Opportunities for in-line, transistor-based technologies on MV and LV power distribution networks

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Declaration

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

[redacted]

Bernard Meyer 10 November 2000

Opsomming

Nuwe geleenthede het na vore getree vir die toepassing van innoverende tegnologië op medium- en laagspannings netwerke in antwoord op die uitdagings gestel deur die regering in die vorm van die Nasionale Elektrifiseringsprogram (NEP). Die elektrifisering van 'n verdere 2,5 miljoen huishoudings waarvan die grootste gedeelte in yl bevolkte plattelandse gebiede is, word in vooruitsig gestel. Spanningskompensasie van lang laag- en mediumspannings netwerke word nou moontlik gemaak deur middel van elektroniese spanningsreguleerders, gemonteer aan die sekondêre kant van distribusie transformators en in diensaansluitingskaste op laagspannings voerders.

Verder is dit ook nou moontlik om afgeleë landelike plase met enkelfase krag, gerugsteun deur eindverbruik tegnologië in die vorm van elektroniese fase omsetters, te voorsien. Die beskikbaarheid van hierdie tegnologië elimineer die vraag na drie-fase krag. Hierdie hibriede kombinasie van toevoer- en eindverbruik tegnologië in kohesie met die selfbou beleid van Eskom, maak dit moontlik dat 'n droom van Eskom voorsiende elektrisiteit, in 'n werklikheid omskep word.

Abstract

Once more opportunities exist for innovative technologies to be applied on MV and LV power distribution networks to meet the new challenges set by government through its National Electrification Programme (NEP) to electrify a further 2,5 million households of which a large majority are in low-density rural areas. Electronic means of voltage compensation of long MV and LV networks supplying these low-density rural areas are now possible in the form of electronic voltage regulators mounted on the secondary side of distribution transformers and service connection boxes along the LV feeders.

Furthermore, it is now possible to provide remote rural agricultural customers with single-phase supplies supported by end-use technologies in the form of electronic phase converters that eliminate the need for three-phase supplies. This hybrid of supply- and end-use technologies together with Eskom's "self-build" policy has made the dream of Eskom grid power a reality.

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Eskom for their financial support and to allow me the opportunity for further studies.

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List of Abbreviations

µFACTS	micro Flexible AC Transmission Systems
A	Ampére
ABC	Aerial Bundled Conductor
AC	Alternating Current
ADMD	After Diversified Maximum Demand
AMEU	Association of Municipal Electricity Undertakings
ATI	Appropriate Technology Index
BDMD	Before Diversified Maximum Demand
CB	Circuit Breaker
CIC	Capital Investment Cost
CL	Copper Losses
CNE	Combined Neutral and Earth
DC	Direct Current
DCF	Diversity Correction Factor
DT	Distribution Technology
ED	Electricity Dispenser
EHV	Extra-HighVoltage
ELF	Energy Loss Factor
EPC	Electronic Phase Converter
EPRI	Electric Power Research Institute
EVR	Electronic Voltage Regulator
FACTS	Flexible AC Transmission Systems
GC	Generation Cost
HRC	High Rupturing Capacity
HV	HighVoltage
IGBT	Insulated Gate Bipolar Transistor
km	kilometre
KPI	Key Performance Indicator
kV	kilovolt
kVA	kilovolt ampere
kW	kilowatt
kWh	kilowatt hour

LCC	Life-Cycle Cost
LDC	Load Drop Compensation
LSP	Large Single-Phase motor
LV	Low Voltage
m	metre
MCB	Miniature Circuit-Breaker
MV	Medium Voltage
MVA	Megavolt Ampére
MVR	Mechanical autotransformer Voltage Regulator
NEP	National Electrification Programme
Nm	Newton metres
NPV	Net Present Value
NRS	National Rationalised Specification
OCTS	Off-Circuit Tap-change Switch
OLTC	On-Load Tap-Changer
PCC	Point of Common Coupling
PEN	Protective Earth and Neutral
ph	phase
ph-ph	phase-phase
PV	Photovoltaic
R	Rand (South African)
RDP	Reconstruction and Development Programme
SCB	Service Connection Box
SHS	Solar Home System
SIL	Surge Impedance Loading
STD	Standard
SWER	Single-Wire Earth Return
TCL	Total Cost of Losses
TMC	Total Maintenance Cost
TRFR	Transformer
UCF	Unbalanced voltage Correction Factor
USE	Universal Semiconductor Electrification
V	Volt

Chapter 1

Introduction

1.1 Universal access to electricity

South Africa boasts a modern electricity supply industry that is equal to the best in the world. This, together with the availability of cheap coal, enables our country to produce electricity at a cost that is the second lowest in the world.

Yet when South Africa entered the last decade of the 20th century, the majority of South Africans in disadvantaged communities did not have electricity in their homes. At the beginning of the 1990s Eskom and municipalities commenced with the electrification of homes in disadvantaged communities. This endeavour was given a major boost when the Reconstruction and Development Programme (RDP) set ambitious electrification targets.

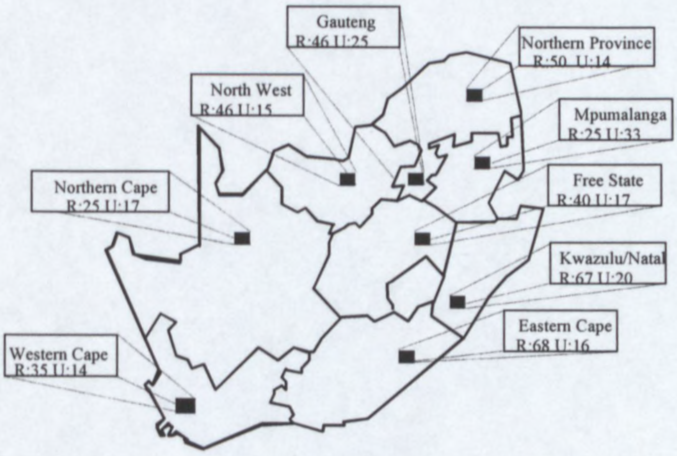


Fig. 1: Percentage houses not electrified as at the end of 1999. (R = Rural, U = Urban) [15] [16]

The targets provided for 450 000 new households to be electrified per year from 1994 until the turn of the century, of which Eskom committed itself to a target of 300 000 new connections per year. These targets were met and exceeded by the electricity suppliers, Eskom and municipalities. Electricity was installed in 2,8 million homes, improving the quality of life of approximately 20 million people and creating jobs for many.

However, an estimated 34% of South African households still have to do without electricity. The challenge for the electricity suppliers is to bring electricity to these people, specifically in the rural areas where more than 50% (2 million) of the dwellings are not electrified. This can be seen in Fig. 1 and Fig. 2 [15][16]. These figures depict the relationship between urban and rural distribution of electricity as at the end of 1999 with specific emphasis on rural dwellings still to be electrified. The unbalanced distribution of access to electricity is clearly noticeable. Fig. 2 also clearly indicates that the focus areas of rural electrification for years to come still remain in the Eastern Cape, Kwa-Zulu Natal and Northern Province, as has been the case up to now.

Government has now committed itself to making this initiative a reality through its National Electrification Programme (NEP) whereby an average of R1 billion per annum will be spent on electrification projects over a period of 12 to 15 years to electrify the outstanding total of nearly 2,5 million households in urban and rural areas [31].

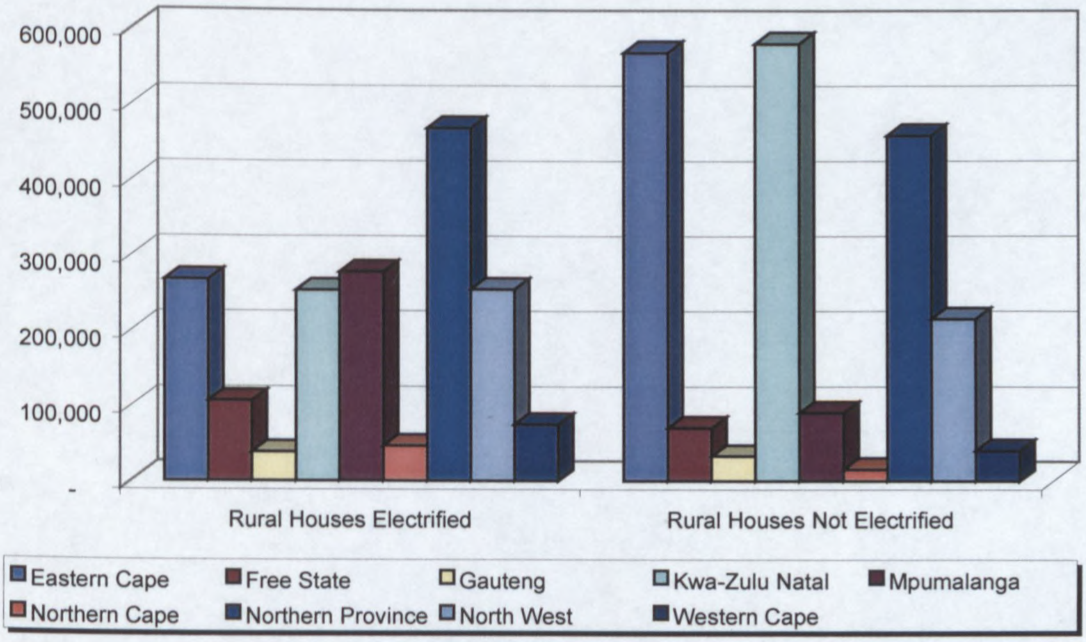


Fig. 2: Electrification statistics (rural) as at the end of 1999 [15] [16]

Prior to the 1990s Eskom supplied electricity mainly to large customers such as mines and municipalities. Although Eskom was at that stage already one of the largest electricity generators in the world, the utility only had about 120 000 customers. In 1988 Eskom developed the "Electricity for All" concept intended to supply electricity directly to the large masses of domestic customers (urban and rural areas) that did not have access to electricity at that stage.

With this ever-increasing demand for electrical energy in the developing parts of our country, the Eskom Distribution Group had to adapt to the new business challenges posed by the RDP. Innovative technological concepts are required to support this socio-economic drive of government in the form of its RDP. As many of these developing areas are in sparsely populated regions with little or no infrastructure, these potentially small electrical loads are located far from existing electrical backbone networks or generating plants and this normally does not economically justify the establishment of common medium- to high-capacity sub-transmission and distribution networks.

1.2 Electrification cost targets

Initial cost-saving options were mostly achieved through optimisation of existing engineering practices. These practices included delayed capital expenditure through ADMD (After Diversified Maximum Demand) optimisation ("15-year ceiling levels" brought down from 4 to 1.5 kVA per connection for urban and from 1.5 to 0.4 kVA per connection for rural areas), improved township layout planning (mid-block vs street-front networks), optimised line spans and bend points, and designing closer to the thermal and voltage regulation limits of lines (reducing conductor size). Further optimisation was achieved through sharing of line structures with other essential services such as telephone lines. Due to the long payback period (over 20 years) for these projects, it is essential to reduce the initial capital cost. The engineering philosophy of delayed capital expenditure will be discussed more fully in section 2.3.

Unfortunately the technologies required to meet the very strict cost targets (refer Table 1) were not fully in place in the early to mid 1990s, but this was offset against the fact that initially higher-density urban areas (4000-6000 stands per square kilometre) were electrified (refer Fig. 3).

Table 1: Cost per connection targets for Eskom (in 1996 SA Rands) [15]

	1996	1997	1998	1999	2000
Cost per connection target	R3 200	R2 982	R2 588	R2 484	R2 484

However, this picture has since changed in that current areas targeted for electrification are rural and "deep-rural" in nature with densities in the order of less than 200 stands per square kilometre.

Fig. 3: Example of a typical high-density area – Khayelitsha on the Cape Flats

Low load density areas are associated with low diversity loading. This combined with long distances means higher cost per kilowatt delivered as well as high per unit current fluctuations in the lines. Fig. 4 shows a graph indicating the exponential increase in cost per connection as the load density drops. The electrification tendency is to target the high-density areas ("cherries") first and to postpone the electrification of the low-density areas due to very strict business cost targets set.

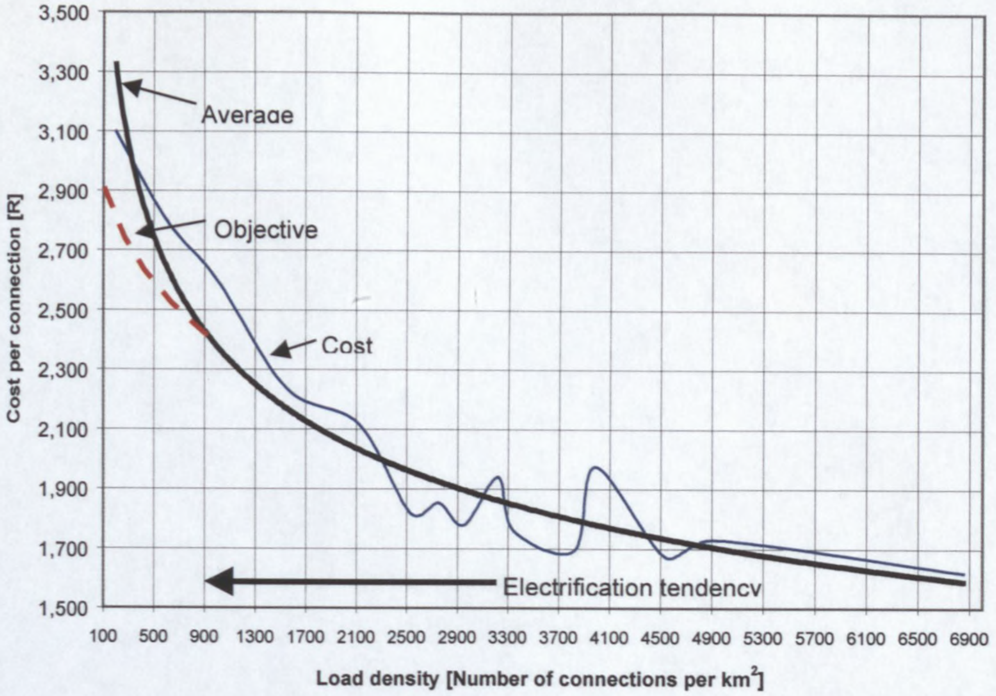


Fig. 4: Typical electrification cost versus density

The first objective of this thesis was to identify possible cost-saving opportunities for rural electrification with a specific focus on low population density (<200 stands per square kilometre) and low power consumption (2.5 A load limiting supplies) areas (refer Fig. 5 and Fig. 7). The second objective was to address the needs of customers requiring three-phase supplies in remote rural areas for agricultural farming activities.

The proposed supporting technologies had to break the "barrier" of previously set planning and design constraints such as increased capital cost, supply capacity and voltage regulation. The ultimate objective is the reduction in capital cost (refer Fig. 4), whilst offering fit-for-purpose supply solutions.

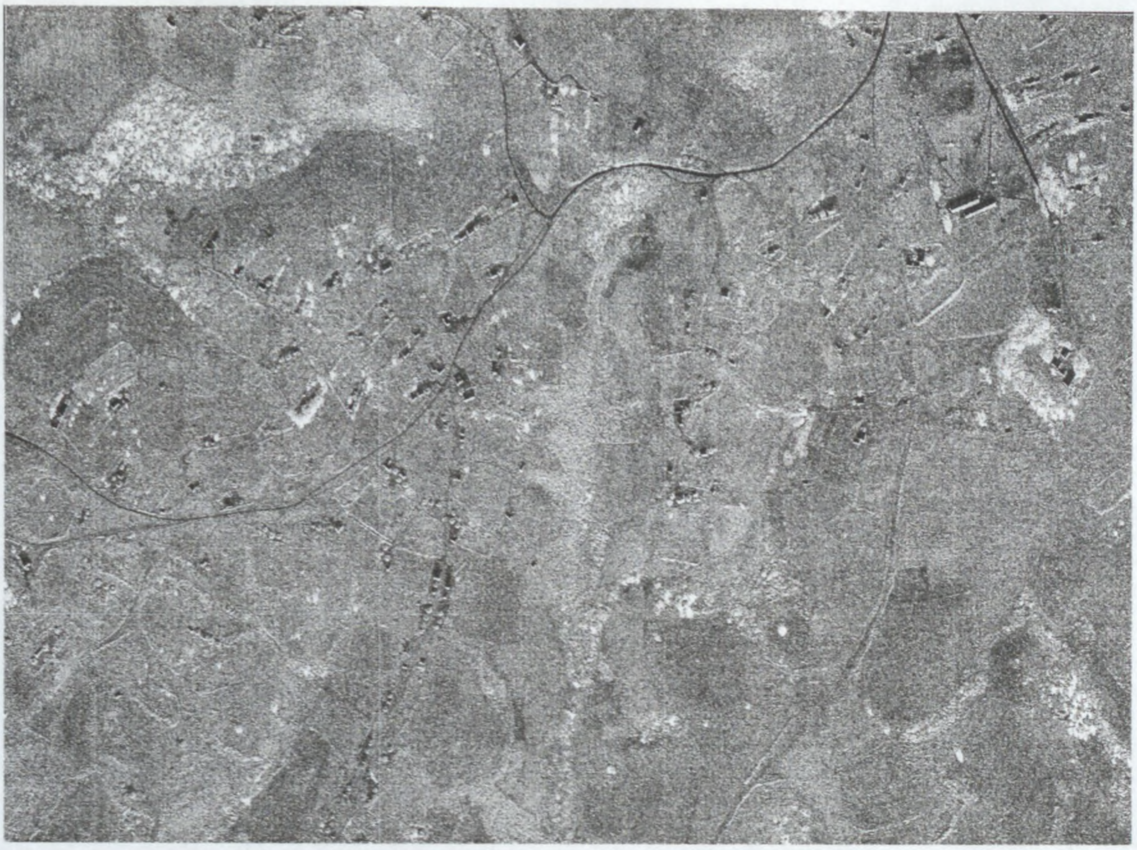


Fig. 5: Example of a typical low-density area – Magwa in the former Transkei

1.3 Paradigm shift

Since the medium-voltage (MV) link line's cost contribution in relation to the overall cost per connection to these remote rural communities increases due to distance from nearest source, the choice of alternative line technologies (Single-Wire Earth Return (SWER) or phase-phase MV) or optimal conductor sizing is required (refer Fig. 6). These technologies are as applicable to rural agricultural supplies as they are for rural electrification. To put this into perspective, the current Business Plan [1] indicators are reviewed below. The required cost per transformer ratio for the year 2000 amounts to R35 000, which relates to an overall average three-phase line cost of R53 000 per kilometre. This is 29% lower than the 1999 target of R45 000 per transformer and if not achieved relates to a summated (core business and electrification) budget risk of R176 million [1].

