintenance of voltage control of the electricity network is fundamental for DNSP's. The issues, which are generally well known to experienced distribution engineers, are reviewed and updated.

2 QUALITY OF SUPPLY

2.1 General

Although the prime focus of this paper is with respect to the specific issue of voltage control within the distribution network, it is necessary to consider the overall issue of quality of supply and the terminology that is used to describe some of the issues.

Quality of supply is a matter that is under increasing scrutiny from regulators. Worldwide regulators are applying pressure on DNSP's to reduce operating costs through reduced revenue caps. At the same they are increasingly focusing on the matter of quality of supply and seeking improvement in performance indices. These are somewhat conflicting pressures which will ultimately require adoption of innovative solutions

The DNSP seeks to ensure that the quality of the electricity supply is as continuous as possible from both an economic and technical point of view, and the voltage in terms of magnitude, waveshape and frequency is within acceptable industry standards for the electrical equipment.

Where there is a gap between the quality of power supply that the DNSP can provide and the quality required by a consumer for specific applications (such as supply to critical process equipment, computers or other vital plant) then, in general, the end-user needs to take specific action to address the issue. This could include the provision of uninterruptible power supplies (UPS), line conditioners and/or standby generators.

In Australia, at the low voltage level the ideal voltage level at the customers point of connection has traditionally been a sinusoidal voltage supply of 415V(phase-to-phase) /240V (phase-to-earth) at 50Hz. (The impact of the 230V/400V standard will be discussed later). In practice there are a wide range of disturbances that cause deviations between the ideal sinusoidal wave and the actual waveform.

Power quality disturbances can be categorised as follows (some examples shown in Figure 1):

- Interruptions of supply (short duration, long duration)
- Frequency events (rarely occur)
- Voltage events (long term, short term, voltage unbalance, random fluctuations, protection system operation)
- Waveform events (harmonics, interharmonics, notching, transients (lightning strikes or switching), high frequency noise).

Illustrations of examples of various types of voltage disturbances (unrealistically compressed into a single example) are shown in Figure 1.

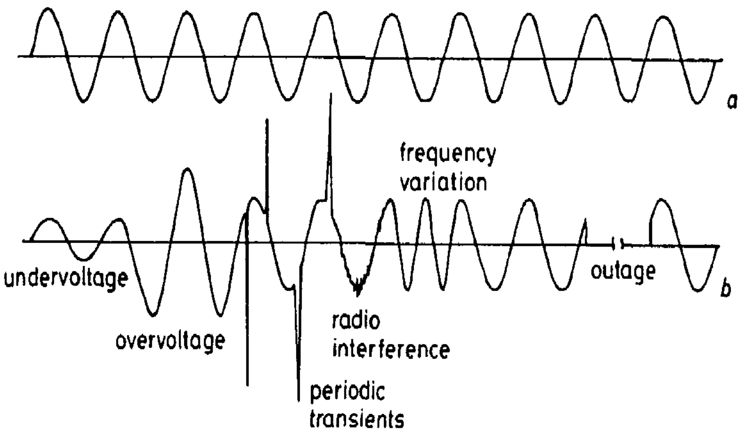


Figure 1 Examples of voltage disturbances **(Ref 7)**

The issue of Quality of Supply is covered by the AS/NZS 61000 "Electromagnetic Compatibility" series of standards . These are based on the IEC 61000 series of standards and amongst other standards is replacing the AS 2279 series. They concentrate on all issues associated with harmonics, fluctuating loads, etc.

In addition considerable work is continuing within the electricity industry to develop various Power Quality Indices that can be used to provide a measure of the performance of the network. These include indices such as:

CAIDI	Customer Average Interruption Duration Index
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
$MAIFI_N$	Momentary Average Interruption Frequency Index (N%)
$SARFI_X$	System Average RMS (Variation) Frequency Index
THD	Total Harmonic Distortion
$SATHD_{CP95}$	System Average Harmonic Distortion $_{CP95}$

This paper concentrates on long term voltage events to ensure that the design of the network results in a satisfactory voltage range at the customer terminals in terms of long duration voltage levels.

2.2 Voltage Regulation

Ensuring that the long-term voltage events on the network are within a satisfactory range deals with the issue of "system voltage regulation" of the network. The objective is to ensure that the voltage at the consumer's terminals is at an acceptable level and within the limits of permissible spread. In that regard the two key considerations are:

- The voltage must approximate to some optimum level
- The voltage spread must not be greater than certain established limits.

If the selected voltage level is incorrect or voltage limits are too narrow, economic considerations may prevent practical implementation. Furthermore, in some cases it is not possible to satisfy the requirements at all times. The best that can be achieved is that is that the majority of consumers are provided with acceptable supply practically all of the time.

With pressures on DNSP's to "drive the system harder", parameters that have traditionally been used for the design of networks are being reviewed with the result that at times design parameters that are used attempt to provide an adequate voltage level for the majority of the time rather than at peak loading conditions.

3 GENERAL ISSUES

3.1 Methods of achieving voltage control

Some of the methods available to achieve system voltage control include:

1) Adjust subtransmission voltage levels at transmission substations
2) Utilise zone substation automatic "On Load Tap Changing" (OLTC) transformers
3) Vary the bandwidth (dead-band) of voltage regulators
4) Add line drop compensation
5) Add additional feeders or distributors
6) Increase conductor size of existing feeders
7) Rearrange the system, transfer loads
8) Balance loads between phases
9) Convert single phase networks to three-phase
10) Close loops
11) Add distribution transformer capacity
12) Alter tap settings on distribution transformers
13) Install voltage regulators
14) Increase distribution voltage levels
15) Install switched shunt capacitors
16) Install series capacitors
17) Install Flexible AC Transmission System (FACTS) devices

Usually there are a number of alternative strategies that can be used to deal with a particular situation. The challenge is to select the most appropriate option taking into account future load growth issues and economic factors. The situation is usually complicated by the fact that one is usually dealing with incremental load growth and future requirements are not necessarily known.

3.2 Records and Data required

An essential requirement in undertaking an investigation is to have complete and accurate records in order that network characteristics, network configuration and loading details are well known.

The collection and maintenance of accurate and complete records associated with a large distributed network is vital for successful analysis. The use of computer systems and relational databases for collection and storage of large volumes of data is becoming increasingly vital for efficient operation and control of a distribution network. Integration of this data with geographic information systems (GIS) associated with the physical location of assets as well as the network connectivity allows the data to be input into computer based analysis engines for the computation of voltage conditions.

