Application of Risk-assessed Design to LV Networks

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Synopsis

The difficulty in designing low voltage networks – especially for "green-field" sites e.g. new residential (or commercial/industrial) estates - is the uncertainty about the actual loads that will finally get connected to the network. In the past, the most common response in attempting to deal with this uncertainty has been to design conservatively – to "play it safe"!

The return-on-assets imperative that now drives the priorities of electricity utility's capital investment decisions has generally rendered this past approach unacceptable. More rational and constructive approaches must be applied to the design of LV networks.

One such approach is to apply "risk-assessed design" principles.

This requires, firstly, an evaluation the risks - and consequences – that will result from errors in loading estimates under different circumstances. Then it is necessary to be able to employ a design methodology that can produce designs that respond to the set risk factors chosen to suit the individual circumstances of each project. So it is highly desirable that the design tool employed facilitates the use of varying design criteria to reflect these varying assessed risks and consequences.

This paper reviews the principles of "risk-assessed designs" and discusses the relevance of these to LV network design.

It also highlights what are the expected natural outcomes when any risk-assessed design procedures are used to try to find the "right" balance between under- and over-design.

Finally, the paper illustrates how these principles have been applied in an enhanced version of the LVDROP[1] software and summarises the results obtained by the use of different risk criteria when applied to the design of a sample residential estate.

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[1] LVDROP © 1992-2002 Energex Limited

Introduction

The LV network has a significance that far exceeds the importance normally given to its design and management. In urban networks designed to standards common in Australia and New Zealand – or anywhere that UK practices have prevailed – the LV network is the most extensive part of the distribution system. It also accounts for a large part of network capital expenditure – often 20%, or more - and it is responsible for a large proportion of system losses and power quality complaints from customers.

The design of LV networks also has a real impact upon the M.V. network, because it determines the number and siting of distribution substations.

The return-on-assets imperative that now drives the priorities of electricity utility's capital investment decisions requires more measured approaches to design of not only LV networks, but to network design in general.

However, the approach of many organisations to the design of LV networks is still haphazard. Design methods and design standards for LV networks are often not well-founded and are rarely subject to detailed review. In fact, there is a perception that it is because most LV networks are so over-designed that few ever fail to meet the purpose for which they were designed, so that few reviews are ever prompted!

Quest for "Right" Design

The difficulty in designing low voltage networks – especially for "green-field" sites e.g. new residential (or commercial/industrial) estates - is the uncertainty about the actual loads that will finally get connected to the network.

In fact, in the face of such uncertainty it needs to be accepted at the outset that there is little likelihood of the designer of, say, the LV network for a new residential estate of ever producing a design that proves to be exactly "right". That is if by "right" we mean that the realised loading on the network – at least at the time of LV feeder maximum demands – either matches exactly (or is effectively the equivalent of) the loads anticipated by the designer. In this context, being "right" implies an accurate anticipation of both the aggregate loads for individual feeder circuits and transformers, as well as the distribution of load along feeders (to match design feeder voltage profiles)!

Once this prognosis is accepted, then the issue for LV network design becomes this:

- What degree of mismatch exists between the design model and the (eventually proven) reality? … and
- Is the type of mismatch one of under- or over-design?

Under-design implies excessive losses, adverse power quality (low voltage, excessive voltage variation, etc.) and, in more serious cases, costly remedial work. On the other hand, over-design implies a waste of resources (money and material), over-investment in the network and the inevitable adverse affect on return on assets.

Principles of Risk Assessment

With uncertainty comes risk. If, in a design, the parameters that should be used are not clear and precise – for example, if there is a range of possible values for some criteria and the design is sensitive to these – then even though the values used may be carefully chosen, there remains a risk that the design model will fail to be a sufficiently good representation of reality.

In these circumstances – which are the rule, rather than the exception, in LV network design - what the designer needs to do is to effectively assess and manage this risk.