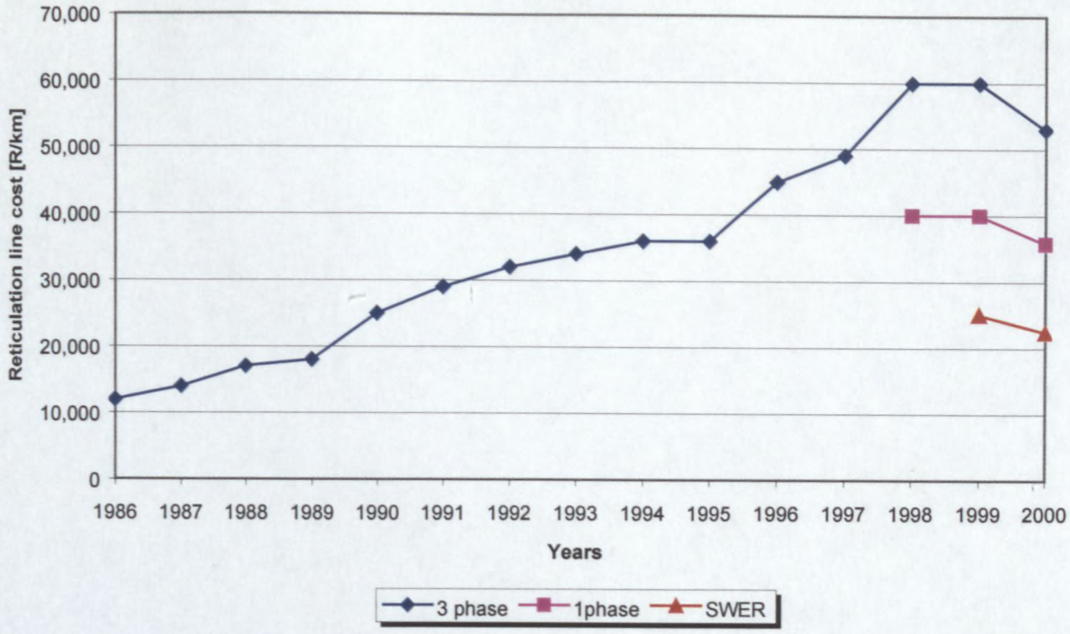


Fig. 6: Historical medium voltage reticulation line costs [2][3]

It is clear that in order to reach the cost targets and at the same time ensure the financial well-being of the company, Eskom has to find ways to reduce these costs significantly. Medium- and low-voltage (LV) networks provide greater scope for saving than the high-voltage (HV) systems due to the proportional relationship of overall capital expenditure for network expansion, available technologies and network growth in rural areas. Therefore, it is evident that a paradigm shift is required from the more traditional to cost effective technologies that support the load requirements of these new, long and lightly loaded networks. As clearly demonstrated by Hingorani *et al.* [10], the emphasis therefore is to design networks to be extremely "light" initially with high flexibility by means of practical and cost effective upgrade paths to ensure that optimum use is made of resources and capital.

1.4 Summary

This chapter started by sketching the background to one of the main problems Eskom and municipalities currently face, i.e. electrification of a vast number of households, specifically in the deep rural areas. An idea of the cost implications was given and it was indicated that a paradigm shift from using three-phase high-capacity lines to single-phase lines is crucial.

Chapter 2 focuses on line technologies and addresses issues of importance for "stretching the network" with the final objective of developing an evaluation technique to decide on the best technology choice for each network supply option.

Chapter 3 focuses on the support of lines stretched beyond their previously accepted limits and also addresses customer requirements for three-phase supplies in remote rural areas.

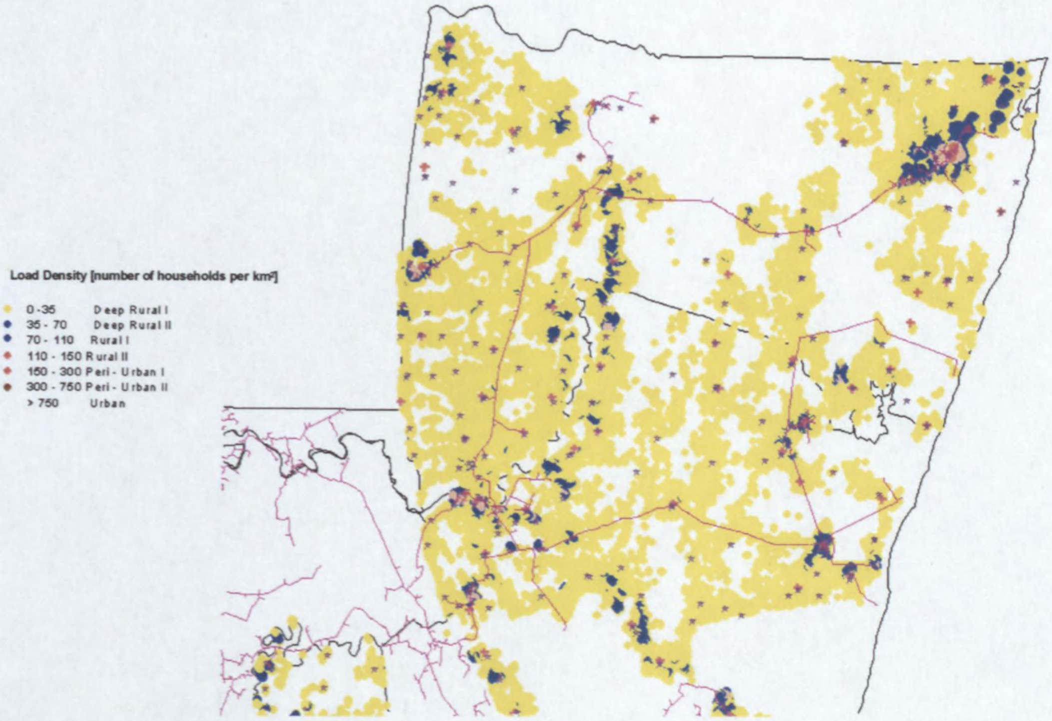


Fig. 7: Load density distribution (households per km^2) – Lubombo in Kwa-Zulu Natal

Chapter 2

New Challenge for distribution line technologies

2.1 Introduction

This chapter will focus on the current initiatives already launched in the Eskom Distribution business in order to make rural electricity supplies more affordable. The specific focus to date has been on alternative MV line technologies and the effective use of LV single- and dual-phase systems. The load reach and transfer capabilities of the various line technologies are also compared and discussed. Attention is also devoted to the importance of delaying capital expenditure due to the uncertainties involved in load growth, being just one of the mechanisms for achieving the cost targets. Developing a model that can be applied to compare various technologies objectively on a per project basis concludes the chapter.

2.2 Alternative line technologies

The alternative line technologies in place in Eskom Distribution to support this cost drive are SWER (Single-Wire Earth Return), phase-phase MV networks and dual-phase LV networks. These technologies are often more appropriate, especially when dealing with the type of loads described in section 1.3.

The main cost advantages of these alternative line technologies are:

- Longer span lengths can be achieved due to increased electrical and wind span limitations (single or double conductor configurations);
- Less line hardware (e.g. insulators, cross-arms, conductor ties, etc.) required, thus also increasing the system reliability;
- Transformers are less costly;
- Increased weight spans of single- and dual-phase LV aerial bundled conductor.

These supply technologies with a specific focus on the LV reticulation options are shown in Fig. 8, Fig. 9 and Fig. 10. A typical three-phase LV system with standard three-phase MV, 50 and 100 kVA three-phase transformers and the combined protective earth and neutral (PEN) conductor is shown in Fig. 8. Similarly the transformer types, LV conductor options and MV line technologies for dual-phase and single-phase systems are shown in Fig. 9 and Fig. 10.

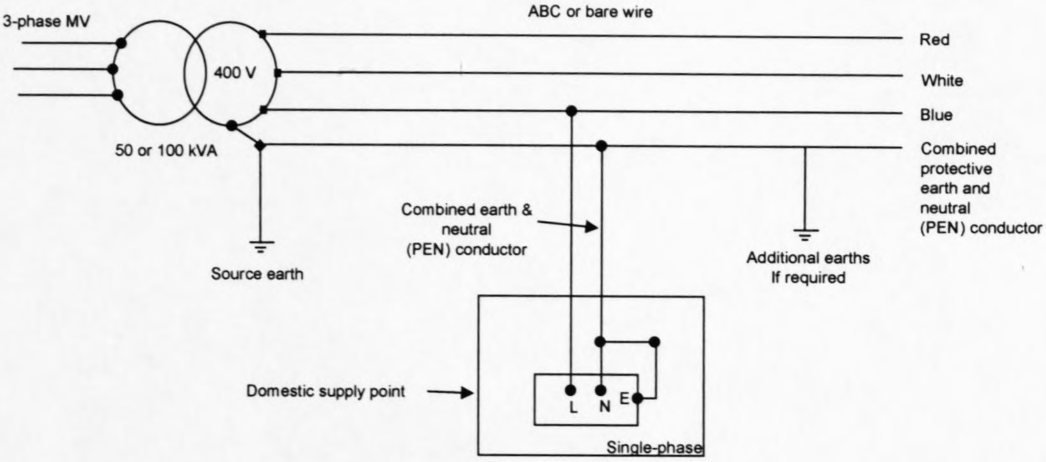


Fig. 8: Typical three-phase LV system

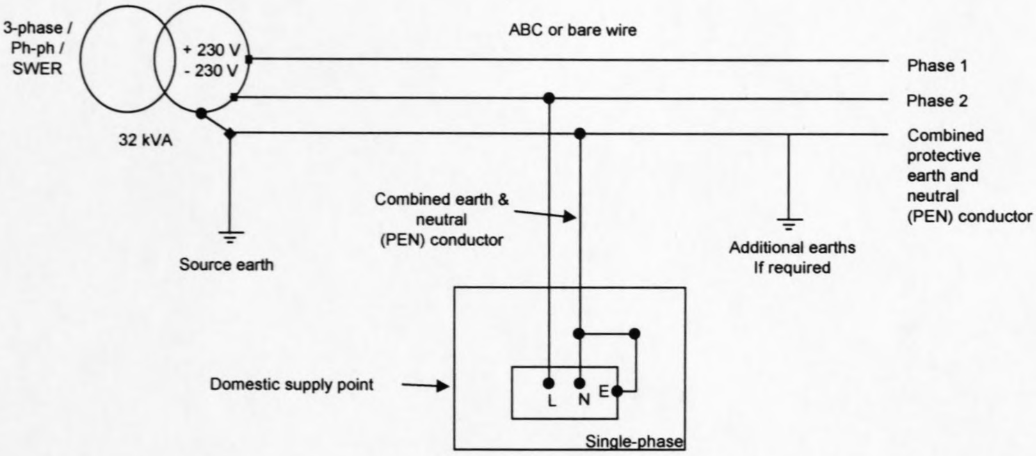


Fig. 9: Typical dual-phase LV system

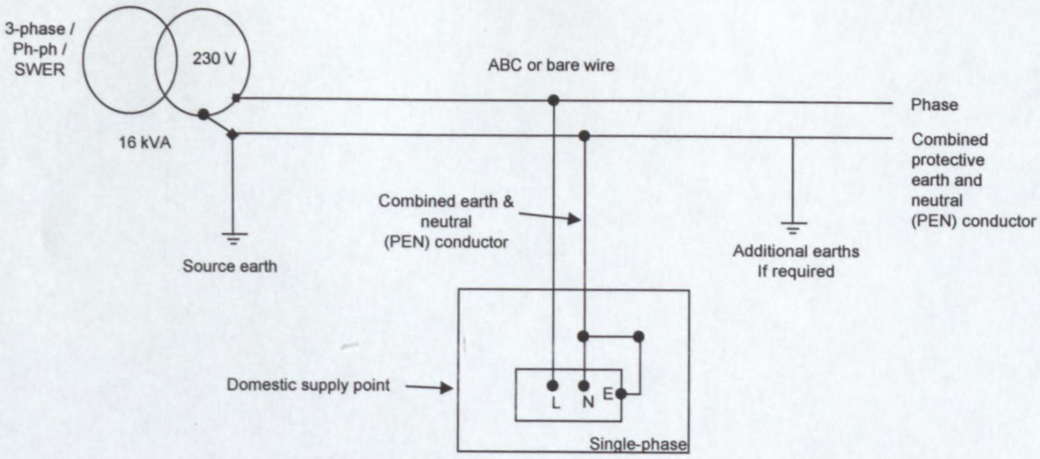


Fig. 10: Typical single-phase LV system

However, most Eskom Distribution Regions are still reluctant to implement the “new” network options as many decision-makers are still locked in the paradigm that a three-phase network should be the minimum supply type offered to the customer. Some changes (tariff rebates) have already been made to the Eskom Pricing Policy [2] to encourage the use of least-cost technologies (refer Table 2). These incentives take the form of financial rebates that are proportionate to the cost of the MV line technology. For example, the line rebate distance for a three-phase supply is only 135 metres (R60 per metre) compared to 320 metres (R25 per metre) in the case of a SWER line. All future rural distribution (Landrate tariff) customers are to be quoted considering least-cost technologies (SWER and phase-phase MV) as a first option prior to recommending traditional three-phase supplies.

Table 2: Eskom tariff rebates for agricultural rural supplies (1999) [2]

Tariff	Line rebate (m)	Line rebate (R)	Transformer bank rebate (R)	Total rebate (R)
LANDRATE 1&4	135 m – 3 ϕ 200 m – 1ϕ 320 m - SWER	R8 000	R14 808	R22 808
LANDRATE 2	135 m – 3 ϕ 200 m – 1ϕ 320 m - SWER	R8 000	R16 290	R24 290
LANDRATE 3	135 m – 3 ϕ 200 m – 1ϕ 320 m - SWER	R8 000	R24 575	R32 575

RURAFLEX 1	200 m	R12 000	R16 290	R28 290
RURAFLEX 2	200 m	R12 000	R24 575	R36 575

2.3 Cost advantage of delayed capital expenditure

As already mentioned, the delaying of capital expenditure due to the uncertainties involved with load forecasting and thus increasing the risk for total over-design, is another justified method of achieving the cost targets.

The matrix in Table 3 provides a useful picture of the time value of money in the context of rural electrification designs. The table shows that if a design is scaled down and a saving of 25% (column 7) on initial capital infrastructure is achieved, a re-investment of 50% (row 6) of the total initial cost (on the 75% scaled-down design) would show a positive return on investment after six years. Thus, 50% of the initial capital can be spent on upgrading the network in year six.

Table 3: Cost advantage of delayed capital expenditure (time value of money)[17]

Year of upgrade	Percentage of final design cost used for initial design (e.g. 0,4 kVA instead of 1 kVA)														
	50	55	60	65	70	75	80	85	90	95	96	97	98	99	100
10				100	85	65	50	35	22	12	9	7	4	2	0
9				100	80	60	47	33	20	11	8	7	4	2	0
8				90	70	57	43	30	18	10	8	6	4	2	0
7			100	85	65	53	40	28	17	9	7	5	3	2	0
6			100	80	60	50	37	26	16	8	7	5	3	2	0
5			90	75	57	45	33	24	14	8	6	4	3	1	0
4		100	85	70	53	40	30	22	13	7	5	5	3	1	0
3		95	80	65	50	35	25	20	11	6	4	4	3	1	0
2	100	90	70	60	40	30	20	10	10	5	3	3	2	1	0

Hence the time value of money challenges an old engineering philosophy of designing and building networks for a 20-year life, especially considering the uncertainty of forecasting for 20 years in today's fast-changing world.

2.4 Conventional technologies and the need for innovative technologies

In order to ensure that the correct focus of this thesis is achieved, it was necessary to identify the most important Eskom business plan risk areas. Therefore the outcome of this work, together with the research projects undertaken by the Department of Electrical and Electronic Engineering of the University of Stellenbosch, has to be aligned with both Eskom's business as well as its and technology plans.