Data, while vital for carrying out analysis, is nevertheless expensive to both collect and maintain. Accordingly, it is vital that any data that is collected is useful for other purposes, such as for monitoring of the loading of distribution transformers to establish if capacity is exceeded, operational purposes and system development. Typically records that are used include:

a) Routine recordings of MDI readings on distribution transformers. Whereas in past years these readings were taken routinely at least twice per year and thus provided an accurate source of data for summer and winter loading of substations, cost pressures facing the industry have resulted in the regular readings being suspended. The loss of this information has been found to be a major problem in managing the distribution network. As a result action is being taken to restore this process, at least in part.

b) Detailed geographic information system (GIS) showing the geographic representation of the transmission, subtransmission, 22kV, 11kV network and low voltage network. The GIS record details the network connectivity, the length of each section of conductor, the conductor sizes, location of zone and distribution substations, location of high voltage switches and links, reclosers and regulators.

c) Network feeder load currents as monitored through the SCADA system, together with loading on the zone substation transformer loading.

d) Load cycle curves for zone substations monitoring the energy, demand and power factor for transmission and zone substations.

e) Records of tap settings for all distribution transformers.

f) Voltage levels, bandwidths and line drop compensation settings for transmission and zone substation transformers.

g) Voltage recordings on busbars at transmission, substransmission substations on the high and low voltage sides.

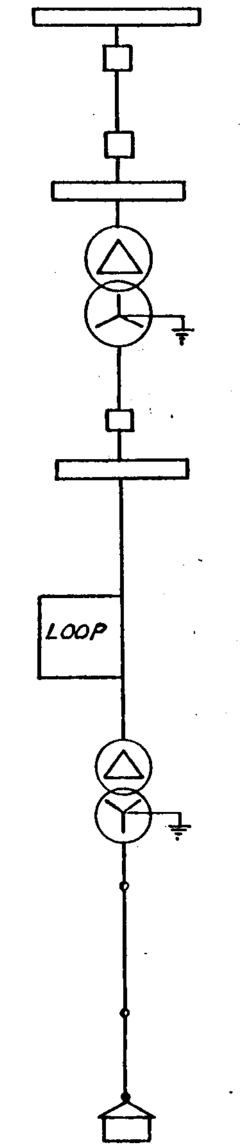
h) Load cycle data associated with major customer substation loads as obtained from metering data. Access to this data is being coming increasingly more difficult as a result of retail contestability where the information is considered confidential to the customer and retailer.

3.3 Characteristics of a Typical Network

Typical voltage levels, float voltages, band widths, tapping ranges and voltage drops for the Integral Energy system are shown in Table 1:

The values shown in Table 1 are only typical values. Due to the range of equipment that is installed on the network, there is large variety of combinations of tap change voltage ranges, transformer voltage steps, impedance values and settings of bandwidths and LDC’s.

Table 1 Typical characteristics

Single Line Diagram	Equipment	Voltage Ranges or Regulation
	**Transgrid Supply Points** 330kV/132kV (20x1.00%)	132.0kV ± 0.75%
	132kV Network	Voltage range dictated by power flow and reactive power requirements ± 5% typical
	Transmission Substations	66.0kV or 33kV ± 1.5%
	66kV or 33kV Network	Rural: 10% regulation Urban: 3%
	O.L.T.C Zone Transformers 66kV or 33kV (+7x1.5%) (-14x1.5%) / 22kV or 11kV 66kV or 33kV+(7x1.25%) (-14x1.25%)/22kV or 11kV	 72930V - 52140V / 22kV or 11kV 36465V - 26070V / 22kV or 11kV 71775V - 54450V / 22kV or 11kV 35888V - 27225V / 22kV or 11kV
	22kV or 11kV Busbar **22kV:** 22kV ± 1.4%BW 2.0%LDC **11kV**: 10.9kV ± 1.4%BW 2.0%LDC	 21700V - 22750V 10750V - 11275V
	22kV or 11kV Feeders Urban: Semi-Rural: Rural:	 2.5% (3.5% max) (<2.0% if mostly underground) 3.5% (4.5% max) 6.0% (10% max where no LV network)
	Distribution Transformers **22kV**: 20kV-22kV/433-250V 0.5kV steps **11kV:** 10kV-11kV/433-250V 0.25kV steps	 3.0% Regulation (Full Load @ 0.95 PF) 2.0% Regulation (Full Load @ 0.98 PF)
	Low Voltage Distributor Urban Rural	 4.0% (6% in some cases) 4.0% (1.0% in some cases)
	Service Mains	0.5%
	Customer Worst Condition	240V +6% / -6% (254V – 225V) 230V + 10% / - 2% (253V – 225V)

4 ELEMENTS OF VOLTAGE CONTROL

4.1 General

The key parameters that determine the nature of the voltage levels on various parts of the electricity network, from its source at the generation level, through the transmission voltage level down to the distribution voltage level are as follows:

a) Voltage ratio of the transformers at each part of the network from the generation source, the transmission voltage level, subtransmission and distribution networks

b) Voltage taps available on the transformer for adjustment of voltage, either on load tap changing or off-load tap changers

c) Float voltage which determines the mid-range voltage set for the regulating relay

d) Bandwidth (dead-band)of the voltage regulating relay which is the range in which the voltage regulating relay will not initiate the timing circuit for initiation of a tap-change operation

e) Line-drop compensation is used to bias the mid-range voltage set for the regulating relay in proportion to the load on the transformer, such that the output voltage is increased as a function of load on the transformer.

f) Voltage drop associated with the power flow through the impedance of the network conductors and through the impedances associated with transformers, reactors or regulators.

The following considers aspects of the above parameters at various parts of the network.

4.2 Transmission Network

Integral Energy's supply is obtained from Transgrid's network generally at 132kV from Transgrid's Bulk Supply Points although from two of the BSP's supply is at 66kV. Within the Integral Energy area there are ten (10) BSP's.

The tap change steps at the BSP's are typically 1% with a short time-out period between taps (typically 20 seconds on fine control and 1 second on coarse control). Similarly, the bandwidth on the voltage regulator is typically set at 0.75%. Accordingly, output voltage from the BSP's is maintained within a narrow band.

Additionally, some of the BSP's supplying Integral Energy have LDC facilities installed (Sydney West and Regentville) which results in voltage boost as a function of load.

4.3 Subtransmission Network

Supply to the subtransmission network is obtained at either 132kV, 66kV, or 33kV levels. In the case of 132kV and some 66kV, supply is taken from Transgrid's BSP's , while in the case of the rest of the 66kV supply and all of the 33kV subtransmission network, supply is from Transmission Substations which are owned by Integral Energy (following the transfer of 132kV assets).

The float voltage at Transmission Substations is set at a level that suits the particular part of the network, taking into account the available tapping ranges of the transformers in the various zone substations.

The bandwidth (dead-band) of the voltage regulation relay is typically set at ± 1.5% and a time out period greater than the BSP (typically 45 seconds), thus ensuring that the transmission substation regulates the voltage at the local level and does not respond to area wide voltage levels experienced by the BSP.

Normally in the urban areas, heavy conductors are used in the subtransmission network to achieve required capacity. Accordingly, the incoming voltage into the zone substation has only a limited spread and the transformer tap changer can readily accommodate this.

In rural areas, where the voltage regulation on the transmission and subtransmission network is large as a result of reduced conductor ratings and the long lengths of subtransmission, care needs to be taken with selection of the tapping range of the transformer. This is necessary to ensure that the tapping range is adequate to cope with the potential voltage regulation on the transmission and subtransmission system both under full load conditions, lightly loaded conditions and as a result of voltage rise due to capacitive currents.