But we need to be clear about the meaning of the terms such as Risk, Risk Assessment and Risk Management[2]:

- **Risk** is the probability that an adverse event or outcome occurs during a stated period of time
- **Risk Assessment** is the identification of the outcomes, the estimation of the magnitude of the associated consequences of these outcomes and the estimation of the probabilities of these outcomes
- **Risk Management** is the process whereby decisions are made to accept a known or assessed risk and/or implement actions to reduce the consequences or the probability of occurrence.

There are a number of clearly identifiable risks and consequences associated with the design of LV networks.

Risk Factors in LV Network Design

The main risks factors in the LV networks design relate principally to the estimation of the magnitude of loads to be supplied from the network and, to a lesser extent, their distribution along the LV feeders.

The principle adverse outcomes (consequences) that may arise in the design of LV networks due to the inadequate estimates of loading are[3]:

- Excessive cable voltage drop
- Overloaded cables
- Overloaded transformers

Each of these are dealt with in detail in the following sections.

Excessive Cable Voltage Drop

If an under-estimate of loading results in excessive voltage drop some form of augmentation may be required. The severity of the consequences is closely linked

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[2] Definitions from Reference 2.

[3] Unbalanced loading between is also a significant factor when designing multi-phase systems. Though the Multi-stat Edition of the LVDROP software specifically takes unbalance into account, the topic of phase unbalance is beyond the scope of this paper.

to the nature of the LV mains involved eg. aerial conductors, ducted underground cables, or direct-buried underground cables.

Aerial conductors may be augmented relatively easily, as may underground cables installed in ducts, while direct buried underground cables are likely to be very expensive to change and may also detrimentally affect customer relations if it is necessary to excavate across the front of their properties, disrupt access, have prolonged supply outages, etc.

In cases of severely under-estimated loads/voltage drops, it may be necessary to introduce additional distribution transformer substations to redistribute loads amongst feeders and to reduce the lengths of LV feeders from substations

Overloaded Cables

Overloading of cables will generally be a less likely consequence of under-estimating loads to be carried because in most – but not all – cases the design will be constrained by voltage drop limits. Cables, especially direct buried cables, have a capacity to carry overloads for some time before any substantial detrimental effects occur - usually loss-of-working-life of the cable insulation due to elevated working temperatures. Where residential type loads are involved cables will generally have a good short-term overload capacity because the peak loads are usually of a very short duration.

However, if remedial work is required then similar consequences as outline in the previous section for “excessive voltage drop” also apply here.

Overloaded Transformer

Overloaded transformers may usually be replaced relatively easily, provided the substation is able to accept a transformer of a higher rating! Besides the costs of replacement there is also the costs and adverse effects on customers of the outage for the transformer change.

Risk Assessed Design

A “Risk assessed Design” involves the application of risk assessment and risk management principles to the design process.

To be able to implement a risk-assessed design, the design methodology and tools used must be facilitate the selection of suitable factors to reflect varying degrees or risk deemed appropriate to the task at hand … and the design methodology must be sensitive to those factors. This means that if the designer assesses a lower risk, for example, because an underground network being designed is to consist of ducted, rather than direct buried, underground cables, then the resulting design should reflect this. Compared to the equivalent design for a direct-buried cable network, the ducted cable system design should propose either smaller cable to be used, or longer cable runs of the same cable size, or lower assessed maximum voltage drops values for the design load (assuming the design is volt-drop constrained).

It is highly desirable – perhaps essential - that whatever settings are used to determine how tight or conservative a design may be are clearly identified and that for any aspect of the design there is only one such setting. If such conservatism is built in at a number of points in the design process, then their overall cumulative effect may not be obvious. For example, if design loads are over-estimated, conductor resistance are calculated at low operating temperatures (e.g. manufactures' data sheet 20^{o} C values), and generous allowable design voltage drops are set, then it is difficult to judge what the overall results really mean from a risk management point-of-view.

Optimised Designs

How should the success of LV network designs be judged?

If one design fails to cope, has the design process failed?

If no designs fail – unless the network load is grossly different to what could be anticipated at design time – does this lack of failures indicate a successful design strategy?