As was mentioned earlier, both MV and LV networks lend themselves to more versatile and innovative techniques for cost reduction and, given with the large number of households in rural areas still to be electrified, the focus therefore should be on developing supporting technologies for this technology sector [14].

It is therefore necessary to take a step back and list the perceived engineering limitations of rural electrical networks and explore the reasons for the inability to meet the cost targets.

Some of the aspects impeding the achievement of cost targets are:

- The fact that traditionally deep rural areas have not been electrified due to the fact that more often than not such areas are considerable distances from the utility MV supply and the closest point of connection is likely to be towards the end of a radial feeder in a rural community;
- The availability of low-cost and readily available 3-phase induction motors primarily used for irrigation purposes;
- The high cost of large-sized single-phase induction motors (typically double the cost of 3-phase motors);
- The lack of cost-effective single-to-three-phase inverter technology for small to medium-size motor loads;
- The perception that SWER, single- and phase-phase MV networks are less reliable;
- The steady-state voltage-regulation problems associated with long-distance MV networks supplying small to medium-sized loads;
- Quality of supply constraints due to the voltage fluctuations on LV networks as a result of low diversity and the impact of this on the conductor cost;

- The conservative sizing of distribution line conductors.

Possible solutions to these aspects are [14]:

- Low-cost small to medium-sized single- or three-phase power electronic voltage regulators with dynamic voltage regulation capability of up to 40% from nominal;
- Low-cost single-phase to three-phase inverters to drive small to medium-sized induction motors from single-phase lines;
- A probabilistic approach to system (e.g. conductors) sizing;
- Direct-current (DC) transmission at distribution voltage levels.

For this work, application opportunities of only two types of in-line, transistor-based power electronic devices in support of the technology and cost drivers already mentioned will be investigated: the electronic voltage regulator (EVR) and the electronic phase converter (EPC).

2.5 Stretching the network

One of the most important criteria in distribution network design is the voltage level at the customer end. Customers depend on a stable alternating-current (AC) voltage much more than they often realise. Most of the appliances used by residential and commercial customers operate only within a narrow band of operating voltages. When provided with a supply voltage outside of that narrow range, many types of equipment and appliances will not operate, and may even be damaged.

NRS 048 defines voltage regulation as *the ability of the steady-state rms voltage to remain between the upper and lower limits* [29].

2.5.1 Conventional voltage regulation practices in Eskom

It is standard practice within Eskom Distribution to maintain the MV voltage (≥ 500 V) at +5% and –7.5% of nominal system voltage and all LV supplies (<500 V) at ±10% of nominal system voltage, as required by the Electricity Act [12].

Fig. 11: Typical layout of MV reticulation network inclusive of voltage-regulation equipment [39]

This is normally achieved through the use of (refer Fig. 11):

- on-load tap-changers (OLTC) on major power transformers of various standard ratings up to 160 MVA (5% buck and 15% boost in 16 steps of 1.25%) within the sub-transmission substations by means of circulating current-controlled tap-change relays [44];
- series-connected, single-phase, (open or closed delta connected) mechanical, autotransformer, voltage regulators installed on MV reticulation networks of standard ratings – 50, 100 & 200 A (10 or 15% buck and 10 or 15% boost in 32 steps of 0.625%) [45];
- shunt-connected (un)switched capacitor banks (150, 300 or 450 kVAr) [46]; and
- off-circuit, tap-change switches (OCTS) on pole-mounted distribution transformers (6% buck and 6% boost in steps of 3%) [47].

The line reach capability of any MV feeder is better utilised if the busbar voltage at the sending-end sub-transmission step-down substation is raised during periods of high loads and reduced during low load periods. Compensation is then achieved for both voltage drops in the HV network up to the MV busbar as well as beyond the busbar for the MV distribution lines.

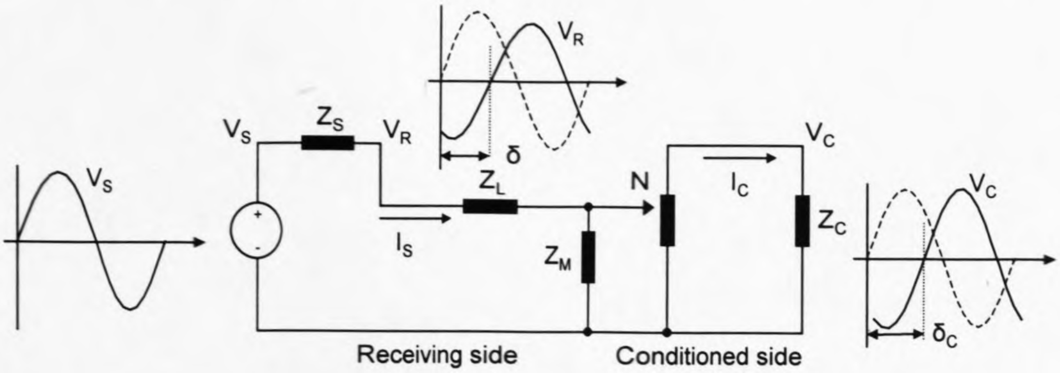


Fig. 12: Equivalent circuit diagram of an autotransformer voltage regulator [24]

The equivalent circuit diagram of an autotransformer voltage regulator is shown in Fig. 12. An electro-mechanically controlled tap-changing mechanism changes the turn ratio N. Thus, regulation increases the phase shift (δ_c) in the compensated voltage. Note must be taken of the additional voltage drop that is caused by the leakage impedance Z_L. This impedance is connected in series with the line impedance.

Further optimisation of MV busbar voltages can be achieved by compensating for load current (Load Drop Compensation – LDC) so as to protect the MV network from over-voltage during low load conditions. This voltage regulation philosophy becomes complicated to set up for feeders with mixed customer classes and unequal load distribution. A typical example of this is rural step-down substations supplying both smaller municipal loads and rural reticulation networks (refer Fig. 13). The step-down substation is then normally positioned close to the municipal load centre and optimum voltage regulation is not easily obtainable due to the unequal load distribution over the long MV feeder with different load peaking periods. In the example given (refer Fig. 13), 66 kV to 11 kV step-down substations are positioned near or within the towns of Riviersonderend, Villiersdorp, Caledon, etc. whilst at the same time supplying long MV rural networks. In these applications the simple philosophy of constant busbar voltage is followed; however, the full potential for voltage regulation can then not be achieved.

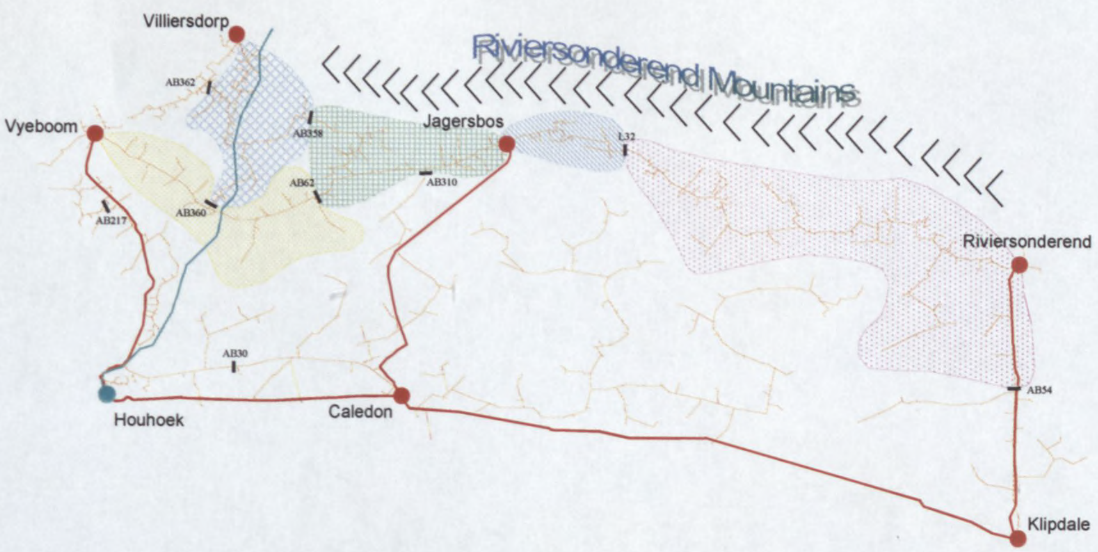


Fig. 13: Typical geographical layout of HV / MV rural distribution networks [50]

Since it is not uncommon to find more than one 32-step autotransformer voltage regulator on long MV distribution lines, care should be taken in the setting of the time delay for tap changes (minimises tap changing on down-line regulators) of upstream devices. Thus voltage regulation response time to sudden load changes takes place over a few seconds, typically 15 to 30 seconds.

With reference to the case study of a fast-growing MV network as shown in Fig. 11, the feeder load reach capabilities of both sending-end substations (Stellenbosch and Wemmershoek) became limited due to voltage-drop problems at the end of the feeders.

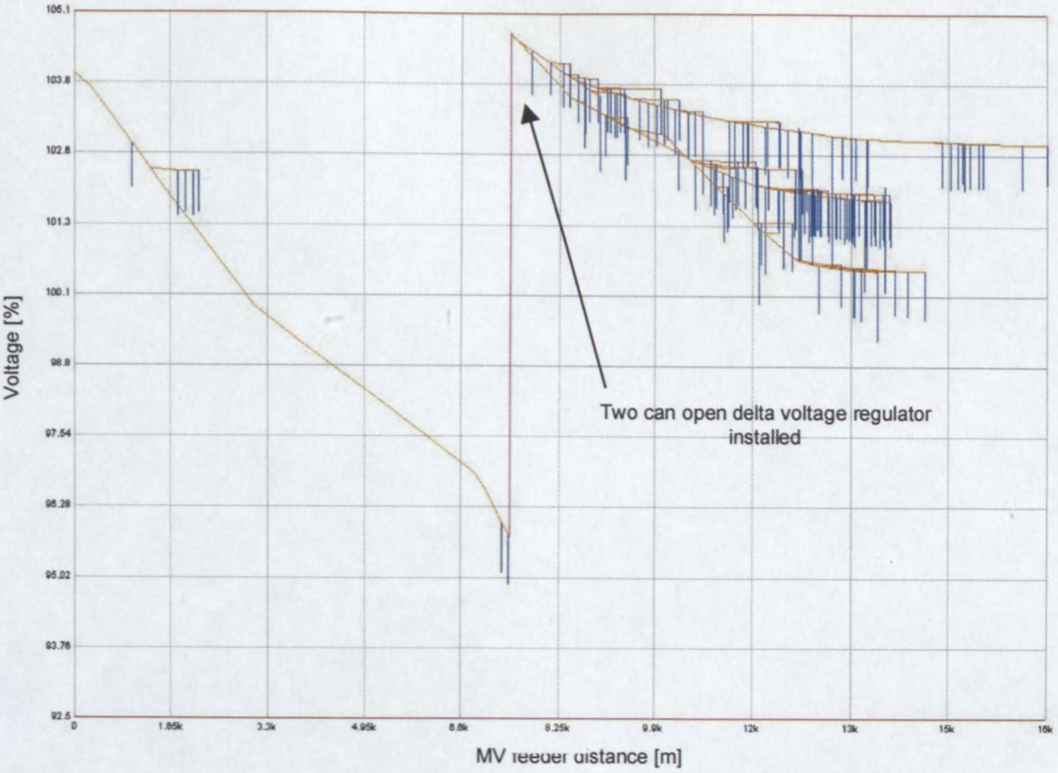


Fig. 14: Voltage profile of the Stellenbosch F2 compensated MV reticulation network [39]

Therefore it was proposed to "stretch" the load reach capability by means of the installation of autotransformer voltage regulators (refer Fig. 14 and Fig. 15). The positioning of this is chosen to ensure that existing and future large power users are on the load-end side and that the maximum current rating (200 A) is not exceeded.

However, as can also be seen from Fig. 11, the future network planning involves the overlay of a 66 kV to 11 kV step-down substation to be positioned at the load centre of this growing network. The motivation for this can mostly be attributed to both feeders' conductor thermal current limits. It would thus not be appropriate to install a second stage of voltage regulators as the line-end voltages are now well within acceptable limits. The upgrade of the network can be postponed should conductor probabilistic loading techniques (refer section 2.6.3) be applied and no critical line clearance problems exist.

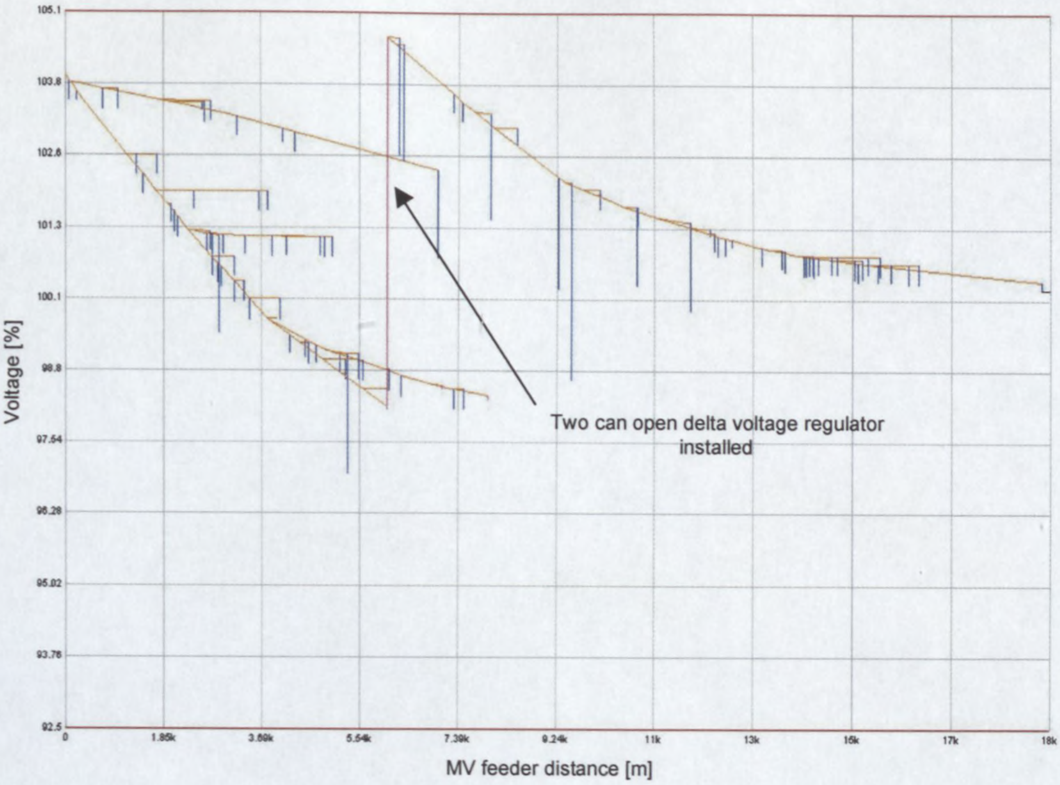


Fig. 15: Voltage profile of the Wemmershoek F2 compensated MV reticulation network [39]

2.5.2 Load reach of MV line technologies

"The distance that an electrical line can move power before encountering limits in its performance due to engineering criteria is called its *load reach"* [5]. If the acceptable voltage drop lower limit is set at a maximum of 7.5%, and a distribution line type has a 2.5% voltage drop per kilometre (determined by the operating voltage and conductor size) at a recommended loading level, then its load reach is three kilometres. If a point load placed at the end of the line requires power to be moved three kilometres or less, then the line is capable of meeting these needs at its recommended loading. But if the requirement is for power to be moved four kilometres, then either the line must be upgraded to one with a 2% or less voltage drop per kilometre, or the size of the point load must be reduced by 25%.

Similarly, the thermal load reach refers to that distance a particular line type can move power at its thermal (deterministic or probabilistic) loading limit. In applying this philosophy it is now possible to determine the thermal load reaches of various line technologies at various voltages. The results of this study (22 kV networks only) are shown in Fig. 16.

Fig. 16 shows that a reduction in voltage-drop restrictions implies an increased conductor length by more than 3 to 4 times. This "relaxed" voltage regulation criterion has obvious cost advantages and is further explored in detail in section 2.5.3.