The utilisation of bundled conductor construction provides both a larger conductor capacity and as well reduces the reactance of the line. With utilisation of standoff insulators, bundled conductor construction is not possible, and thus the advantage of reduced reactance of bundled conductor construction is lost.

4.4 Zone Transformers

Zone transformers have tap-changers installed in order to regulate the voltage on the 11kV or 22kV output busbar. Typically, the bandwidth of the voltage regulating relay is set at ± 2% with the tap steps of the transformer at 1.5% or 1.25%. As a result, bandwidth (dead band) is typically 4%.

In recent years Integral Energy has reduced the bandwidth of many of its zone substations to ±1.36% in order to tighten the voltage band of the output from the zone substations. The time delay for tapchanger action is typically set at 60 seconds, and is slower than the Transmission Substation tapchanger. Nevertheless, the impact of reducing the bandwidth on the zone substation transformer is to increase the frequency of tapchange operations.

LDC on zone substations is typically set at 2% at full load, depending on the load mix from the zone substation. As the LDC affects the voltage on the complete busbar, where there is large mixture of feeders having residential, industrial and commercial loads characteristics, LDC needs to be reduced to prevent the output voltage being too high on feeders that are lightly loaded at the time of maximum demand on the zone substation.

A detailed analysis of determining the combined effect of subtransmission voltage regulation, bandwidth, LDC, and transformer impedance is included in Ref 6.

The methodology developed in Reference 6 allows for a visualisation of the effect of supply point bandwidth, subtransmission voltage regulation, line drop compensation and transformer voltage regulation.

Under no-load conditions the transformer primary and secondary voltages are governed by the turns ratio shown in the following equation:

$$V_P = N(T)\, V_S \qquad (1)$$

where N is the turns ration as a function of the tap position number “T”

Referring to Ref 6 this relationship is plotted by expressing the turns ratio (V_P / V_S) on the vertical axis and the secondary voltage (V_S) on the horizontal axis.

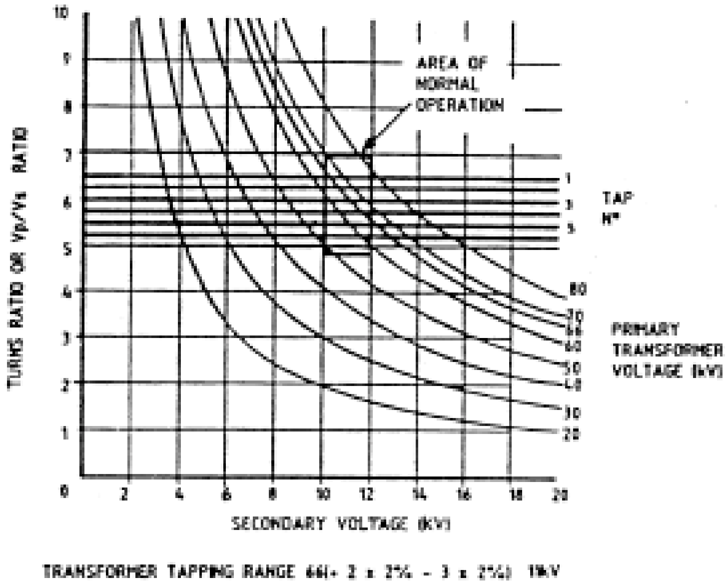


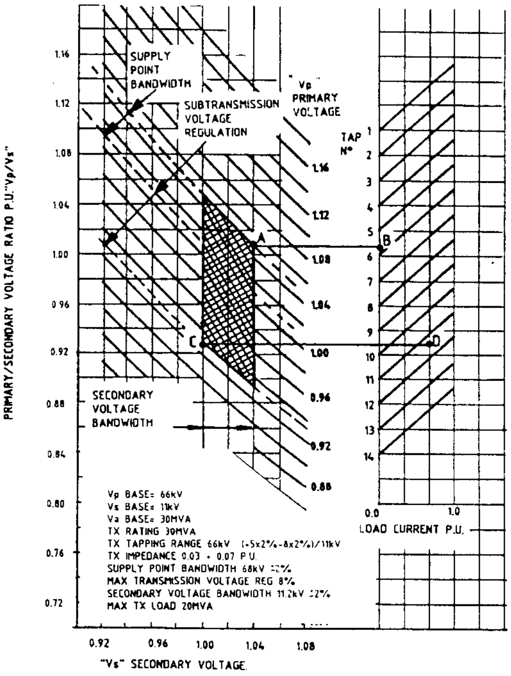
Figure 2 No-load transformer characteristic showing turns ratio

Utilising the section of the curve that relates to the normal operating range, the tapping range that a transformer will operate within can be determined. This takes into account the input voltage variation as a result of supply point bandwidth and feeder regulation, the effect of transformer impedance and bandwidth and the effect of LDC.

Referring to Figure 3 the effect of variation of subtransmission voltage regulation is incorporated into the graphical analysis. In the example in Figure 3, the subtransmission voltage regulation is 8%. The tapping range required is Tap 5 to Tap 12.

In Figure 4 the effect of line drop compensation on the transformer is shown by shifting the output voltage as a function of load current. In this example the tapping range is shown to Tap 5 down to tap beyond the present range.

It will be noted from this that by widening the bandwidth of the voltage regulator, the number and range of transformer taps required reduces, and the range of output voltage range increases. Conversely, as the bandwidth is reduced, the number and range of transformer taps required increases and the output voltage range decreases.



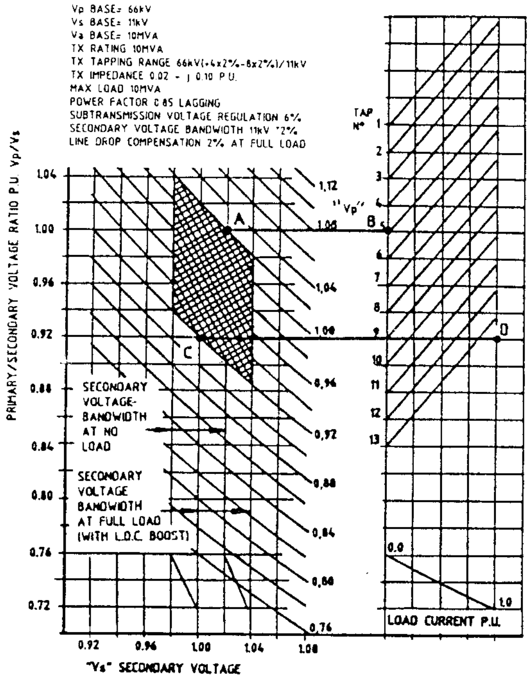


Figure 3 Determination of zone transformer voltage regulation considering effect of subtransmission volt regulation and bandwidth

Figure 4 Effect of line drop compensation on OLTC Transformer operation

It is also noted that with a rising load, the tap changer tends to be at the bottom of the band and thus the voltage tends to be low as the tap changer attempts to catch up with the required voltage. With a dropping load, the voltage tends to be at the top of the band, and thus the voltage tends to be high as the tap changer attempts to lower the voltage to bring it into the band. When the load is fluctuating, the regulator swings through the voltage band and can be varying between the high and low side of the band.