Firstly, it must be said that success or failure in this context cannot be determined on the basis of a single project. Rather there needs to be a number of designs reviewed over time for any objective judgement to be made - and caution should be exercised before any generalisations are made. However, one generalised conclusion that can be made with some confidence is that if, over a reasonable number of projects, none at all are found unable to meet reasonably anticipated network loads, then almost certainly the design process and design criteria are too conservative and the networks are being over-designed!

Theoretically – though somewhat simplistically – it can be said that some designs should fail, but that the proper application of optimised design processes should result in designs that – compared to less stringent designs - are sufficiently tight to yield sufficient savings in the installed costs of networks that are able to offset the costs of remedial works that may be required to augment networks that do prove to be inadequate. (see Figure 1)[4].

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[4] These curves should probably be based on the Total Cost of Ownership, rather than just installed costs and Remedial Costs should include both tangible and intangible costs.

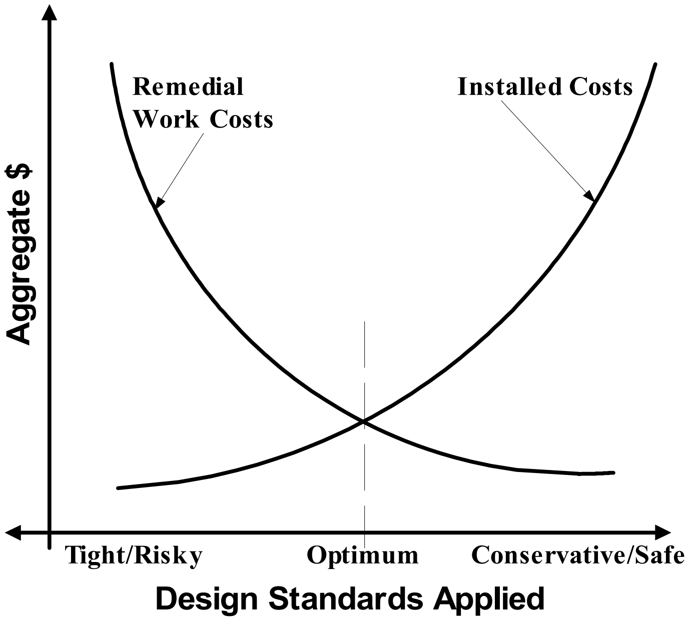

Figure 1: Finding the Right Balance in Design Standards

This conclusion is in accord with the definition of Risk Management given earlier, and it is also consistent with other quality control processes, for example in the manufacturing industry, where the costs of quality control inspection procedures are optimised against the cost of later rectification of defects.

The above graph is conceptual only. It is not suggested that any network designer can readily construct such a graph - but it does neatly encapsulate the principles of an optimised risked-assessed design process. In practice, it would only be by an ongoing process of review of the actual in-field performance of networks and their design criteria that would provide a basis for “balancing” the risks, rewards and consequences.

Most engineering staff are not particularly comfortable with the prospect of having some designs fail – and some are very sceptical about the success they may have in attempting to justify to management the failure of some individual designs as the “necessary” part of an optimised design process!!

The message that needs to be taken from this is that if optimised risk assessed designed procedures are to be applied in an organisation then the implications this decision and its consequences must be understood an accepted at all levels of the organisation and thatmanagement must set the design o bjectives it considers appropriate!

Load Modelling in the LVDROP Software

The LVDROP software uses a statistically defined model of loads[5] that is suited to risk assessed design processes.

It is a model that yields aggregate Maximum Demands that exhibit the well-known effects of diversity. However, in contrast the Diversity Factor design method[6] that uses an *After Diversity Maximum Demand* (*A.D.M.D.*) load value adjusted by *Diversity Factors* (based on the number ofloads being supplied from and through any section of the LV Network), it instead uses a *Mean* load value and the *Standard Deviation* of the Normal Distribution of variations in measured load values load values around the Mean.