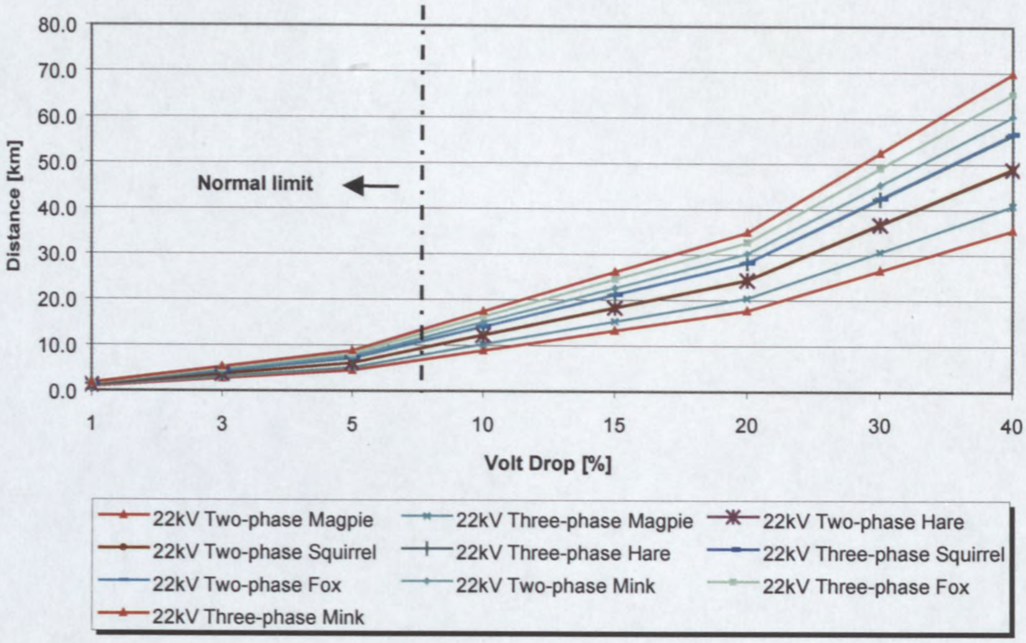


Fig. 16: Conventional line technology thermal (deterministic) load reach (22 kV)

The financial benefit of accepting a wider voltage regulation window in LV supply voltage limits from ± 6% to ± 10% can possibly best be illustrated by means of the 3 – 5% cost saving on the 1999 Eskom National Electrification budget of R800 m [14].

One of the objectives of this thesis is to investigate the impact of increasing the voltage drop limitations of MV and LV networks beyond the acceptable norm of 7.5 and 10% up to 40% and to propose cost effective mitigation techniques in the form of Electronic Voltage Regulators (EVRs). These in-line connected voltage "compensators" will then be strategically placed at the far end of MV (transformer secondary side) or LV feeder lines to cost-effectively resolve the voltage-regulation problems. The direct cost of this should be compared to other means of achieving acceptable voltage regulation.

2.5.3 MV line transfer capabilities

An analysis has been made to illustrate the effectiveness of different MV line technologies from a load capacity [kVA], transfer capability [kVA.km] and capital cost [R] point of view [18][27].

Fig. 17 summarises these findings for the different line technologies, voltages and conductor sizes. Also shown in Fig. 17 is the effect on line technology transfer capability by increasing the MV voltage regulation limit up to 40% as compared to the norm of 7.5%.

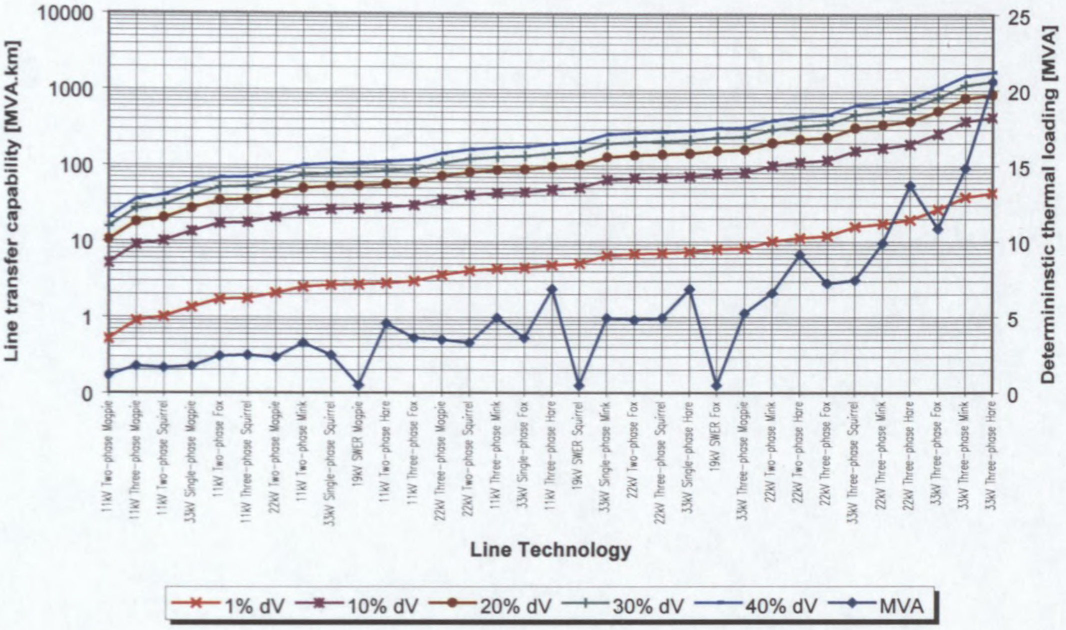


Fig. 17: MV line technology transfer capability (point load)

These graphs show that higher voltage lines can transfer more power, since power is proportional to the square of the voltage. They normally cost more due to more expensive insulation, but this is offset by the much increased transfer capability. Fig. 18 illustrates the cost per transfer capability of a particular line technology. This graph basically illustrates the cost associated of transferring 1 MVA of load (power factor = 0.95) over a distance of 1 kilometre or combinations of load and distance. Cost ratios per load transfer capabilities of more than 100 are easily achieved. As discussed previously, MV lines are designed to operate up to voltage drops of 7.5%. Also illustrated in Fig. 18 is the impact on cost per transfer capability for voltage drops up to 40%. For example, an 11 kV three-phase Magpie line is 35% cheaper than a Mink line on equal transfer capability at 40% allowable voltage drop.

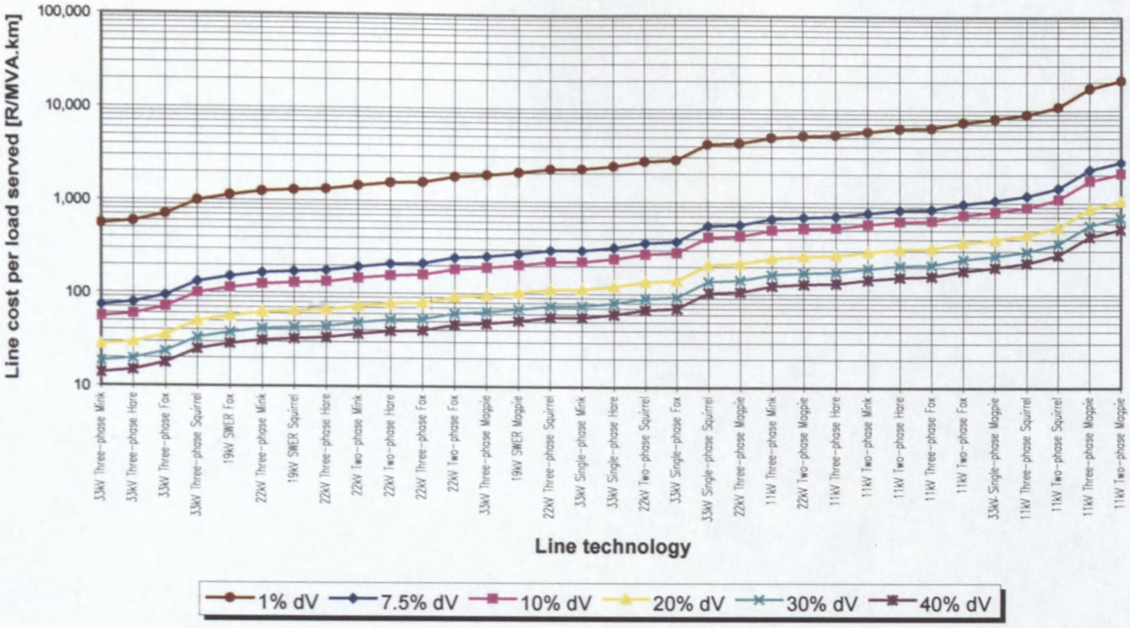


Fig. 18: MV line technology cost per load served (point load)

2.6 MV line technology optimisation

Line segments and transformers are the building blocks of the distribution system. They are available in a variety of voltage levels, conductor types and sizes, and number of phases; as already illustrated they also have capacities and reaches that vary from very small to quite large (refer Fig. 16, Fig. 17 and Fig. 18). Since the distribution voltage ranges (e.g. 11, 22 & 33 kV) and conductor types and sizes (e.g. Magpie, Squirrel, Fox, Mink and Hare) have already been standardised through the standardisation initiatives of Distribution Technology (DT), the ranges are adopted without change for this work [19][56].

2.6.1 Network limitations caused by voltage regulation

Distribution planners interested in achieving an overall economic distribution feeder system want to make certain that they have a variety of conductors available to choose from, and that they apply the correct economic evaluation to select the best line type for each segment in their system.

For medium-voltage lines without reactive power compensation, voltage regulation is usually the more important consideration. For instance, in the design of a line to carry a certain load one wishes to determine the proper distribution voltage and conductor size. Based on an assumed allowable regulation, several voltages and conductor sizes will be found to transmit the load, the final choice being based upon the economics for which the line efficiency is desired.

2.6.2 Combining the effect of losses and voltage regulation

As already stated, the voltage regulation and efficiency (percentage copper ($I^2.R$) and iron (transformer) losses) of a distribution line or feeder are fundamental properties of its performance. Both voltage drop (determining factor for load-reach) and losses depend on the impedance of the line. Line impedance is a function of the phasing (three-phase, phase-phase, etc.), conductor resistance and conductor spacing. Generally, when additional capacity, lower voltage drop, or lower losses are desired, larger conductors are specified. However, for certain load conditions and load profiles, choosing a conductor size larger than required nullifies the returns in terms of voltage drop and losses. Thus it is of utmost importance to accurately assess and apply the correct line impedances in the evaluation of distribution feeders.

The percentage copper losses and voltage regulation of a given line with resistance R and reactance X are determined by the following formulas [6][43]:

$$Copper\ \ losses\ (\%loss) = \frac{\sqrt{3}\cdot R\cdot l\cdot I_{ph}}{V_L\cdot\cos\theta_R}\cdot 100 \tag{2.1}$$

$$Voltage\ regulation\ (\%dV) = \frac{S\cdot l}{V_L^2}\cdot(R\cdot\cos\theta_R - X\cdot\sin\theta_R)\cdot 100 \tag{2.2}$$

where:

R = conductor resistance [Ω/km]

X =conductor inductive reactance [Ω/km]

l = line length [km]

I_{ph} = phase current maximum [A]

S = apparent power (maximum load) [MVA]

V_L = line-line voltage [kV]

θ_R = phase angle [deg]

The voltage regulation and loss relationship of MV line feeders are shown in Fig. 19. The case study illustrates this relationship for three different line conductor sizes over a 10-kilometre line with various point loads. It is interesting to note that up to the normal voltage regulation limit for each conductor size, the percentage loss values are either equivalent or less. Above that limit the loss percentage especially for the smaller conductor range increases dramatically.

Two basic means exist to reduce losses. The first is to increase the conductor size and the second is to either increase the supply voltage for constant power loads or lower it for constant impedance loads.

Increasing voltage is effective where the load is of constant power type. Most industrial loads and hence loads at transmission and sub-transmission voltages are of this type. The voltage can be increased by installing reactive compensation to ensure a flatter voltage profile along the line or by increasing the sending-end voltage by regulating the sending-end busbar at a higher level (e.g. 108% instead of 104%).

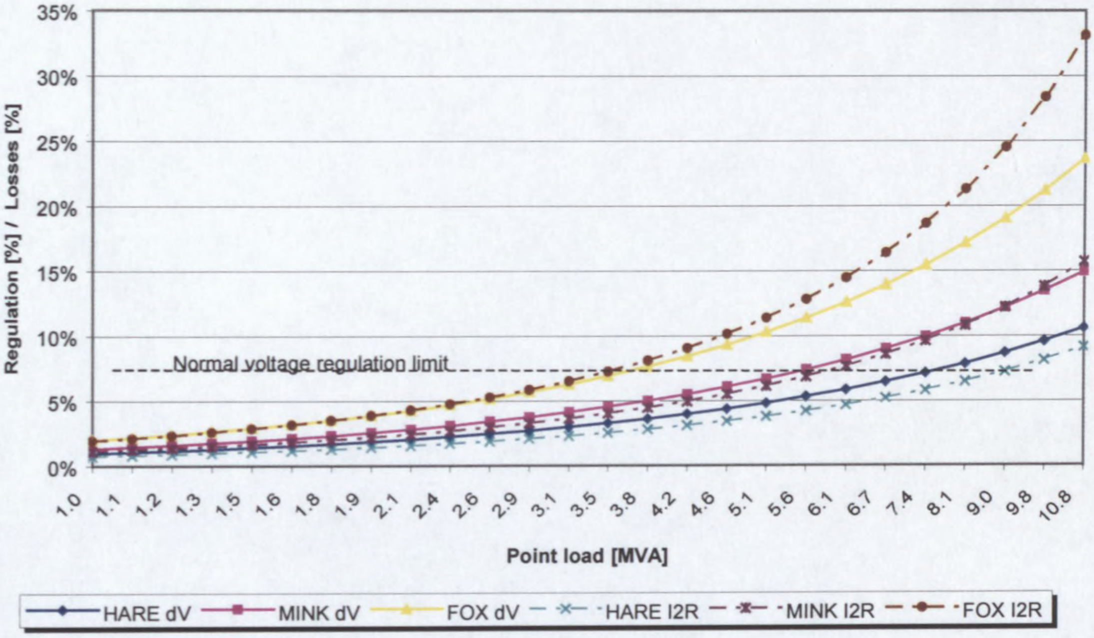


Fig. 19: Typical voltage regulation and loss chart (10 km 22 kV line)

The drawback of increasing voltage is that the equipment is stressed, which in turn reduces its lifespan. This increases the probability of flashovers and failures, which in turn reduce the quality of the supply voltage. Recent studies performed by DT [7] have yielded the results shown in Table 4, which is an approximate guide for the life expectancy of transformers under ideal, absolutely consistent voltage conditions. Each case needs to be carefully analysed prior to its implementation.

Table 4: An approximate guide for the life expectancy of transformers [7]

Nominal Voltage	Approximate life expectancy
U_n	Full life expectancy
$110\%U_n$ (U_m)	Full life expectancy
$113\%U_n$ (103% U_m)	1 year
$115\%U_n$ (105% U_m)	5 minutes
$137\%U_n$ (125% U_m)	5 seconds
$165\%U_n$ (150% U_m)	1 second
$185\%U_n$ (170% U_m)	0.25 seconds

Therefore, losses cannot be reduced through acceptable means other than increasing the conductor size. This option is costly and the importance of losses on distribution networks should rather be investigated.

The overall percentage losses are directly proportional to the square of the load factor of the distribution line or feeder. This proportionality is quantified by the so-called energy loss factor (ELF) [9].

$$ELF = x \cdot lf + (1 - x) \cdot lf^2 \tag{2.3}$$

where:

lf : load factor is the actual energy supplied [kWh] over a period divided by the maximum demand [kW] over that period multiplied by the time period selected (i.e. actual energy supplied divided by potential energy supplied).

x : constant determined by statistical evaluation (0.2)

Similarly the total cost of losses per annum can be calculated as:

$$\text{Cost due to losses} = 8760 \cdot ELF \cdot GC \cdot CL \quad [\mathrm{R}] \tag{2.4}$$

where:

GC: Generation cost [R/kWh]
CL: Copper losses [kWh]

From (2.3) and (2.4) a very important deduction can be made – reduced load factors imply reduced losses. *Thus peaky loads with load factors in the order of 0.2 – 0.4, such as electrification loads, show a much reduced loss factor.*

Building lines with larger conductors imply increased capital cost incurred. It is therefore a requirement that the cost of losses is used as outflows of capital in the determination of the Net Present Value (NPV).

A graph (refer Fig. 20) is derived from the initial capital outlay and cost of losses as a function of the mean power expected down the line. In this case study a 22 kV line was considered connected to a point load over a distance of 10 kilometres. The annual load factor was chosen as 0.4 and annual feeder load growth as 10%. Three standard conductor sizes were compared and the total life-cycle cost considered over a period of 25 years was calculated.

From the graph it is clear that the smaller conductor ("Fox") is the most cost-effective choice to serve the intended load for most of the network lifetime (lowest life-cycle cost). Only in the 19th year (associated with a 6 MVA load) does the next available larger size conductor ("Mink") prove to be more cost effective. The effect of reducing the load factor even further to only 0.2 is shown in Fig. 21.