4.5 22kV and 11kV Network

Within most distribution utilities, the most challenging problems with respect to voltage control, occurs between the zone substation output busbar and the customer point of supply.

Where the 22kV or 11kV network is an underground cabled network, due to the size of conductor that needs to be used to achieve adequate current rating of the network, the issue of feeder regulation is not particularly critical. As a result, the feeder regulation on cabled systems is typically less than 2%,

Where the 22kV or more particularly the 11kV system is an overhead network, the feeder regulation can be a significant component. The main areas for investigation therefore include:

a) Voltage drop experienced on the feeder
b) Tap settings of distribution transformers
c) Capacity of the feeder
d) Size of conductors used on the feeder
e) Line Drop Compensation settings.

An illustration of the voltage profile for a typical medium voltage feeder up to the customer point of supply is illustrated in

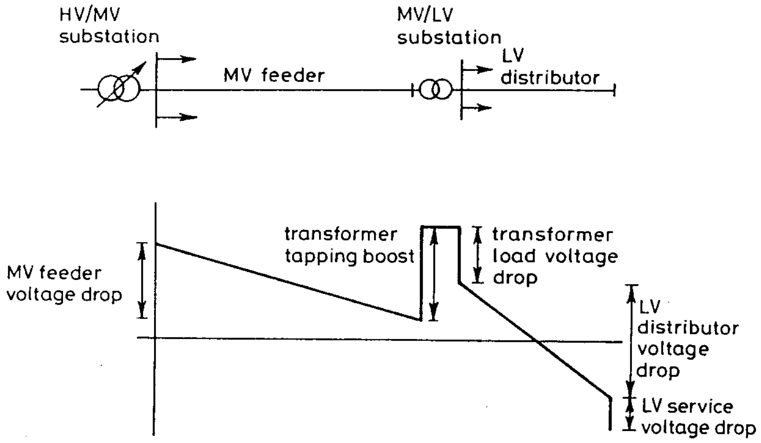
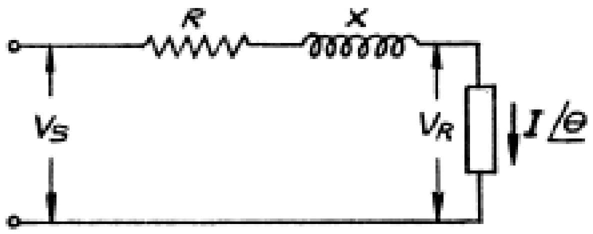


Figure 5 Feeder regulation profile (Ref 7)

4.6 Feeder Regulation

The equivalent circuit for a transmission line and its vector diagram are shown in the diagram below:



V_S	=	Sending end voltage
V_R	=	Receiving end voltage
I	=	Load Current
θ	=	Power Factor Angle of Load

Figure 6 Equivalent Circuit

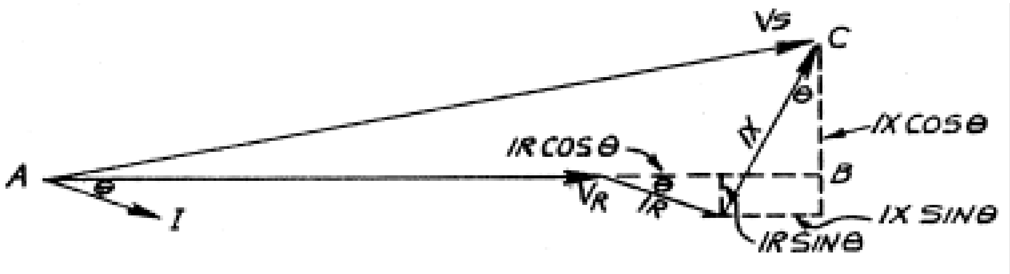


Figure 7 Vector Diagram

Feeder regulation is determined by the formula shown in the following equations:

$$\% \text{ Regulation} = \frac{(V_S - V_R)}{VR} \times 100 \qquad (2)$$

$$V_S = \sqrt{(V_R + IR\cos\theta + IX\sin\theta)^2 + (IX\cos\theta - IR\sin\theta)^2} \qquad (3)$$

Accordingly, to determine the regulation of feeder it is necessary to know the following:

a) Configuration and impedance of the feeder
b) Load current for each section
c) Power factor

The configuration and impedance of the network is established by reference to the GIS system and to the single line diagram.

a) Impedance

The impedance of each section of the network is established by determining the length of each section and the construction type for each section of network. The construction type needs to identify the conductor size, the conductor configuration (for overhead networks it is necessary to establish the geometric mean diameter (GMD) of the construction) and conductor type. Typically, a database is usually established and the construction type is linked for each element to a table in the database.

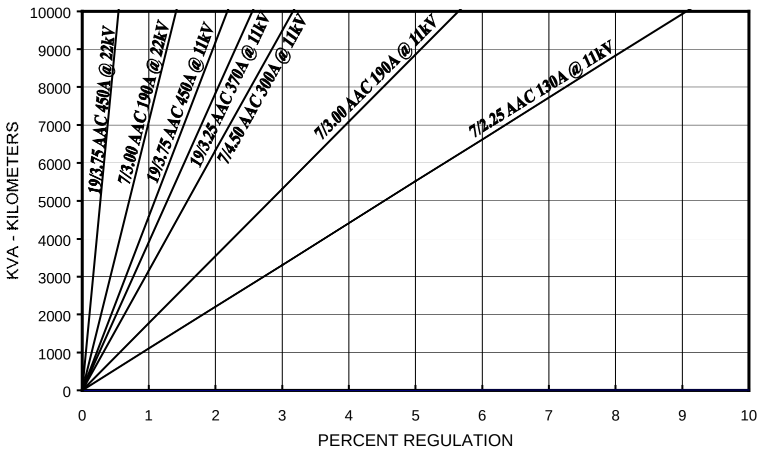


Figure 8 Voltage regulation (at 0.9 PF)

b) Load

To establish the load current for each section of feeder, it is necessary to establish the loading on each of the substations along the feeder length and estimate the load cycle that is relevant for the particular substation. In this regard, regular reading of MDIs mounted on the substation and storing this data into a database provides an important source of information. In the absence of MDI readings, an estimate of the load as a percentage of the substation rating is often used.

c) Load Cycle

Identifying the nature of the substation by the type of load that is necessary in order to estimate the load for various times of the day. Substations are usually categorised as being Residential, Commercial, Industrial or other load types. A typical load cycle is then apportioned for each category. This load cycle could be extended to be able to simulate the load for the various seasons of the year, with particular emphasis on summer and winter as illustrated Figure 9 and Figure 10. The shift from winter peaks to summer peaks on the network is resulting in the need for carrying out analysis in summer as well as winter.