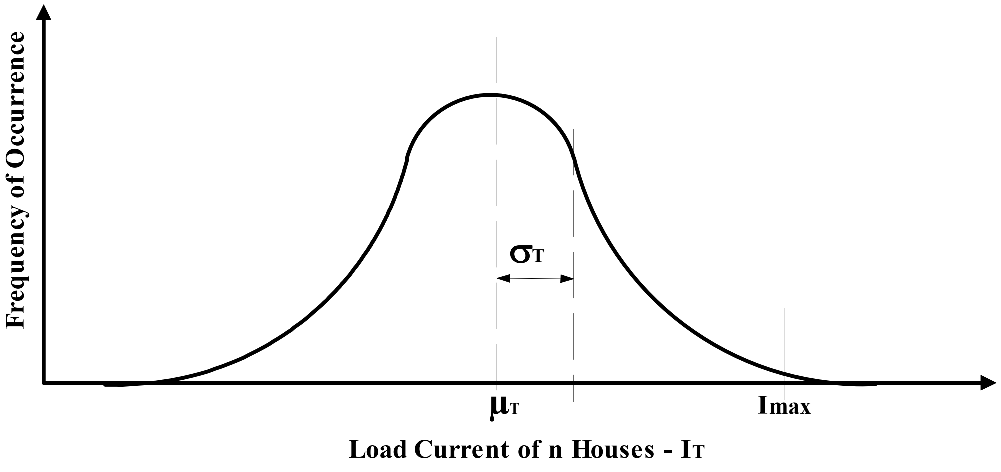

Figure 2: Probability Distribution for the Total Load Current of 'n' Consumers

With this load model the design load current $\mathbf{I_{max}}$ is equal to the Mean value plus a certain number (**k**) of Standard Deviations above the Mean – i.e.:

$$I_{\max} = \mu_T + k\sigma_T$$

The value of 'k' is determined according to what is considered to be an <u>Acceptable Level of Risk</u> for the design being carried out.

Practical values for 'k', known as the *Confidence Factor*, are in the range of 1.28 to 3.00, which correspond to probabilities of between 90% and 99.9% of the design meeting the actual demand.

The factors influencing the selection of the Confidence Factor (k) to be applied in a design include:

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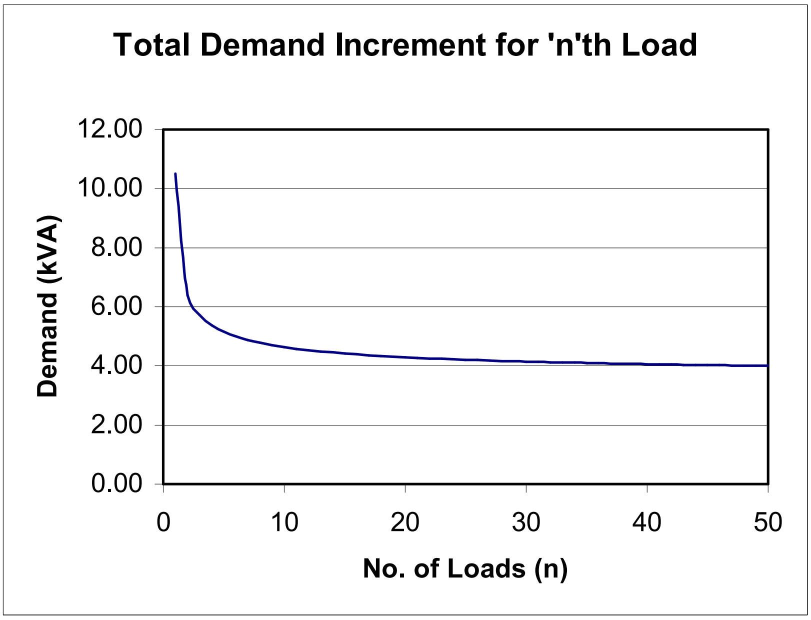
[5] See Reference 1 for full details of the basis of the statistical description of loads used by the LVDROP software.