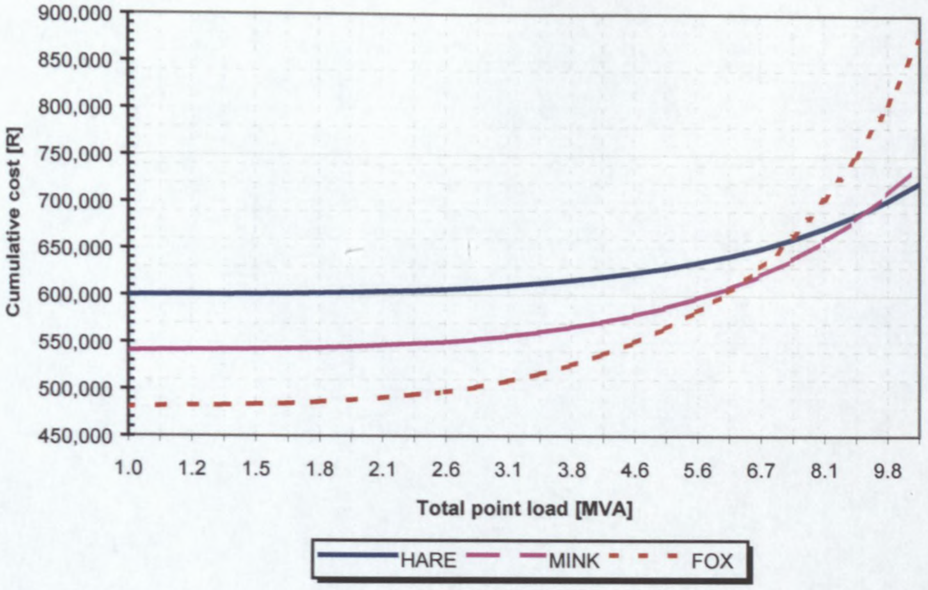


Fig. 20: Cumulative PV cost of capital and losses (load factor = 0.4) [25][40]

In cases where the load profile is very peaky such as the case for domestic loads and more so for electrification, the cost of losses plays a smaller role in the final selection of the conductor. In electrification projects, 70% of the NPV is a function of the initial cost. *This means that losses are almost ignored in the design and only voltage drop is to be considered. Hence a higher percentage of losses is normally associated with electrification loads.*

To illustrate this point, the percentage losses on the Eskom transmission and sub-transmission system are taken as an example and can be very roughly summarised as follows [13]:

Transmission system -	2%	
Sub-transmission system -	4%	
Electrification loads -	7%-8%	(100 kWh/month customers)
	11%-14%	(60 kWh/month customers)

The performance of higher-voltage-regulated lines normally associated with industrial loads (flat load profiles), however, is determined primarily by the line loss.

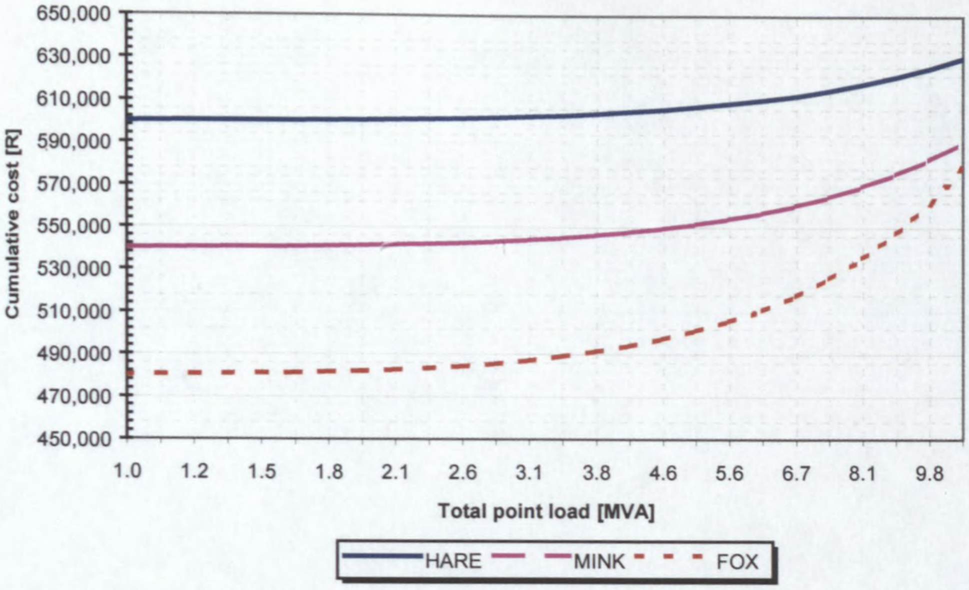


Fig. 21: Cumulative PV cost of capital and losses (load factor = 0.2) [25][40]

2.6.3 Probabilistic conductor current ratings

Although conductor thermal current limits of most line segments or feeders in the intended application of rural low-density networks should not be a limitation in determining its load reach, one needs to consider the combined impact of increased current ratings and extended voltage-regulation capabilities in determining the optimal network design. By combining both parameters, smaller conductor sizes can be chosen to serve the load needs.

During the past few months progress has been made in the optimisation of the current ratings of standard conductor sizes. Previous approaches towards the current ratings of conductors were of a deterministic nature whereby fixed constants were assumed in the calculation of the current rating (commonly known as ampacity rating) of a conductor. A new approach to that of weighing up the probability of risk for a flashover due to environmental conditions (ambient temperature, wind speed and direction, etc.) and ground clearances has resulted in the so-called probabilistic ampacity ratings of standard distribution line conductor sizes (refer Table 5). From the table one can deduce that various conductor choices have similar ratings, although at different templating temperatures. By increasing the templating temperature, the rating of the conductor increases, which in turn implies shorter spans (although the cost penalty is minimal – typically < 5%).

Furthermore, peaky loads (such as electrification loads) are ideally suited to the application of probabilistic techniques and thus higher templating temperature ratings can be applied with confidence. The opposite applies to industrial loads with flat load profiles.

Table 5: Conductor ampacity tables using probabilistic loading techniques [21]

Conductor Type	Templating Temperature (°C)	Normal Loading (A)	Emergency Loading (A)	Conductor Type	Templating Temperature (°C)	Normal Loading (A)	Emergency Loading (A)
Magpie	50	33	40	Fox	80	233	283
Magpie	60	47	52	Fox	90	253	305
Magpie	70	58	62	Fox	100	270	324
Magpie	80	67	70	Mink	50	209	272
Magpie	90	74	77	Mink	60	258	324
Magpie	100	81	84	Mink	70	297	367
Squirrel	50	106	135	Mink	80	330	402
Squirrel	60	130	160	Mink	90	357	434
Squirrel	70	149	181	Mink	100	382	461
Squirrel	80	165	198	Hare	50	292	380
Squirrel	90	178	213	Hare	60	357	454
Squirrel	100	190	227	Hare	70	408	515
Fox	50	148	192	Hare	80	455	565
Fox	60	184	228	Hare	90	496	609
Fox	70	210	258	Hare	100	529	647

2.7 Appropriate technology index of MV / LV line technologies

As already illustrated in section 2.6.2, it is very important to consider the life-cycle costs (LCC) of a chosen line technology to include all related costs over the lifetime of the network segment (refer Fig. 22). This key performance indicator together with other KPIs, such as the ampacity rating of the chosen conductor and the voltage regulation of the network, can be combined (summated) using weighting factors to obtain the overall technical "performance" (also termed appropriate technology index (ATI)) of the line technology [11].

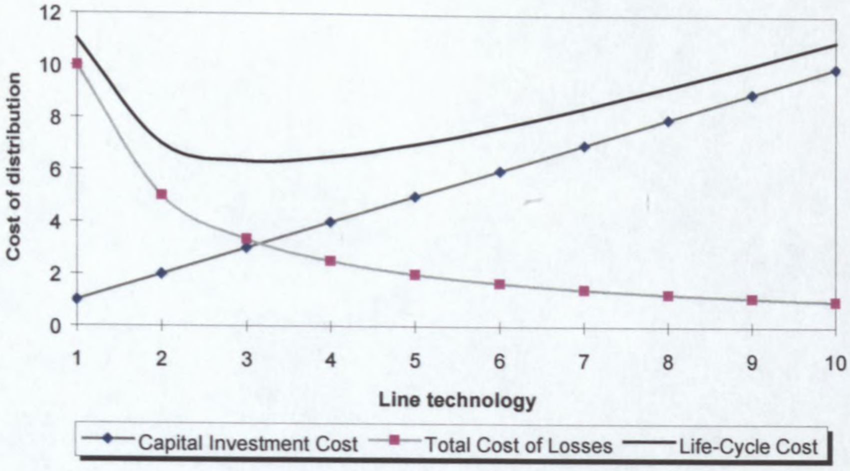


Fig. 22: Typical total life-cycle cost of any line technology [11]

This philosophy of determining the ATI of various line technologies has been successfully applied in the past for EHV (Extra-High Voltage) and HV line design optimisation at various voltage levels and will be further explored in this section for MV networks [20]. The same KPIs (cost, capacity and voltage regulation) will be used for MV networks as were applied for HV networks, with the exception of surge impedance loading (SIL). The influence of the SIL for MV networks will be ignored due to the fact that the SIL is inversely proportional to the square of the line voltage (refer equation (2.10)) and it is a measure of the importance of quality of supply with a stability focus. MV networks rarely suffer from stability problems and are normally operated at or close to their thermal limits.

Similarly, the ATI technique can be applied to LV networks with an added KPI (as compared to MV networks) in the form of measuring the dynamic response of the voltage regulator employed to compensate for voltage fluctuations due to sudden load changes. The results of this study are given in section 3.3.13.

Fig. 23 provides a summary of the proposed KPIs to be considered for the line technologies at the three major voltage classes (HV, MV and LV). At HV levels the KPIs to consider are e.g., life-cycle cost, capacity, voltage regulation and stability. It may be necessary, depending on the technology applied, to add additional KPIs, such as reliability and maintenance cost (added to *K1*), to those already listed.

The index can be successfully used not only to compare the influence of conductor sizes and structure geometry, but also for various technologies such as phase-phase, three-phase MV, SWER and HV DC Light. At the same time the cost and influence of various means of voltage compensation can be measured.

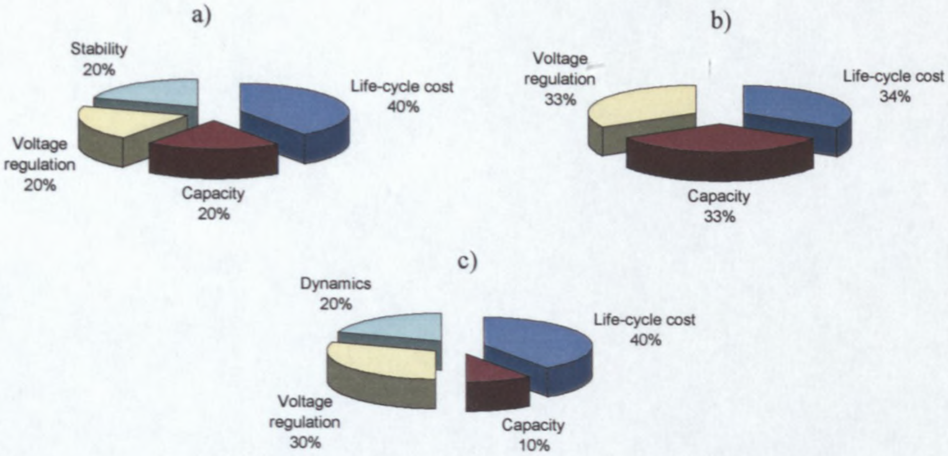


Fig. 23: KPIs for line technologies at various voltage levels: a) HV b) MV c) LV

Care should be taken with the interpretation of the results as they are not absolute (due to the influence of weighting factors and the mere fact that maintenance costs are still ignored) and are project specific; however, they do provide a quantative measure for the best technical option.

The ATI is defined as:

$$ATI = K1 \cdot w1 + K2 \cdot w2 + K3 \cdot w3 + K4 \cdot w4 \qquad (2.5)$$

where $w1$ to $w4$ are weighting factors quantifying the importance of the variables $K1$ to $K4$ for a specific project. The KPIs ($K1$ to $K4$) are determined by the technology applied and the weighting factors ($w1$ to $w4$) are project specific.

The first variable, $K1$, is the total life-cycle cost (*LCC*) normally taken over a period of 25 years. This in turn is calculated by summating the capital investment cost (*CIC*), the total cost of losses (*TCL*) (refer equation (2.1), (2.3) and (2.4)) and total maintenance cost (*TMC*). The total maintenance cost is ignored in most cases as it is assumed to be the same for all comparisons, although this assumption must be revisited where the technology offers clear benefits in terms of requiring little or no maintenance.

$$K1 = LCC = CIC + TCL + TMC \qquad [R] \qquad (2.6)$$

The formula as derived in equation (2.6) representing the total life-cycle cost of a given power network can be modified to include the additional costs associated with a network requiring voltage compensation.

$$K1 = LCC = CIC_{line} + CIC_{comp} + TCL_{line} + TCL_{comp} + TMC_{line} + TMC_{comp} \qquad [R] \qquad (2.7)$$

Where:

CIC_{line} =	Capital Investment Cost of power line	[R]
CIC_{comp} =	Capital Investment Cost of voltage compensator	[R]
TCL_{line} =	Total Cost of Losses of power line	[R]
TCL_{comp} =	Total Cost of Losses of voltage compensator	[R]
TMC_{line} =	Total Maintenance Cost of power line	[R]
TMC_{comp} =	Total Maintenance Cost of voltage compensator	[R]

Although the efficiency of the voltage-compensating device is at best equal to 95%, the efficiency of the device were assumed to be 100% for all studies.

The second variable, *K2*, is the line cost per probabilistic power rating of the line technology to be compared. This variable is an indication of the importance of continuity of supply under heavy loaded conditions above its previous deterministic thermal current rating.

$$K2 = \frac{CI}{MVA_{emerg}} = \frac{CIC}{\sqrt{3} \cdot U \cdot I \cdot N \cdot l} \qquad [R/km/MVA] \qquad (2.8)$$

As with variable *K1*, the influence of the voltage compensator can be added to the calculation to determine the overall cost per probabilistic power rating of the line technology.

$$K2 = \frac{CI}{MVA_{emerg}} = \frac{CIC_{line} + CIC_{comp}}{\sqrt{3} \cdot U \cdot I \cdot N \cdot l + \Delta S} \qquad \text{[R/km/MVA]} \tag{2.9}$$

where:

CIC_{line} = Capital Investment Cost of power line [R]

CIC_{comp} = Capital Investment Cost of voltage compensator [R]

CI = Capital Investment [R/km]

U = System voltage (line-line). [kV]

I = Ampacity current [A]

N = Number of conductors in bundle

l = line length [km]

ΔS = Apparent power increase due to compensator [MVA]

Although additional capital cost is added, it is also possible to increase the power transfer capacity of the power network. This is mostly determined by the network topology of the compensating system (series or series-shunt).

The third variable, *K3*, is the line cost per surge impedance loading (SIL) of the technology to be compared. This variable determines the importance of quality of supply with a stability focus. In practical networks the steady-state thermal ratings of a distribution line are around three times the SIL. However, some HV lines are not suitable for loading above their SIL limit, because of problems associated with stability due to the fact that the network is mechanically controlled. This variable is ignored for its application at MV voltages, since stability is not a major problem on MV networks.

$$K3 = \frac{CI}{MVA_{SIL}} = \frac{CIC \cdot Z_e}{U^2 \cdot l} = \frac{CIC \cdot \sqrt{\frac{|Z|}{Y}}}{U^2 \cdot l} \qquad \text{[R/km/MVA]} \tag{2.10}$$

where:

CIC = Capital Investment Cost [R]

CI = Capital Investment [R/km]

$|Z|$ = Magnitude of the positive sequence impedance [Ω]

Y = Positive sequence susceptance [S]
U = System voltage (line-line) [kV]
l = line length [km]

The fourth and last variable, *K4*, is the percentage voltage drop over the total length of the feeder. This variable measures the ability of the particular line technology to meet the set voltage regulation requirements.

$$K4 = Voltage\ drop = \frac{\sqrt{3} \cdot I \cdot (r \cdot l + x \cdot l \cdot \tan(\alpha))}{U} \cdot 100 \qquad [\%] \qquad (2.11)$$

where:

U = System voltage (line-line) [kV]
I = Line current [A]
r = per unit length resistance of the line [Ω/km]
x = per unit length inductive reactance of the line [Ω/km]
l = line length [km]

In order to equalise the four independent variables (KPIs) to one measuring scale, the upper and lower limits per variable have to be set. The upper limit represents the best-case result (score of 10) and median value of 3 represents the average of existing solutions. The lower limit represents a score of zero. The rest of the values per variable are then linearly extrapolated between the high and low values.

The weighting factors are used to indicate the dominance of a variable. The value of a weighting factor is between 0 and 1 (1 = dominant and 0 = no or very little influence at all) and the sum of the weighting factors should be equal to one.

2.7.1 Implementation of ATI

The weighting factors (0.2, 0.3, 0.5) mean that the life-cycle cost (importance of initial capital expenditure and losses) is 20% dominant, the probabilistic current rating (capacity) 30% dominant and the voltage drop is 50% dominant. The weighting factors are chosen per assessment and can be scaled to compare the sensitivity of each factor per chosen line technology in simple matrix format.

Consider the following example with network parameters as given in Fig. 24.

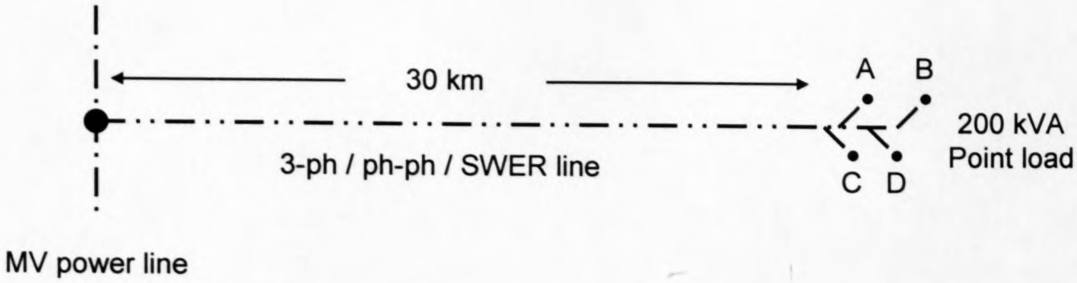


Fig. 24: Typical MV network extension off backbone to supply remote load

The technology choices to serve the load needs in the most cost-effective means possible can be relatively ranked using the ATI philosophy. For this study an 11 kV three-phase network with different conductor sizes was chosen; however, the model could support any technology choice. The results of this study are represented in Fig. 25.