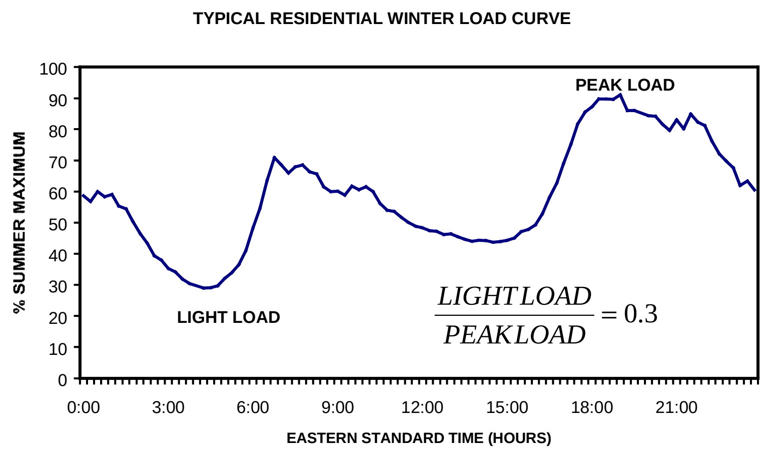


Figure 9 Typical Residential Winter Load Cycle

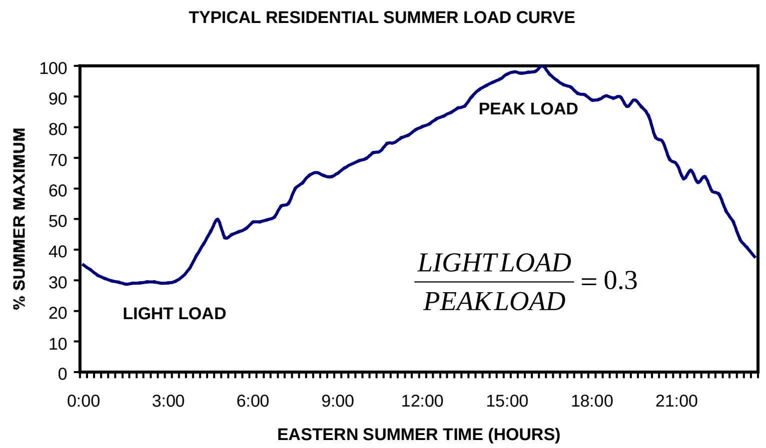


Figure 10 Typical Residential Summer Load Cycle

d) Feeder Load

Accumulation of the estimate of load for each substation along the feeder (taking into account the estimate of load cycle) produces an estimate of the undiversified maximum demand for the feeder. As the maximum demand on each of the substations is likely to occur at a slightly different time, the undiversified total will be higher than the actual maximum feeder load. Accordingly, an estimate must be carried out of the coincidence factor for the feeder load.

$$\text{Coincidence Factor (CF)} = \frac{1}{DiversityFactor(DF)} \qquad (4)$$

$$CF = \frac{1}{DF} = \frac{\text{Feeder load at Zone Substation for time of day}}{\text{Undiversified total (MDI reading * load cycle)}} \qquad (5)$$

Typically, the coincidence factor for residential loads is in the range of 0.85 – 0.95.

e) Power Factor

The power factor for the network has a significant effect in terms of the computation of voltage regulation. For industrial and commercial loads, where a significant proportion of the load consists of some form of motor load, the power factor tends to be in the low range of 0.85 to 0.9. For residential load in winter, the power factor at the time of system maximum demand tends to be high in the range of 0.95 to 0.98. This trend is, however, being affected by the increase in proportion of air-conditioning load on the system As a result, for networks where the maximum demand occurs in summer, the power factor is low

For the purpose of computation of voltage regulation, the typical power factor that is used is 0.9. For winter, this tends to be a conservative figure and provides a "worst case" result, while for summer, it can be considered to be a realistic value.

The effect of power factor on voltage regulation is illustrated in Figure 11. For a given value of real power (kW), the voltage regulation is affected by the actual power factor.

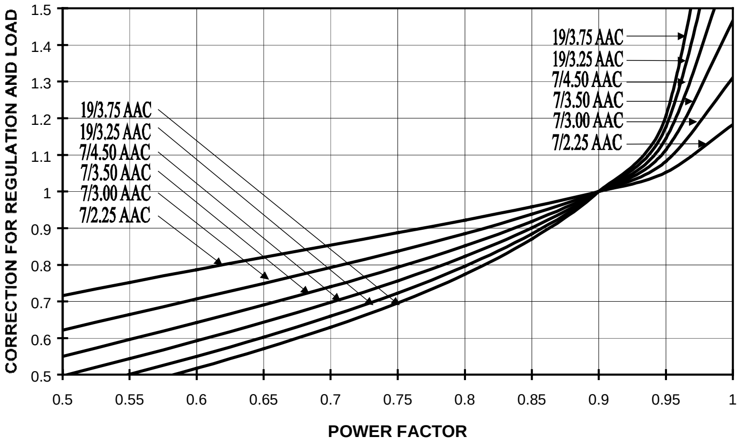


Figure 11 Correction of voltage regulation for Power Factor

To determine the appropriate regulation, divide the calculated regulation by the Correction Factor established from Figure 11.

4.7 Tap Setting of Distribution Transformers

Having established the actual regulation value for the feeder, it is necessary to establish the float voltage of the supply equipment and establish the tap setting for the distribution transformers on the feeder.

As referred to above, at Integral Energy, the float voltages selected for the zone substations transformers are typically as follows:

22kV system:	22.0kV	Bandwidth ± 1.36%	LDC	Varies 0 to 2%
11kV system:	10.9kV	Bandwidth ± 1.36%	LDC	Varies 0 to 2%

For the purpose of establishing the appropriate tap setting of the distribution transformer, consideration must be given to the regulation of the feeder under full load conditions and under light load conditions. Typically, the light load condition is computed utilising a load of 25% of the maximum load.

Table 2 Tap Settings of Distribution Transformers – No load transformer voltages

(1.36% Bandwidth, 2.0% LDC)

11kV Feeder Full Load Condition			Dist Transf. Tap	11kV Feeder ¼ Full Load Condition		
% Reg	HV Range	LV Range		% Reg	HV Range	LV Range
0	10970–11175-11270	249-253-256	11000 / 250	0	10800-10950-11100	246-249-252
0.5	10910-11060-11210	248-251-255			10790-10940-11090	245-249-252
1.0	10860-11010-11160	247-250-254		0.25	10780-10930-11080	245-248-252
1.5	10800-10950-11100	246-249-252			10770-10910-11060	245-248-251
2.0	10750-10900-11050	244-248-251		0.5	10750-10900-11050	245-248-251
2.5	10700-10840-10990	241-246-251			10740-10890-11030	244-247-251
3.0	10640-10790-10930	240-245-250		0.75	10720-10870-11020	244-247-250
3.5	10580-10730-10880	238-244-249			10710-10860-11000	243-247-250

Table 3 Tap Settings of Distribution Transformers – No load transformer voltages

(2.0% Bandwidth, 2.0% LDC)