[6] The Diversity Factor design method originated in the UK in the mid-1950's and was subsequently widely adopted in the Australian/New Zealand region. Many organisations' design methodologies that are based on the use of charts, nomograms, spreadsheets, or "home-grown" computer programs are based on the Diversity Factor design method … though frequently many present-day users are unaware of this!

- The consequences of actual demand exceeding design levels. For most residential estates the limiting design parameter is voltage drop. Voltages below statutory limits on a few very rare occasions are not catastrophic, as would be the case with exceeding conductor current ratings causing annealing or excessive loss-of-life to conductor insulation.
- The ease of reconductoring should voltage problems be encountered at a future time. For example, with direct buried cables, where upgrading to larger cables is extremely difficult and expensive, it would be advisable to select a higher value for k

A Confidence Factor of 2.0, corresponding to a probability of 97.7%, has been recommended for mains consisting of aerial conductors and 3.0 (99.9% probability) for direct buried underground mains.

The following graph illustrates how the LVDROP load model reflects the effect of diversity between loads. This graph is based on loads with a Mean of 3.5 kVA, a Standard Deviation of 3.5 kVA, and a Confidence Factor of 2.0.



Those familiar with the Diversity Factor method will recognise that this graph closely resembles the form of a graph of Diversity Factors and in fact the Y-axis could easily be scaled to be “Equivalent Diversity Factor”. However, while closely resembling the Diversity Factor graph, the use of the statistical description of loads was chosen by the originators of the LVDROP software because it overcomes the main disadvantages of the Diversity Factor design method. These are its inability to deal with:

- mixed loads i.e. loads with different characteristics
- loops, rings or parallel sections of mains the network

Case Study

The design of small residential estate has been used as a case study to illustrate the varying results obtained by the use of different Confidence Factors (risk factors) with the LVDROP software. The network and more detailed results are included in the Appendix.

Confidence Factors	Maximum Voltage Cable Drop (volt)	Maximum Cable Current (amp)	Assessed Transformer Loading (amp)
1.28	9.8	187.9	187.9
2.00	11.9	211.7	211.7
2.50	13.3	228.2	228.2
3.00	14.7	244.7	244.7
1.82/2.12/1.65*	11.4	215.6	200.2

* In this instance, individual Confidence Factors are applied to each aspect of the design – using factors of 1.82, 2.12 and 1.82 for Cable Voltage Drop, Cable Current and Transformer Loading respectively. This ability to concurrently apply individual Confidence Factors to each of the main design criteria is a differentiating characteristic of the "Multi-stat Edition" of the LVDROP software.

In normal use the implication of these different results would be reflected in the choice of cable sizes, the lengths of runs of particular cable sizes, transformer sizing etc. and overall would materially affect the region and number of loads that were assessed as being able to be supplied from individual distribution substations.

Conclusions

It is implicit in the use of Risk-assessed Design procedures with finite probabilities of risk deemed acceptable, then some failures of designs can be expected to occur – at least in the long run (i.e. over many designs). But these instances of failure should be controlled to an acceptable number where the aggregate savings accruing from other optimised designs will offset the costs of remedial action needed on those that fail.

However, to apply risk-assessed designs requires design tools that isolate any conservatism used in the design be clearly identified and free-standing design criteria. This is both so that a conscious decision is made about by the designer of what is an appropriate degree of risk to accept for the project involved and so that others reviewing the design can easily recognise the choice that has been made. Normally this choice would be based on pre-defined design standards.

For LV network design, the LVDROP software "Multi-stat Edition" enables the designer to assign risk factors individually to the main aspects of the design model it produces – voltage drop, cable loading and transformer loading - with factor each chosen according to the assessed risks and consequences of those assessed values being exceeded in practice.

The case study detailed has demonstrated the relative differences in results obtained by varying the risk factors used in the design of a sample network.

References

1. Gosden, K.: A Statistical Method for Analysing L.V. Distribution Networks Presented at the Annual Conference of the Electricity Supply Engineers' Association of NSW, Sydney, August 13-16, 1990
2. Kobal, B. et al: A Risk Assessment Approach to the Design of an 11kV Distribution Network. Presented at the Annual Conference of the Electricity Supply Engineers' Association of NSW, Manly, August 15-17, 1994.
3. SEQEB: Distribution Planning Manual, 1993.