The influence of voltage compensation by means of line support technologies was also tested, with results as shown in Fig. 26 and Fig. 28.

Table 6 provides a summary of the KPIs and weighting factors for the three case studies. The upper (score of 0), lower (score of 10) and median (score of 3) limits for each KPI are as indicated. The sensitivity of these weighting factors on the total ATI score is clearly noticeable in Fig. 25, Fig. 26 and Fig. 28.

Table 6: Summary of KPIs and weighting factors

			KPIs and weighting factors					
			Life-cycle cost [R]		Line cost per probabilistic power rating [R/km/MVA]		Voltage drop [p.u.]	
Study	Load growth [%]	Annual load factor	w1	K1	w2	K2	w4	K4
1 Fig. 25	4	0.3	0.25	Upper (0) = R1,300,000 Lower (10) = R700,000 Median (3) = R1,120,000	0.25	Upper (0) = 25 Lower (10) = 1 Median (3) = 18	0.5	Upper (0) = 0.4 Lower (10) =0.02 Median (3) = 0.29
2 Fig. 26 Compensated	4	0.3	0.4	Upper (0) = R1,400,000 Lower (10) = R700,000 Median (3) = R1,190,000	0.1	Upper (0) = 35 Lower (10) = 1 Median (3) = 25	0.5	Upper (0) = 0.4 Lower (10) =0 Median (3) = 0.28

3 Fig. 28 Compensated	4	0.3	0.3	Upper (0) = R1,400,000 Lower (10) = R700,000 Median (3) = R1,190,000	0.2	Upper (0) = 35 Lower (10) = 1 Median (3) = 25	0.5	Upper (0) = 0.4 Lower (10) =0 Median (3) = 0.28

The results of Fig. 25 show that if voltage drop is the dominant factor to be considered for an uncompensated network, the two larger conductor sizes (Squirrel and Fox) should be chosen. The voltage drop for various loads (4% load growth) over the lifetime of the line (assumed to be 25 years) can be seen in Fig. 27. It clearly indicates the inability of both Magpie and Squirrel (although in this case only in the last quarter of its lifetime) conductor to sustain an acceptable supply voltage over the length of the line.

Fig. 25, Fig. 26 and Fig. 28 also show that for the majority of the lifetime of the line, the better technical option would be to string the line with a Squirrel conductor.

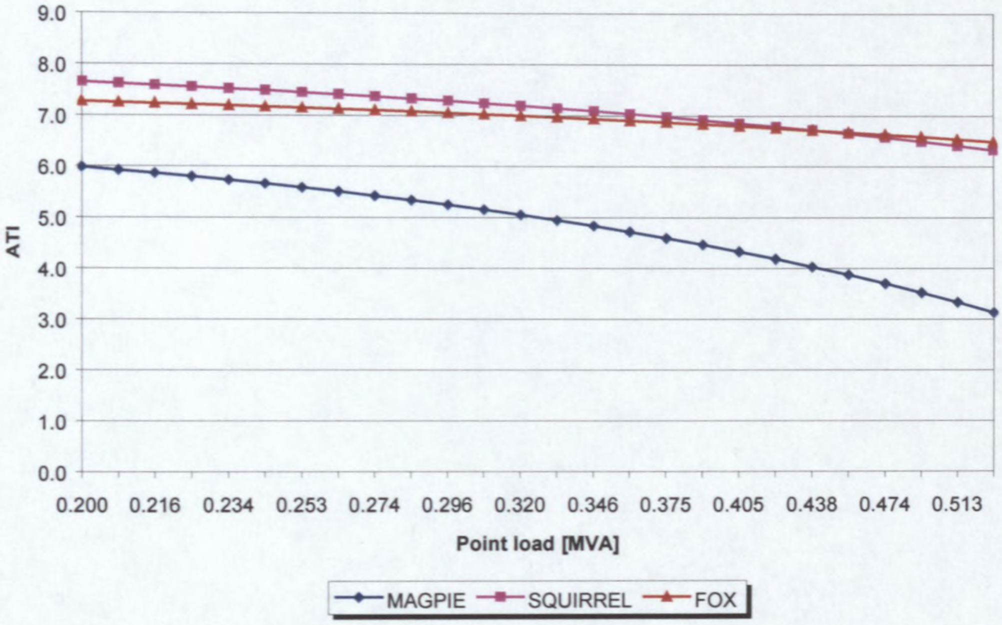


Fig. 25: ATI of uncompensated MV network with weighting factors (0.25, 0.25, 0.5)

2.7.2 ATI of a compensated MV network

As mentioned in the preceding section, the Magpie (year 3) and Squirrel (year 20) conductor network would require voltage compensation during the lifetime of the network. It is possible to provide compensation either in the form of an autotransformer voltage regulator or by means of an electronic voltage regulator (mounted on transformer secondary winding side) to compensate for the voltage drop. More detail on a comparative cost study performed to prove that the electronic voltage regulator at these low ratings is the most cost-effective option follows in section 3.3.4.

Table 7: Capital cost summary of line and compensator

Conductor type	Line cost [R/km]	Compensator cost [R/kVA]
Magpie	28,756	700
Squirrel	31,216	700
Fox	42,763	Not required

Again the ATI technique will be applied to determine the preferred technical option. The additional capital cost for the electronic voltage regulator is added to the overall life-cycle cost for the Magpie and Squirrel networks and the weighting factor of voltage regulation slightly decreased to 50% and the capital cost weighting increased to 40%; both conductor options improve in overall rating (refer Fig. 26). A summary of the capital cost structures for the three line conductor options and the electronic voltage regulator is provided in Table 7.

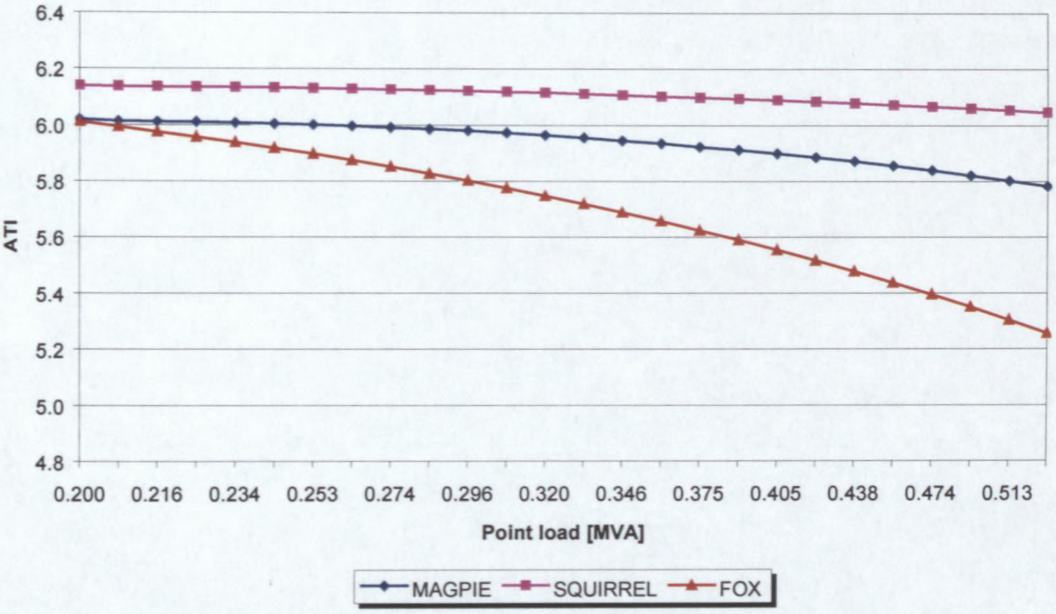


Fig. 26: ATI of compensated MV network with weighting factors (0.4, 0.1, 0.5)

Likewise, when the sensitivity factor of the ampacity rating of the three conductor choices is made more dominant (with results as shown in Fig. 28), the limited rating of the Magpie conductor is clearly visible.

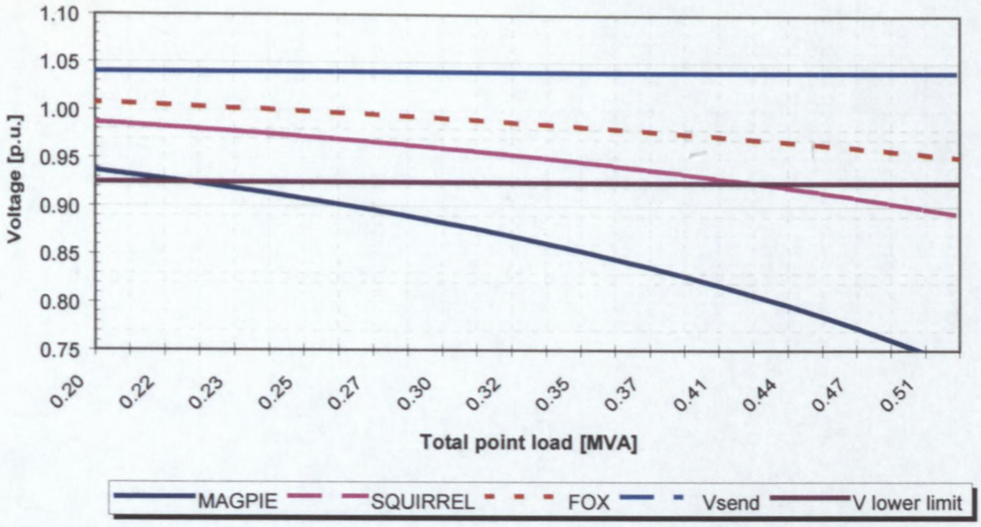


Fig. 27: Voltage drop over 30 km 11 kV uncompensated network

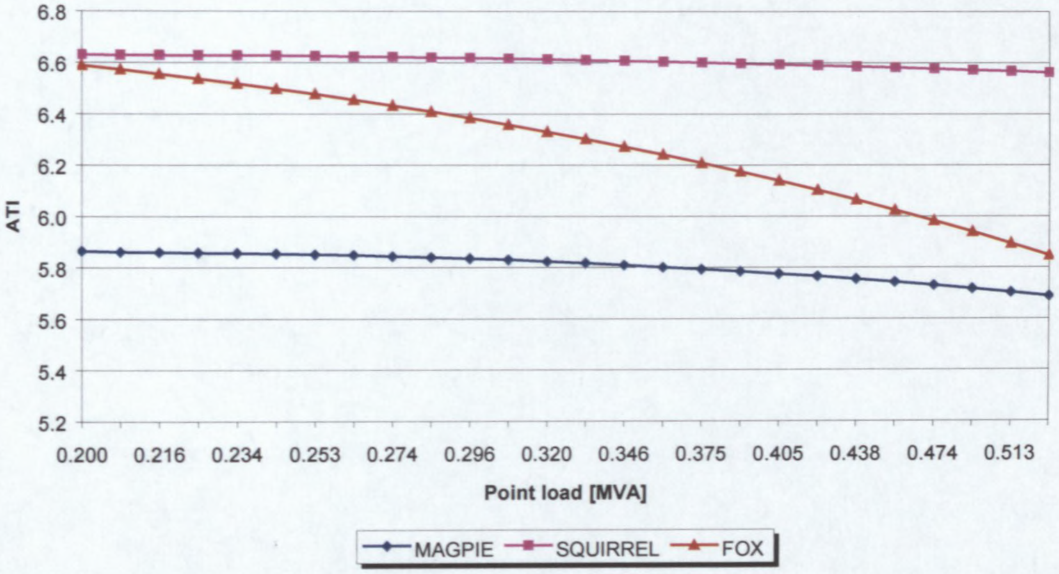


Fig. 28: ATI of compensated MV network with weighting factors (0.3, 0.2, 0.5)

Fig. 29 provides a summary of the present value of capital costs and losses over the lifetime of the network. Even though provision has been made for voltage compensation equipment for the Magpie and Squirrel conductor options in the form of electronic voltage regulators, the overall life-cycle cost is still lower than the Fox conductor option.

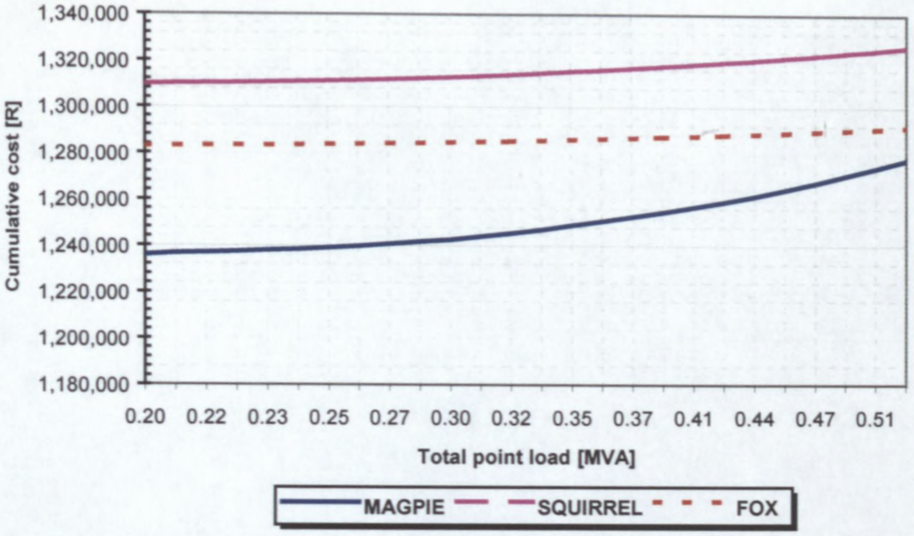


Fig. 29: Cumulative PV cost of capital and losses for 30 km 11 kV compensated network

As already pointed out, the results are normally not absolute, but provide a simple means for comparison on the basis of equal criteria and should be interpreted as such.

2.8 Summary

This chapter has listed some of the current initiatives and new proposed ones in making rural electrification a reality. The focus was on the extension of the load reach abilities of MV and LV networks by increasing the voltage regulation margin by more than 30% and to propose compensation in the form of electronic voltage regulators. It was also proven that it is possible to develop a technology index to compare objectively various technologies on a per project basis.

Chapter 3

Supporting technologies for MV/LV distribution feeders

3.1 Introduction

In recent years active power electronic devices have come to the forefront. The Electric Power Research Institute (EPRI) has paved the way for the use of these devices in utility applications, such as the Flexible AC Transmission Systems commonly referred to as FACTS devices [22]. The term “FACTS devices” is reserved for the transmission voltages above 132 kV, and hence the devices intended for the MV and LV levels are referred to as “μFACTS devices”. Both terms involve power-electronic devices with microprocessor control that make the transmission and distribution of electricity controllable, more reliable, more efficient and hence more cost effective.

As was mentioned earlier, MV networks lend themselves to more versatile and innovative techniques for cost reduction. The USE (Universal Semiconductor Electrification) concept can be implemented as one such innovative technique [24]. The concept employs an in-line, back-to-back, transistor-based, static power converter to perform load-end regulation in order to compensate for extreme distribution line voltage drops at the load end of MV or LV systems.

Voltage regulation (up to 60% of nominal voltage and higher) on single- or three-phase LV networks are being performed by boosting the input voltage to a constant direct voltage link between the input and output stages, as shown in Fig. 30 and Fig. 31. The transistor-based device can control active and reactive power independently. Active power is transferred through the system and reactive power on each side is independent from the other side. More detail on the in-line voltage regulation concept is provided in section 3.3.2.