11kV Feeder Full Load Condition			Dist Transf. Tap	11kV Feeder ¼ Full Load Condition		
% Reg	HV Range	LV Range		% Reg	HV Range	LV Range
0	10900–11120-11340	248-253-258	11000 / 250	0	10740-10950-11170	244-249-254
0.5	10840-11060-11280	246-251-256			10720-10940-11160	244-249-254
1.0	10790-11010-11230	245-250-255		0.25	10710-10930-11150	244-248-253
1.5	10730-10950-11170	244-249-254			10700-10910-11130	243-248-253
2.0	10680-10900-11110	243-248-253		0.5	10680-10900-11120	243-248-253
2.5	10620-10840-11060	247-252-257	10750 / 250		10670-10890-11100	248-253-258
3.0	10570-10780-11000	246-251-256		0.75	10650-10870-11090	248-253-258
3.5	10510-10730-10940	245-250-255			10640-10860-11080	247-253-258

Table 4 Tap Settings of Distribution Transformers – No load transformer voltages

(2.0% Bandwidth, 0% LDC)

11kV Feeder Full Load Condition			Dist Transf. Tap	11kV Feeder ¼ Full Load Condition		
% Reg	HV Range	LV Range		% Reg	HV Range	LV Range
0	10680–10900-11120	243-248-253	11000 / 250	0	10680-10900-11120	243-248-253
0.5	10630-10850-11060	242-246-251			10670-10890-11100	242-247-252
1.0	10580-10790-11000	240-245-250		0.25	10650-10870-11090	242-247-252
1.5	10520-10740-10950	245-250-255	10750 / 250		10640-10860-11080	247-252-258
2.0	10470-10680-10900	243-248-253		0.5	10630-10850-11060	247-252-257
2.5	10420-10630-10840	242-247-252			10620-10830-11050	247-252-257
3.0	10360-10570-10780	241-246-251		0.75	10600-10820-11040	247-252-257
3.5	10310-10520-10730	240-245-250			10590-10910-11020	246-251-256

Assuming that the voltage regulation across the transformer at full load is 2% (PF approx 0.98), the voltage drop on the low voltage terminals is 4.8V at full load and 1.2V at ¼ full load.

To select the appropriate tap setting of the distribution transformer, it is necessary to ensure that the output voltage under full-load and light load conditions results in an acceptable range of voltage at the output terminals.

It will be noted that in Table 2, as the bandwidth is more than compensated by the LDC, the nominal 11000V/433V/250V tap would be selected for feeder regulations up to 3.5%. In Table 3, where the bandwidth and LDC are both at 2%, the 10750V/433V/250V tap is selected when the feeder regulation is 2.5% or greater. In Table 4, where no LDC is available, the 10750V/433V/250V transformer tap can be selected when the feeder regulation is only 1.0%

4.8 Low Voltage Network

Consideration of the voltage drop associated with the low voltage network is a vital factor in determining the voltage at the customer point of supply. It is a complete subject in itself. Accordingly, it is beyond the scope of this paper to give detailed consideration to all of the relevant issues. Reference 5 is a valuable document setting out details of the factors to consider. The following presents a summary of the key issues.

a) Voltage Drop in Low Voltage Mains

The voltage drop that occurs in low voltage mains supplying a number of customers in a particular section is given by:

$$V = K \times ADMD \times \frac{N}{3} \times F_{LD} \times F_U \times L \qquad (6)$$

Where K = A constant related to the impedance of the cable and PF
ADMD = After Diversity Maximum Demand
N = Total number of customers in the section of cable considered (total number across all 3 phases)
F_{LD} = Loss of Diversity Factor correction factor
F_U = Unbalance correction factor
L = Length of cable section

i) ADMD

The After Diversity Maximum Demand (ADMD) is a vital parameter that determines the anticipated maximum demand on the substation and the loading on the low voltage circuit in residential areas. The ADMD is determined by computing the maximum demand of a number of substations by the number of customer connections.

$$ADMD = \frac{Total\ Maximum\ Demand}{Number\ of\ Customers}\ (kVA) \qquad (7)$$

By selection of an ADMD that is too low, voltage drops calculated will be much smaller than actual voltage drops and the loading both on the substation and the cable circuit can exceed design rating. By selection of and ADMD that is too high, the low voltage cable system will be over-designed and have excess capacity.

Traditionally, an ADMD of 5kVA has been used for all-electric areas and 3kVA in gas reticulated areas. Recent studies have revealed that as a result of the extensive installation of air-conditioners, the nature of the residential load has changed significantly.

Although a large proportion of installations have gas installed, the gas is used for water heating, heating and cooking, a predominantly winter consumption. Despite the installation of gas, large proportions of residences, including villas and townhouses, have large split system air-conditioners installed. As a result, the maximum ADMD occurs in summer and is generally higher than the previously adopted value of ADMD. As a result, networks that were only recently installed need to be augmented both with respect to substation capacity and the low voltage network. Provision of three-phase supply to facilitate installation of three-phase instead of single-phase air-conditioning loads is vital.

The values of ADMD that have in recent times been adopted by Integral Energy are as follows:

Table 5 ADMD for design of networks

<table>
<tr><th rowspan="3">Socio-economic Type</th><th colspan="2">Normal Density</th><th rowspan="3">Development Type</th><th colspan="2">High Density</th></tr>
<tr><th colspan="2">ADMD for Distribution System Design</th><th colspan="2">ADMD for Distribution System Design</th></tr>
<tr><th>Gas Area</th><th>Non-Gas Area</th><th>Gas Area</th><th>Non-Gas Area</th></tr>
<tr><td>Low</td><td>5.0kVA</td><td>6.0kVA</td><td>Flats</td><td>3.0kVA</td><td>3.5kVA</td></tr>
<tr><td>Medium</td><td>6.0kVA</td><td>7.0kVA</td><td>Commission</td><td>4.0kVA</td><td>4.5kVA</td></tr>
<tr><td>High</td><td>7.5kVA</td><td>8.5kVA</td><td>Villas</td><td>4.5kVA</td><td>5.5kVA</td></tr>
<tr><td>High*</td><td>7.5kVA to 10kVA</td><td>8.5kVA to 10kVA</td><td colspan="3"></td></tr>
<tr><td colspan="6">* Certain highly affluent areas require a system design greater than 7.5kVA and up to 10kVA</td></tr>
</table>

ii) Loss of Diversity Correction Factor (F_{LD})

As ADMD is based on averages for a large sample, where the number of customers being supplied by any section of low voltage network decreases, the effective load that is seem by the section of cable should be increased per customer connection. This is done to reflect the fact with a reduced number of customers, there is less diversity between the various customers and so the apparent voltage drop for a section of cable will increase.

$$F_{LD} = 1 + \frac{Constant}{A \cdot N} \qquad (8)$$

Where A = ADMD

N = Number of customers.