Appendix A: Case Study Details

The sample subdivision used in the case study is shown below (Figure A-1). The estate consists of a number of houses supplied from existing aerial mains and new underground main supplying a group of houses and a neighbourhood shop.

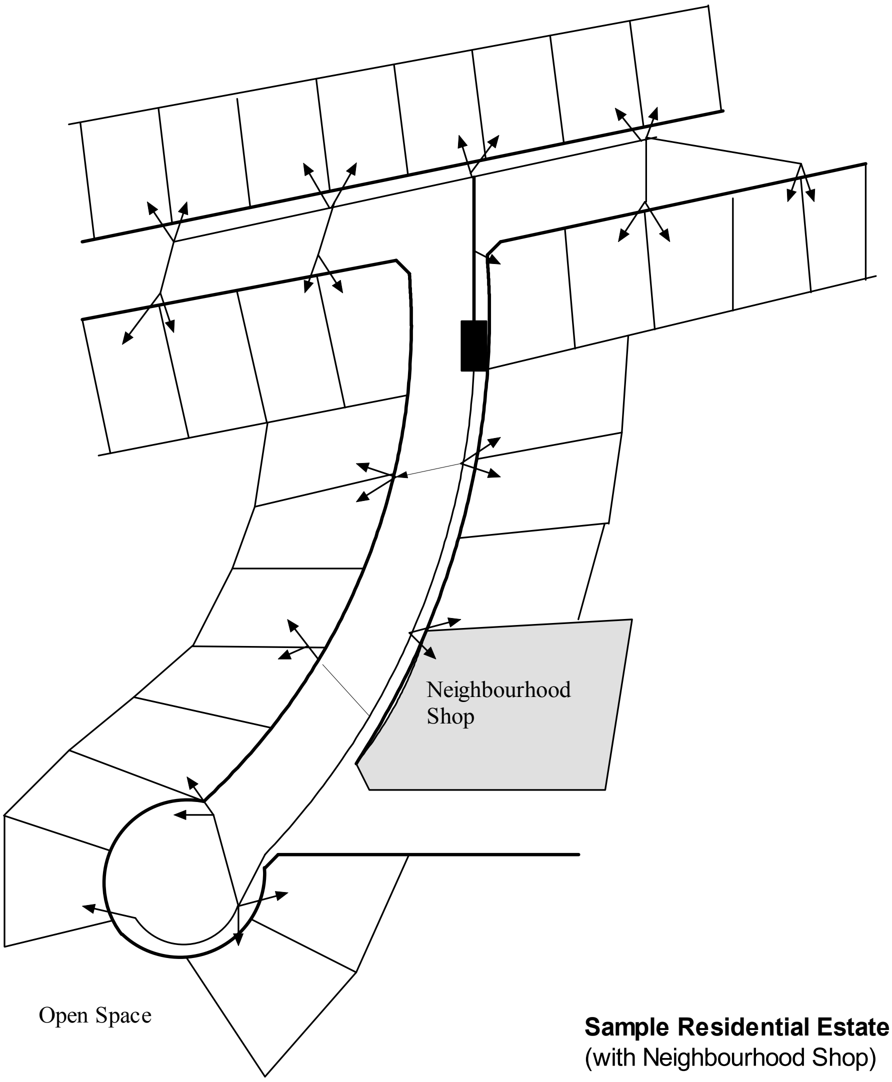


Figure A - 1: Sample Network for Used for Case Studies

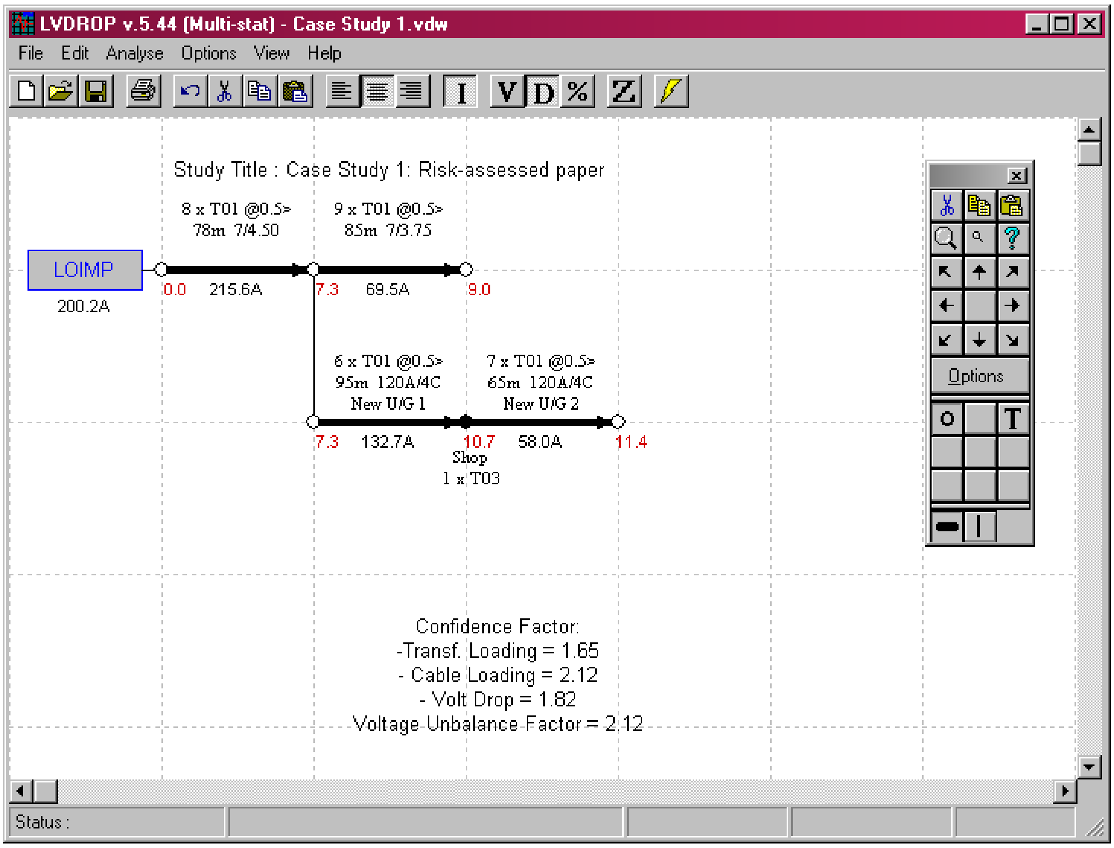
The model of this network in the LVDROP software is shown below (Figure A-2) which also shows results of for one of the study cases.

In this case the model used is based on four (4) feeder segments with distributed loads on each segment and a spot load (the shop) applied to the node connecting segments "New U/G 1" and "New U/G 2".

The user is able to choose between a relatively "high level" approach such has been used in this instance. In instance it is important to use an accurate assessment of the

"Point-of-Application" (POA) factor for the distributed loads on each segment (the LVDROP software has a built in POA calculator). However the user may choose any other level of detail down to the lowest possible level where the designer models each section of LV conductors between service connections as individual segments.

The figures in red beneath each node indicate the assessed voltage drop at the node and the figures below the segments and transformer represent the assessed current loading. (Voltage results are available as absolute voltage levels or as voltage drops in volts, or as a percentage). Parts of the network exceeding the user-defined volt drop thresholds are automatically highlighted, as are currents that exceed assigned ratings.



Study Title : Case Study 1: Risk-assessed paper

Confidence Factor:
-Transf. Loading = 1.65
- Cable Loading = 2.12
- Volt Drop = 1.82
Voltage Unbalance Factor = 2.12

Figure A - 2: Model of the Sample Network in the LVDROP Software

The LVDROP software is distributed in New Zealand by Auckland-based Mahanga Holdings.