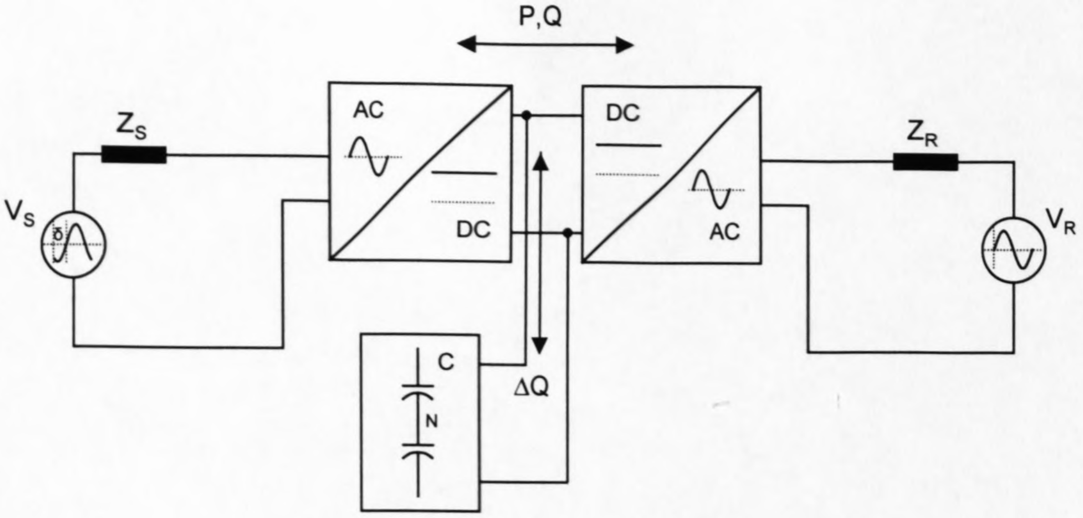


Fig. 30: Schematic of single-phase EVR

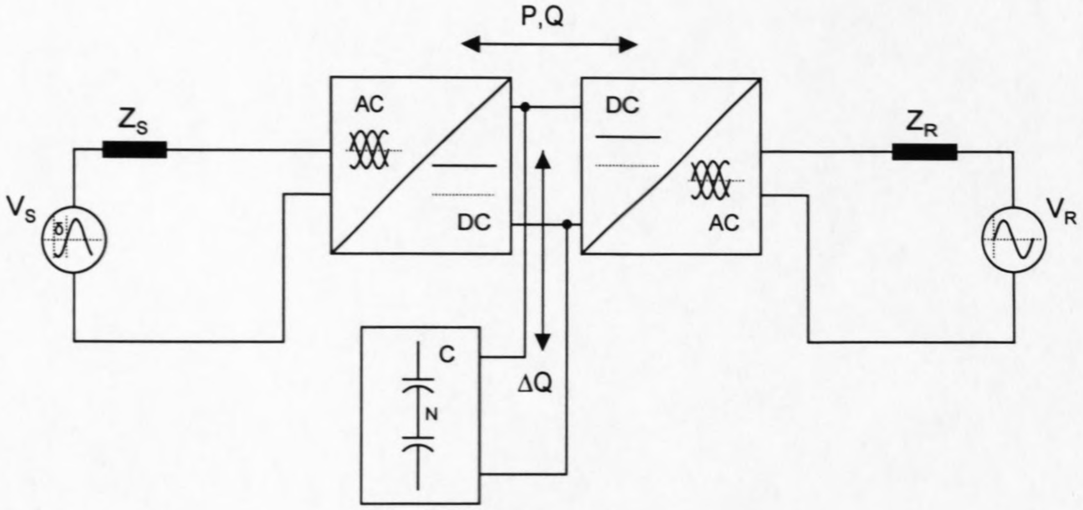


Fig. 31: Schematic of three-phase EVR

The USE converter's functionality was demonstrated in some field trials [33]. After the reliability of this power electronic device had been shown, it was realized that there was not a real need in the Eskom system for it. The need for re-engineering the technology was important in order to establish where and at what ratings the in-line device should be applied in the Eskom system. It was also realized that the device could perform functions other than voltage regulation, which can be applied to the power system, i.e.:

- Single-phase to three-phase conversion

This type of converter can convert a single-phase AC input to three-phase AC outputs (refer Fig. 32). The conversion process is explained in detail in [24] sections 9.15, 9.16, 9.17 and 9.18.

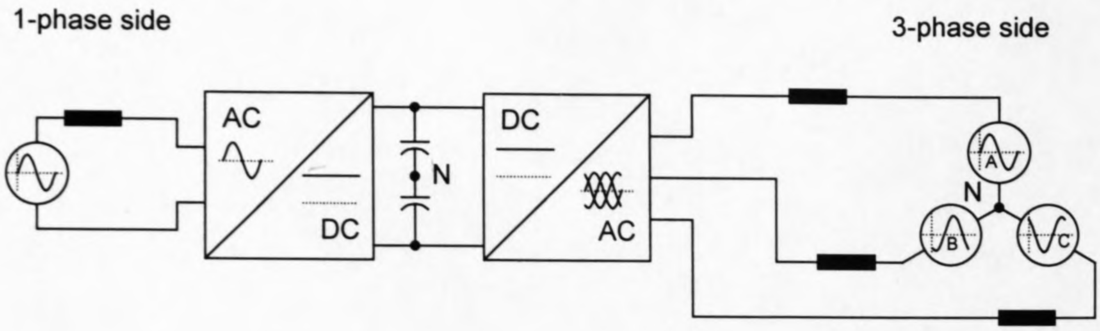


Fig. 32: Schematic of phase converter for three-phase motor loads

- Voltage dip rejection

The converter's dip rejection capability is equivalent to its ability to handle steady-state voltage regulation problems. The dynamics of the controller are fast enough for it to perceive voltage-regulation problems and dips as the same type of "event", even though dips are transient in nature.

- Reactive power compensation and isolation

It is possible to compensate for reactive power of the line or other loads connected to the point of common coupling by means of phase-shifting the drawn current with reference to the voltage. Similarly can the load reactive power requirements be isolated from the source by means of the converter's DC bus capacitors.

In order for transistor-based devices to compete on an equal cost basis (cost/kVA) with conventional means of network strengthening or upgrades, it was realized that the device should be application specific, i.e. the minimum requirements to adhere to a specific need. It was therefore proposed to investigate each functionality of the in-line converter separately and to find application opportunities within the Eskom network. In this process generic devices have been proposed, i.e. the electronic voltage regulator (EVR), compensating for both MV or LV voltages (single- and three-phase), and an electronic single-to-three phase converter (EPC) for induction motor loads.

In doing so the market is better targeted in that the needs of both remote agricultural rural supplies (single-phase to three-phase conversion) and the electrification of domestic supplies (voltage regulation) are met. The reasons for only focussing mainly on induction motor loads for the EPC application were that they were by far the majority (>90%) of three-phase loads, the combined dual-phase LV voltage of 460V resulted in a higher direct voltage link and, lastly, some hardware components could be removed in order to reduce the overall cost.

3.2 Technology and configuration motivation

Although all existing development work through research has up to now focussed on in-line, transistor-based technologies, it was necessary to first take a step back in order to motivate this decision.

There are three basic requirements from any power network. The first is to obtain a desired amount of electrical power from it; the second is to obtain this in an acceptable condition and the third to have it in a usable format. Several issues impede the ability of the utility to meet these requirements, such as line impedances, faults on the network, fluctuating loads, lightning surges, etc. [49]. However, various supporting technologies with different configurations exist to compensate for these limitations.

The technologies can be briefly categorised as fixed, electromechanical, thyristor-based and transistor-based with varying degrees of controllability and cost. The basic difference between the thyristor and transistor technology is that the transistor technology can easily be forced to commutate, which allows any waveform frequency to be sufficiently higher or lower than the fundamental system frequency to be synthesized [49]. Each technology type can in turn be configured as shunt, series, series-shunt and lastly in-line. The basic differences can be briefly explained as follow:

3.2.1 Shunt topologies

With shunt topologies reactive power is sourced or sunk from the network in order to improve power flow or voltage levels. The transistor-based shunt device can be equipped with energy storage, which in turn can reduce the device rating by up to three times [49]. Fig. 33 provides examples of typical shunt configurations.

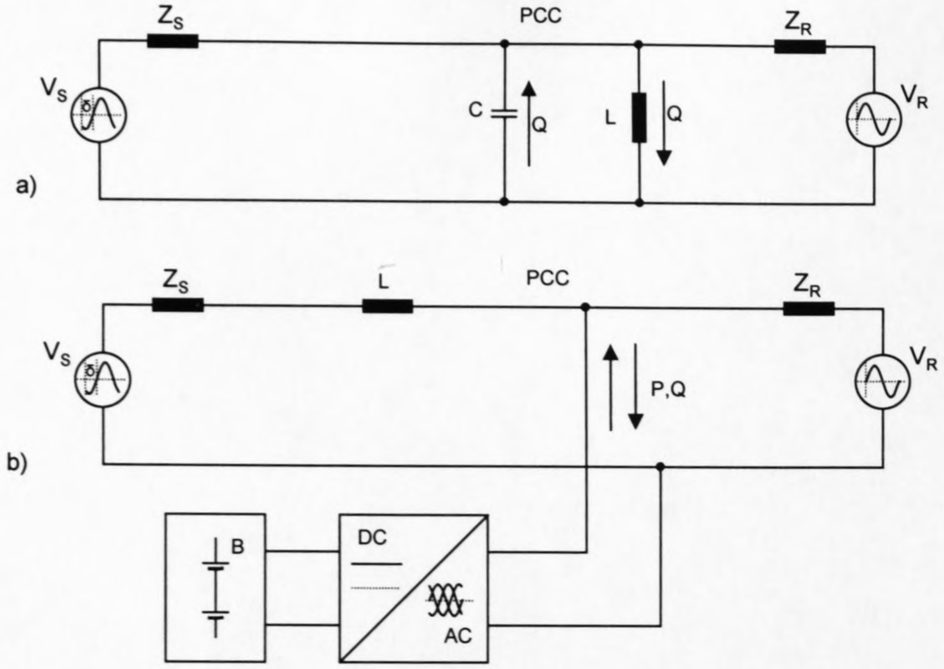
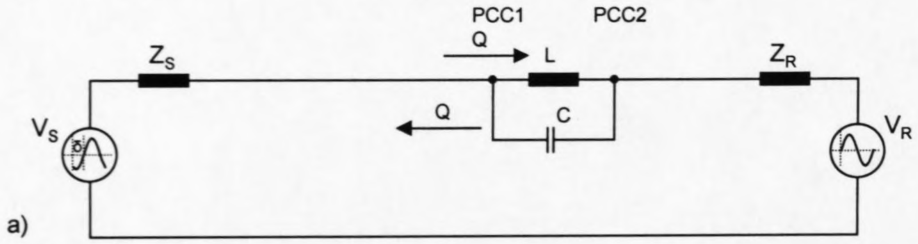


Fig. 33: Shunt configurations: a) fixed capacitor bank b) transistor-based with energy storage

3.2.2 Series topologies

Series devices are selected so that they resonate with the undesired component of the line reactance. They therefore minimize the equivalent series impedance, resulting in higher power transfer capability and better voltage levels. Series topologies are particularly suited for voltage-related problems, due to the fact that they introduce voltage directly into the network [49]. Fig. 34 provides examples of typical series configurations.



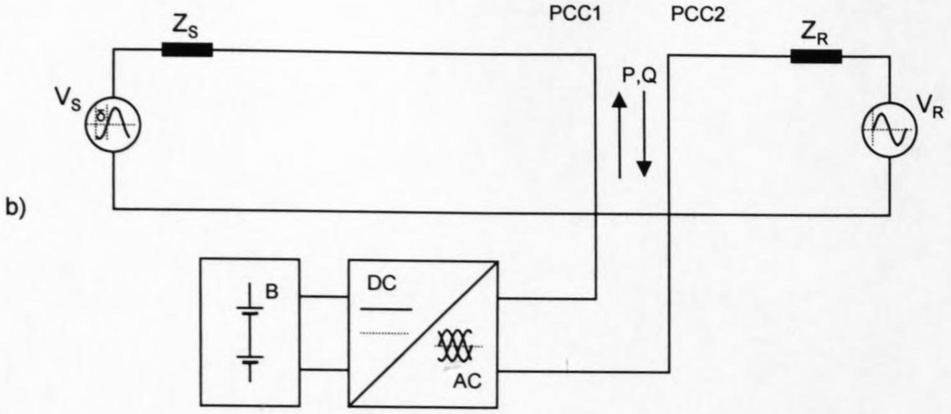


Fig. 34: Series configurations: a) fixed capacitor bank b) transistor-based with energy storage

3.2.3 Series-shunt topologies

Series-shunt devices draw power from the shunt side and inject it as a voltage at the series side. The transistor-based device can again be equipped with energy storage to reduce the ratings of the shunt or series parts. Active power can be transferred through the new power route, which gives this device the same advantages as the active series and shunt devices [49]. Fig. 35 provides examples of typical series-shunt configurations.

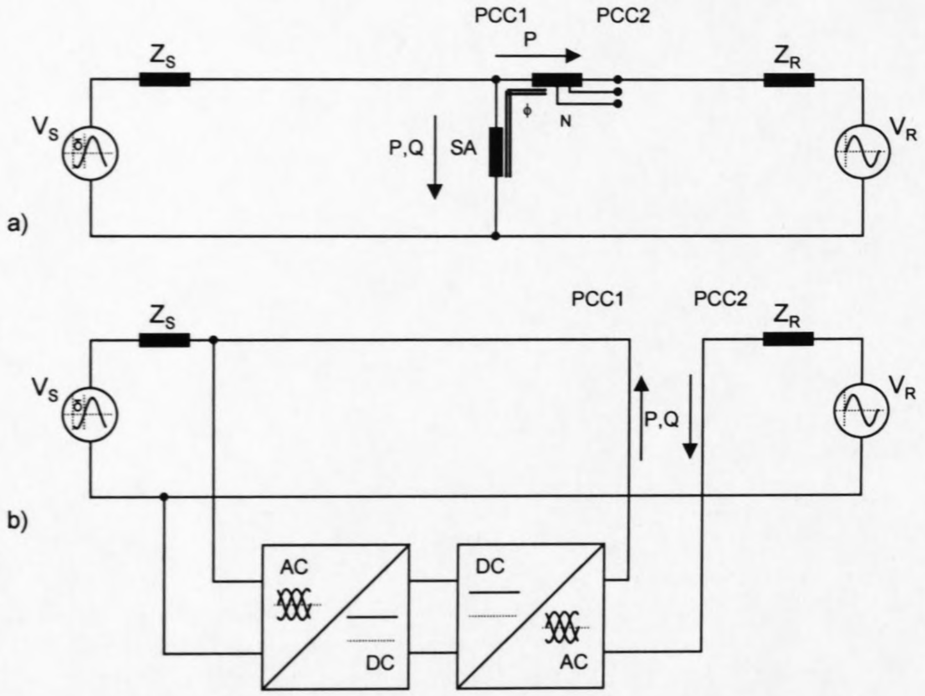


Fig. 35: Series-shunt configurations: a) electromechanically controlled voltage booster b) transistor-based without energy storage

3.2.4 In-line topologies

The most common representation of an in-line device in a power system is a power transformer that converts power from one form to another through a magnetic field. In the same way the transistor-based configurations transfer energy by means of an electric field in a direct voltage link. Fixed and electromechanical versions do not have any control over the power flowing through them. The thyristor-based topology can control active and reactive power, but not independently, since both depend on the same variable, the firing angle of the converter. The transistor-based device can control active and reactive power independently. Active power is transferred through the system and reactive power on each side is independent from the other side [49]. Fig. 36 provides examples of typical in-line configurations.

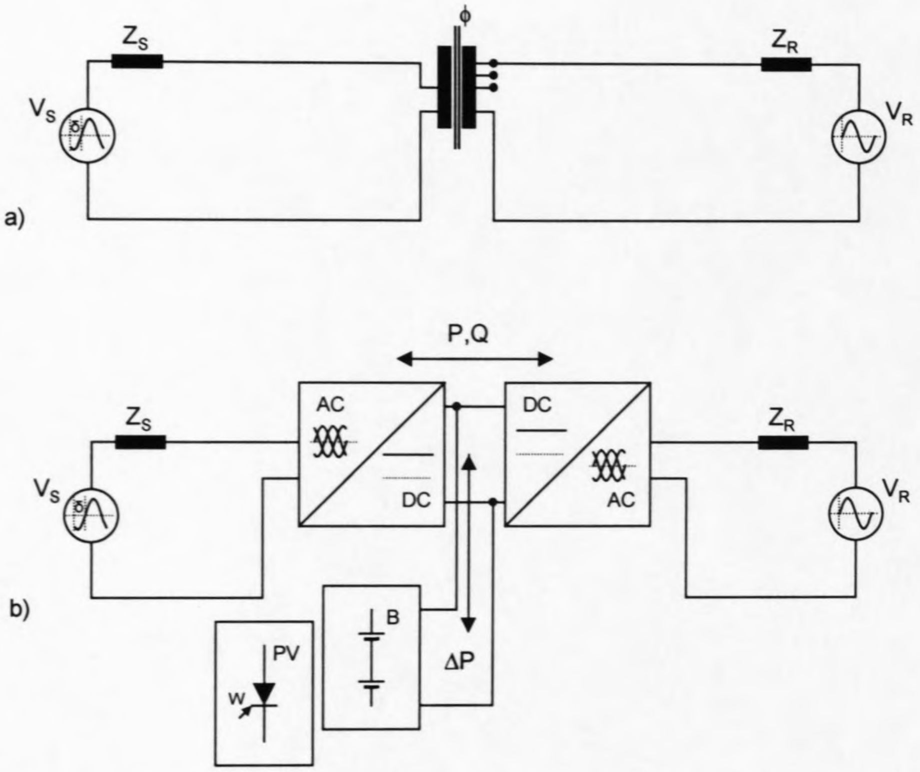


Fig. 36: In-line configurations: a) electromechanically controlled transformer b) transistor-based with energy storage or generation

3.2.5 Motivation for selecting the transistor-based technology and in-line topology

The preceding sections provided an overview of the basic technologies and configurations. The transistor-based technology is the technically superior technology, mainly because it can be turned off independent of all system parameters. This characteristic lends itself to full flexibility and controllability. This means that, by mere software changes, a device can be reconfigured to function completely differently, e.g. active and reactive power can be controlled independently, protection characteristics can be changed, etc.