Constant = 10 (for Integral Energy)

For N = 1 F_{LD} = 3

For N = 30 F_{LD} = 1.07

With the change in the nature of customer load patterns in recent years, particularly in view of the shift towards a summer peak and the occurrence of the peak, typically mid-afternoon and broadening of the peak period, there is a need to carry out new research to establish current realistic values of diversity. ADMD has increased and it is likely that there is less between customers.

iii) Phase Unbalance Correction Factor (F_U)

The phase unbalance correction factor takes into account the following factors:

1) Unbalance is caused as a result of the number of single phase customers connected to any low voltage network cannot be evenly distributed between all three phases when the number of customers is not a multiple of 3.
2) The fact that loads on each phase are not equal at any instant of time (affecting both the phase and neutral voltage drop)
3) Diversity between phases (affecting neutral voltage drop)

The effect of 1) is usually treated mathematically. However, the effect of 2) and 3) is estimated by use of the following formula (Ref. 4):

$$F_U = 1.25 \ x \ \frac{(N+5)}{N} \qquad N > 4 \qquad (9)$$

$$= 5, 3.5, 2.5 \text{ and } 3.0 \qquad N = 1, 2, 3 \text{ and } 4$$

respectively

b) Voltage Drop in Service Cables

The voltage drop in the service cable is related to the undiversified load of a single customer. As it is a single-phase load, the voltage drop needs to be computed both for the phase and neutral.

At an ADMD of 5kVA per customer the undiversified current is approx 60A. For a 7/1.70 mm copper service, the voltage drop is 0.155 V/m at 60A.

In accordance with the NSW Service Installation Rules, the point of supply depends on whether it is an underground or overhead service, and depends on where the service pole or service pit is located.

For the purposes of designing the low voltage network, Integral Energy has developed a methodology for its URD networks based on “correcting” the number of customers connected on a section of mains in accordance with the diversity factor. The number of customers is multiplied by the length of cable section. The total number of customer meters for a low voltage cable is then a function of the effective ADMD for the feeder. Where different ADMD’s apply to a feeder, taking a weighted average of the ADMD for the connected customers assesses the effective ADMD.

For some years Integral Energy has allowed the URD networks to be designed on the basis of a total of 12V voltage drop on the low voltage mains and 4V voltage drop on the service mains up to the point of supply. This is a voltage drop that is rather higher than conventionally accepted, but has been a pragmatic approach to “drive the system harder”. It has been based on an assessment that the voltage drops that occur on the HV network are not as high in URD areas.

Accordingly, based on the use of 240 mm^2 4-core XLPE cable the design parameters that are being used are summarised in Table 6.

Table 6 Integral Energy URD Low Voltage Network Design Parameters

ADMD	Customer Meters for 12V Volt Drop 240 mm^2 XLPE	Maximum number of customers per feeder (250 A Fuses)	Maximum number of customers per padmount

3kVA	16250	57	255
3.5kVA	13920	49	220
4kVA	12190	42	190
5kVA	9750	33	155
6kVA	8120	27	125
7kVA	6970	21	110

4.9 Voltage Profile (example)

Consider an 11kV feeder with feeder regulation of 3.5%, full load (at 0.98PF) on the distribution transformer, bandwidth of 2.0% at the zone substation, and either 2.0% or zero LDC. The

Table 7 Tap Settings of Distribution Transformers

(2.0% Bandwidth, 2.0% LDC)

11kV Feeder Full Load Condition (2% Transformer Regulation)			Dist Transf. Tap	¼ Full Load Condition (0.5% Transformer Regulation)			Voltage Spread	Var
% Reg	HV Range	HV referred to LV		% Reg	HV Range	LV Range		
0	11120 ± 2%	248-253-258	11000 / 250	0	10950 ± 2%	244-249-254	244-258	14
0.5	11060 ± 2%	246-251-256			10940 ± 2%	244-249-254	244-256	121
1.0	11010 ± 2%	245-250-255		0.25	10930 ± 2%	244-248-253	244-255	11
1.5	10950 ± 2%	244-249-254			10910 ± 2%	243-248-253	243-254	11
2.0	10900 ± 2%	243-248-253		0.5	10900 ± 2%	243-248-253	243-253	10
2.5	10840 ± 2%	247-252-257	10750 / 250		10890 ± 2%	248-253-258	247-258	11
3.0	10780 ± 2%	246-251-256		0.75	10870 ± 2%	248-253-258	246-258	12
3.5	10730 ± 2%	245-250-255			10860 ± 2%	247-253-258	245-258	13
	Distribution Transformer							
2%		240-245-250		0.5		245-251-256	240-256	16
	LV Mains Regulation							
4%		230-235-240		1.0		242-248-251	230-251	21
6%		226-231-236		1.5		241-247-252	226-252	26

Table 8 Tap Settings of Distribution Transformers

(2.0% Bandwidth, 0.0% LDC)

11kV Feeder Full Load Condition (2% Transformer Regulation)			Dist Transf. Tap	¼ Full Load Condition (0.5% Transformer Regulation)			Voltage Spread	Var
% Reg	HV Range	HV referred to LV		% Reg	HV Range	LV Range		
0	1 ± 2%	243-248-253	11000 / 250	0	1 ± 2%	243-248-253	243-253	12

0.5	1 ± 2%	242-246-251			1 ± 2%	242-247-252	242-252	10
1.0	1 ± 2%	240-245-250		0.25	1 ± 2%	242-247-252	240-252	12
1.5	1 ± 2%	239-244-249			1 ± 2%	242-247-252	239-252	13
2.0	1 ± 2%	238-243-248		0.5	1 ± 2%	242-246-251	238-251	13
2.5	1 ± 2%	242-247-252	10750		1 ± 2%	247-252-257	242-257	15
3.0	1 ± 2%	241-246-251	/	0.75	1 ± 2%	247-252-257	241-257	16
3.5	1 ± 2%	240-245-250	250		1 ± 2%	246-251-256	240-256	16
	Distribution Transformer				Distribution Transformer			
2%		235-240-245		0.5		244-249-254	235-254	19
	LV Mains Regulation				LV Mains Regulation			
4%		225-230-235		1		241-246-251	225-251	26
6%		219-226-241		1.5		240-245-250	219-250	31

From the Table 7 it is evident that that the voltage at the consumer point of supply at the end of the 11kV feeder is within the range 226V – 252V. This satisfies both the present criterion of 240V ±6% (254V-225V) and the suggested new criterion of 230V +10% -2% (253V-225V). If the power factor of the load on the distribution substation is less than 0.98, the output voltage range at the consumer point of supply would fall outside the acceptable range.

From Table 6, as a result of the lack of LDC, the voltage range at the consumer point of supply at the end of the 11kV feeder is in the range 219V – 250V when the LV mains regulation is 6% and 225V-251V when the LV mains regulation is 4%. With 6% LV mains regulation the voltage range falls below the minimum acceptable voltage of 225V.

Figure 12 and Figure 13 provide an illustration of the results of Table 7 and Table 8.

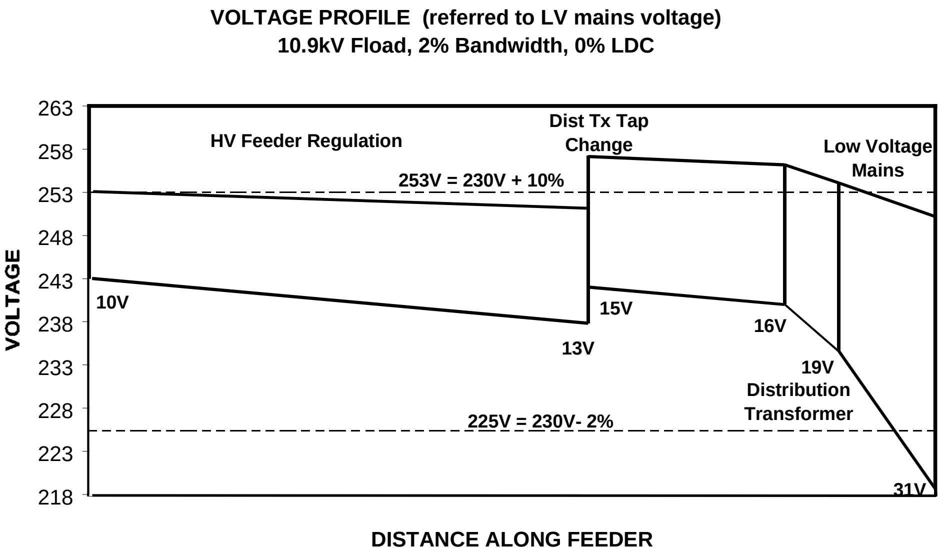


Figure 12 Voltage Profile without LDC

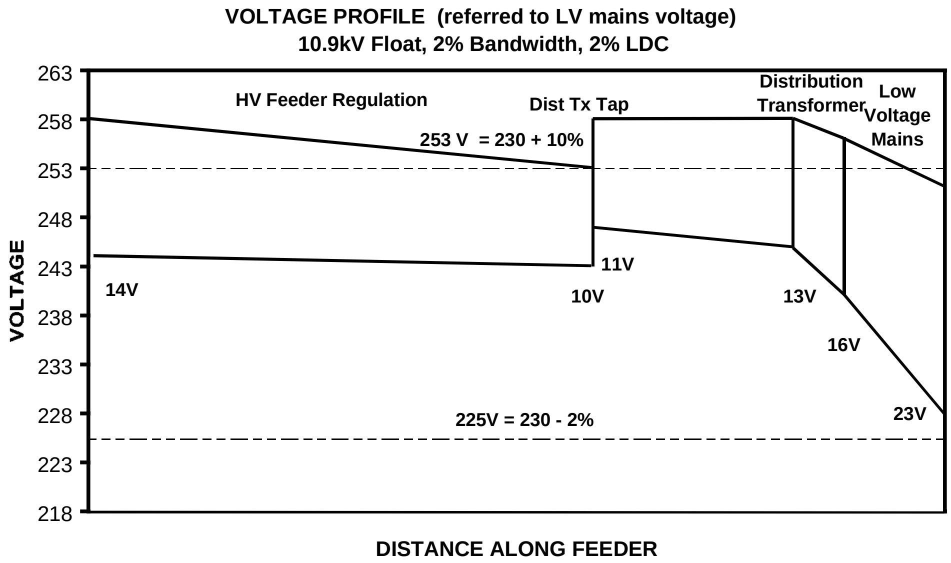


Figure 13 Voltage Profile with LDC

5 AS 60038 – 2000 Standard Voltages

Consideration of the impact of the introduction of the new Australian Standard on Standard Voltages is required by the electricity industry. The area of significance is with respect to the low voltage standard of 230V/400V. Adoption of this standard now brings Australia into line with IEC60038:1983 by utilising the guidance within the IEC standard that countries that have 240V/415V systems should bring the voltage within the range 230V/400V +10%, -6%.

Australia's standard has, however, deviated from the IEC standard with respect to the utilisation voltage range by staying with the long-standing requirements of AS3000 that the voltage drop within the consumer's installations is limited to 5% rather than 4% as required by IEC 60038:1983. In reality, until such time that there is any move to reduce the acceptable voltage band from ±10% to ±6% this is not an issue with respect to products designed to comply with the 230V±10% standard. This, is unlikely to be an issue for the medium term.

The biggest issue is for product manufacturers. Requiring equipment to comply with product specifications through the full range of 230V ±10%, less a further (according to IEC) 4% for the consumer's installation, means that product specifications need to recognise that the utilisation voltage for equipment covers a very wide range. This is both technically difficult to achieve and results in higher costs. The benefit, however, is that the same product can be used almost universally internationally. Manufacturers will continue to press to seek to narrow the voltage range. However, the trend will be that the optimum performance of the equipment will tend towards the nominal voltage (230V).

Australia has been slow in adopting the IEC standard as there are clearly technical and financial disadvantages in reducing the voltage of the low voltage network. However, the reality is that all new product developments worldwide utilise the now internationally accepted 230V standard and adoption of the standard within Australia is timely.

As evidenced from the description above, Australia can continue to utilise in effect its existing standard voltage range of 240 ±6% by renaming the standard voltage range supplied to 230V +10%, -2%. The maximum voltage is in essence the only change through a reduction from 254V to 253V.

Should at any stage in the future there be a move to try to narrow the voltage band from ±10% to ±6%, there would be major implications for the electricity industry. It would then be necessary to take some action to lower the nominal voltage from 240V to 230V. It is unlikely that this will occur as it would have an impact on the full range of existing equipment manufactured in accordance with 240V criteria.

The "simplest" way to implement a reduction in the voltage would be to reduce the float voltage on the 11kV / 22kV network. However, this has the potential for a large economic loss due the increased losses both on the low voltage and the 11kV/22kV networks.

An alternative approach is to have "buck" voltage taps on the distribution transformers in addition to the normal "boost" voltage ratios. This would facilitate any future reduction in the low voltage network without the need for a corresponding reduction on the distribution network.

6 CONCLUSION

An overview has been provided of the issues associated with voltage control on the electricity distribution network. These are basic in determining the performance of the network and represent well understood practices by the experienced distribution engineer. Nevertheless, it is timely to reflect on the issues, particular in view of the issue of the new Australian Standards AS 60038 – 2000 which defines the standard voltage as 230V/400V.

The paper demonstrates that adopting a standard low voltage network voltage of 230V/400V +10%, -2%, the change in the standard voltage can be accommodated without any real change in practices.

7 REFERENCES

1. L A Chappell "The Basis for Control of Distribution Voltages in The Prospect County Council" Prospect County Council 2nd edition, 1974

2. Australian Standard AS 60038 – 2000 "Standard Voltages"

3. EN 50160 – 1994 European Standard "Voltage characteristics of electricity supplied by the distribution systems" published by the European Committee for Electrotechnical Standardization (CENELEC).

4. Prospect County Council URD Review Committee "URD Review April 1989"

5. M A Vinicombe "Notes on the Design of Residential Distribution Network", ESEA of NSW Annual Conference 1972

6. A. Baitch and R.A. Barr "A Tapping Range and Voltage Level Analysis Chart for Tap Changing Transformers" IEEE Transactions on Power Apparatus and Systems, Vol PAS-104 No 11 Nov 1985 pp 3269 – 3277

7 E. Lakervi and E.J.Holmes "Electricity Distribution Network Design" 2nd Edition1995 IEE Power Engineering Series 21 ISBN 0 86341 209 9

8 R. Dugan, M. McGranaghan H. Beaty "Electrical Power Systems Quality" McGraw Hill 1996 ISBN 0-07-018031-8