The only disadvantage is the higher cost involved due to extra filter requirements and more expensive semiconductor switches. However, this penalty is becoming less serious since most development effort is invested in this technology, while the thyristor-based and electromechanical technology cost remains constant or increases with the increase in material cost. This is especially the case at lower power levels, where extra circuitry for protection, measurements, etc. required can be more expensive than the extra cost involved in the technology.

To summarise, the transistor-based technology was selected for the following reasons:

- Flexibility (e.g. phase conversion)
- Controllability (independent of system parameters)
- Increasing rate of development status
- Reducing cost
- Programmability (change characteristic by changing software).

The configuration is selected by first addressing the problem. As discussed earlier in the thesis, the focus area is rural electrification. These customers are in need of electricity for basic needs, i.e. lighting, heating and cooking. These are real power loads. The focus is also on MV and LV networks. For both the loads and networks, real power dominates. The only way of addressing problems in these systems is by means of active power compensation.

There are two mechanisms whereby a support technology can acquire active power, i.e. by means of energy storage (or generation) or drawing power from the line. The first option is not viable, mainly due to the capital and operating cost of energy-storage technologies. This is an even worse scenario at low power levels. The energy required to solve the problem therefore needs to be drawn from the line. This can be done in two ways, i.e. creating a parallel power path or converting the full line power. The first means is the series-shunt option and the second the in-line option.

The in-line technology is technically always the preferred option for the following reasons:

- It is easier to control, since all the line power is merely rectified, then inverted. The series-shunt configuration requires extra control power since power, is drawn or transmitted in an additional power path.
- The protection is easier, since full load power is controlled. In the series-shunt option, control over the line power is not so easy and at high line-fault levels it becomes very expensive.
- The default cost of the series-shunt device is more than that of the in-line device due to the extra injection transformer (rated at fault level) required.

The only disadvantage of the in-line device is that it converts full load power and therefore has a higher power stage and cost. At high power levels the series-shunt option would be the best technical option since the power rating would dominate the cost.

It is estimated that a break-even point for capacity versus cost for the in-line versus series-shunt device would be around 100 kVA. Above this rating the cost component of the power circuit for the in-line device would become too expensive. At lower ratings the power circuit cost in relation to the base system cost are less and therefore more cost effective. The power circuit requirements can be even further reduced if an active energy-storage device (batteries) is added (refer Fig. 36b). However, it was decided not to include this option as the decision was to design a compensating device that requires no or low maintenance. If batteries were included, this would have required a constant refurbishment cycle (limited lifespan due to extreme temperature variations). Refer to Table 8 for component cost comparison for both in-line and series-shunt device.

Table 8: Component cost comparison of a three-phase 50 kVA rated device

	Device component cost	
Module description	In-line [R]	Series-shunt [R]
Controller	2,000	7,000
Measurements	1,000	2,000
Injection transformer	0	6,000
Protection circuit	0	6,000

Power circuit	15,000	10,000
Total	18,000	31,000
System cost [%]	17	68
Power circuit cost [%]	83	32

The table shows that the cost of a 50 kVA device using the in-line configuration is approximately R18,000 and that of a series-shunt device is approximately R31,000. The system cost (controller, measurements, injection transformer and protection circuit) to power circuit cost ratio of the in-line device is 17% to 83% as compared to the series-shunt device with a ratio of 68% to 32%. It is important to realise that the costs presented are not absolute and may change as a result of fluctuations in monetary exchange rates, rate of technology development and mass production of components.

Therefore, based on the reasoning above, it was decided to choose the in-line topology and transistor-based technology for both the electronic voltage regulator and electronic phase converter.

3.3 In-line, converter-based LV voltage regulators

Throughout Chapters One and Two of this work an attempt was made to prove the importance of selecting the correct network option or line technology to serve the end customers' needs in the most cost-effective way. In order to expand on this approach in more detail, it is important to first gain an understanding of the current rural electrification design philosophies and parameters employed in Eskom Distribution. A short summary of this is provided in Table 9.

Table 9: Rural electrification design philosophies and parameters [28]

Description	Design philosophy
MV reticulation	SWER and phase-phase (occasional three-phase)
LV reticulation	Single-phase and dual-phase
Densities [connections per km^2]	< 200
Customer circuit-breaker size [A]	2.5 or 20
ADMD [kVA]	0.2 – 0.4
Transformer LV no-load voltage [V]	240 or 415
Transformer sizes [kVA]	16 or 32

Transformer maximum loading [%]	150%
LV ABC conductor size [mm^2]	35 or 70 (default to 35)
Default service connection cable size [mm^2]	4
LV supply voltage limits [V]	230V – 10% (207V) and +10% (253V)
Maximum LV feeder length [m]	550
Average LV feeder length [m]	450
Benchmark LV feeder length per connection [m]	40
Number of customers per service connection box	1.4 – 1.8
Average LV span lengths [m]	65

3.3.1 Application opportunities of the EVR

One of the main objectives of the thesis was to identify the practical application opportunities of the EVR in support of the existing electrification technology options. These applications are to be configured in such a way that they are at all times technically sound and the most cost-effective solutions available. The technology also has to match existing standard network design philosophies, network layout considerations, standard material items and codes of practice.

In order to achieve the above set goals, the following device requirements were identified:

- Single- or three-phase application determined by network density and/or diversity of the load;
- Low- (10 or 20%) or high- (30 or 40%) capacity voltage compensator determined by feeder length;
- Small (5 A), medium (20 A) and large (100 A) current rating determined by network positioning;
- Integrated over-current protection device (to replace circuit breaker or fuse)

Having considered the abovementioned requirements, the following three standard application areas were decided upon:

- Transformer (TRFR)-mounted;
- Service connection box (SCB)-mounted;
- Electricity dispenser (ED)-mounted.

3.3.1.1 *Transformer-mounted EVR*

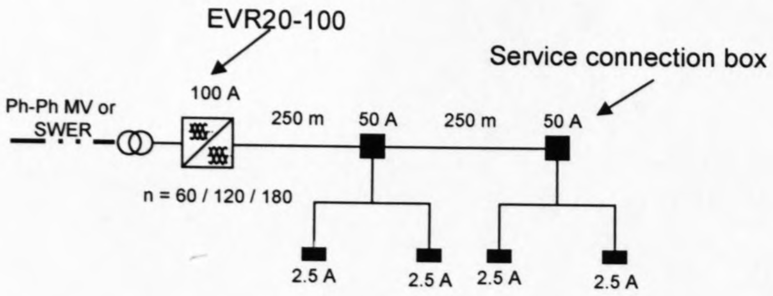


Fig. 37: Transformer-mounted EVR

In this application mode the use of the EVR would be primarily to compensate for MV feeder volt drop at the remote end of a long MV line with only a small number of pole-mounted distribution transformers connected (refer Fig. 37). The total number of EVRs installed would be determined by the cost break-even point for MV voltage compensation by means of an autotransformer voltage regulator (existing back-bone network) or reduction in conductor size for new extensions. *In the case of the voltage regulator comparison, it could typically be a maximum of four 24 kVA (single-phase LV), four 48 kVA (dual-phase LV) or three 75 kVA (three-phase LV) units (refer Fig. 44).* As already illustrated in the example given in section 2.5.3, a reduction in conductor size from Mink to Magpie can lead to a 35% cost saving on the MV line cost. Depending on the MV line length, this could lead to various equivalent or least-cost EVRs being installed.

Table 10: Transformer-mounted EVR standard ratings

Trfr size	LV methodology	EVR rating (1.5 pu) [kVA]	EVR rating (1.5 pu) [A]	Total Customers (0.2 kVA)
16	Single- phase	24	100	120
32	Dual-phase	48	100 / phase	240
50	Three-phase	75	100 / phase	360

Table 11: Transformer-mounted EVR costing structure

EVR rating	Voltage compensation magnitude [%] and type			
	40	30	20	10
24 kVA	R22,000 (R917/kVA) EVR40-100	R19,600 (R817/kVA) EVR30-100	R17,200 (R717/kVA) EVR20-100	R14,800 (R617/kVA) EVR10-100
48 kVA	R44,000 (R917/kVA) EVR40-200	R39,200 (R817/kVA) EVR30-200	R34,400 (R717/kVA) EVR20-200	R29,600 (R617/kVA) EVR10-200
75 kVA	R66,000 (R917/kVA) EVR40-300	R58,800 (R817/kVA) EVR30-300	R51,600 (R717/kVA) EVR20-300	R44,400 (R617/kVA) EVR10-300

The ratings of the transformer-mounted EVRs were chosen to match the standard lower-rated pole-mounted distribution transformers normally associated with low-density rural networks. The capacity ratings are also so chosen as to allow 50% overloading of the transformer for a two-hour period per day in accordance with IEC 60354 [32]. Refer to Table 10 and Table 11 for more detail.

This application is further discussed in section 3.3.4.

As a built-in feature, the EVR will also act as an over-current protection device and will replace the 80 A or 63 A fuses at the transformer. This detail on the LV protection philosophy applied will be further discussed in section 3.3.9 and 3.3.11.

3.3.1.2 Service connection box-mounted EVR

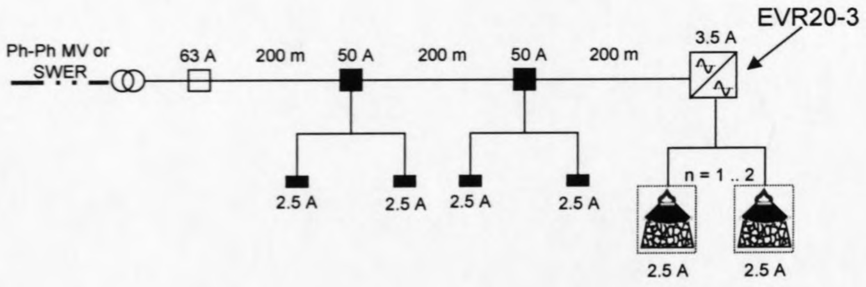


Fig. 38: SCB-mounted EVR at end of 600 m LV feeder

The next logical level of application determined again by density and diversity of the load is that of an SCB-mounted EVR (refer Fig. 38). This application would be for single-phase mode only. Due to the fact that the average number of customers connected to a service connection box varies between 1.4 and 1.8 (refer Table 9), the SCB-mounted EVR should be rated at 0.8 kVA only (refer Table 19). However, provision has to be made for growth in customer numbers and network upgrades. Therefore the 4-way and 8-way SCB equivalent is also chosen. Refer to Table 12 and Table 13 for standard ratings and costing structures.

Table 12: Service connection box-mounted EVR standard ratings

SCB size	EVR rating [kVA]	EVR rating [A]	Customer MCB rating [A]	Total customers (0.2 kVA)
2-way	0.8	3.5	2.5	2
4-way	1.2	5	2.5	4
8-way	2	9	2.5	8

Table 13: Service connection box-mounted EVR costing structure

EVR rating	Voltage compensation magnitude [%] and type			
	40	30	20	10
0.8 kVA	R2,500 (R3,125/kVA) EVR40-3	R2,400 (R3,000/kVA) EVR30-3	R2,300 (R2,875/kVA) EVR20-3	R2,200 (R2,750/kVA) EVR10-3
1.2 kVA	R3,400 (R2,833/kVA) EVR40-5	R3,300 (R2,750/kVA) EVR30-5	R3,200 (R2,667/kVA) EVR20-5	R3,000 (R2,500/kVA) EVR10-5
2 kVA	R4,400 (R2,200/kVA) EVR40-10	R4,200 (R2,100/kVA) EVR30-10	R4,100 (R2,050/kVA) EVR20-10	R3,900 (R1,950/kVA) EVR10-10

LV feeder extensions beyond the previous maximum limit of 550 meters are now possible as this limit was mostly determined by voltage drop. Full advantage can now be taken of longer LV feeder runs up to the maximum now determined by either the LV fault level required to blow the upstream 63 A or 40 A HRC fuse or the impact of creating new transformer zones.

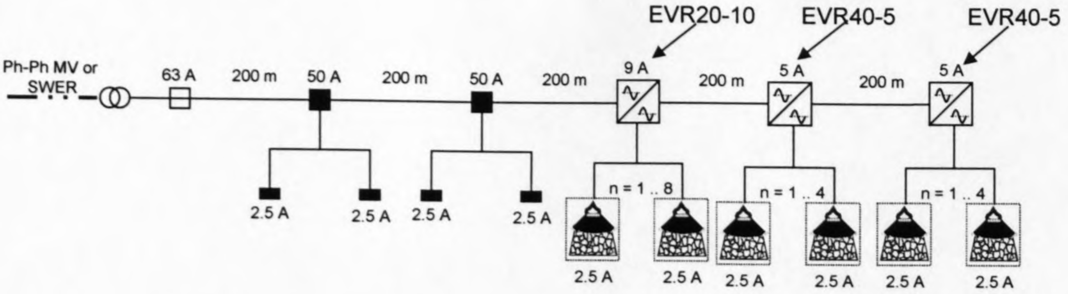


Fig. 39: SCB-mounted EVRs at end of 1000 m LV feeder

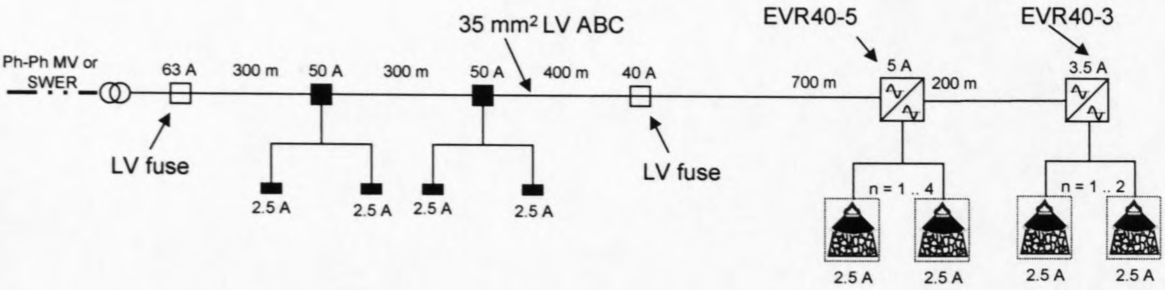


Fig. 40: SCB-mounted EVRs at end of 1900 m LV feeder

Should only a single level of LV fusing be applied, this limit is set at 1000 metres (refer Fig. 39) and can be extended to 1900 metres (refer Fig. 40) if two levels of LV fusing are applied. Again, as with the transformer-mounted EVR, as a built-in feature the EVR will also act as an over-current protection device and will replace the 50 A circuit breaker in the service connection box. Refer to section 3.3.9 and 3.3.11 for more detail on LV protection co-ordination.

This mode of application is further discussed in section 3.3.5.

3.3.1.3 Electricity dispenser (ED)-mounted EVR

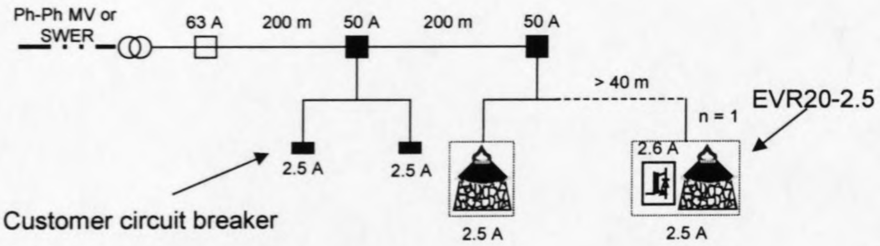


Fig. 41: ED-mounted EVR at remote end

The lowest level of capacity and diversity is that of the ED-mounted EVR (refer Fig. 41). This application is ideally suited for single-point extensions beyond the current 30- to 40-metre limit from the SCB. Refer to Table 14 and Table 15 for standard ratings and costing structures.

Table 14: Electricity dispenser-mounted EVR standard ratings

EVR rating [kVA]	EVR rating [A]	Customer MCB rating [A]	Total Customers (0.2 kVA)
0.6	2.6	2.5	1

Table 15: Electricity dispenser-mounted EVR costing structure

EVR rating	Voltage compensation magnitude [%] and type			
	40	30	20	10
0.6 kVA	R2,300 (R3,833/kVA) EVR40-2.5	R2,200 (R3,667/kVA) EVR30-2.5	R2,100 (R3,500/kVA) EVR20-2.5	R2,000 (R3,333/kVA) EVR10-2.5

Care must be taken as to ensure effective protection grading up to the remotely connected EVR. Refer to section 3.3.11 for more detail on LV protection co-ordination.

3.3.2 EVR concept

The EVR can perform voltage regulation on the LV side (Insulated Gate Bipolar Transistor (IGBT) technology limited to withstand voltages of up to 3.3 kV) of the distribution system. It controls the voltage in real time and frequent changes in load or system voltage do not influence the conditioned voltage V_c [24]. Due to this inherent design feature, the dynamic voltage regulator (EVR) is most suited for its intended application of LV voltage regulation on LV feeders of rural electrification networks. As already stated the load densities of these networks are low, which in turn implies low load diversities with large load fluctuations.

In order to explain the above concept, the equivalent circuit diagram and schematic of the input / output stages of the EVR are shown in Fig. 42 and Fig. 43 [24]. The receiving side is equivalent to a constant current source and the conditioned side is equivalent to a constant voltage source.

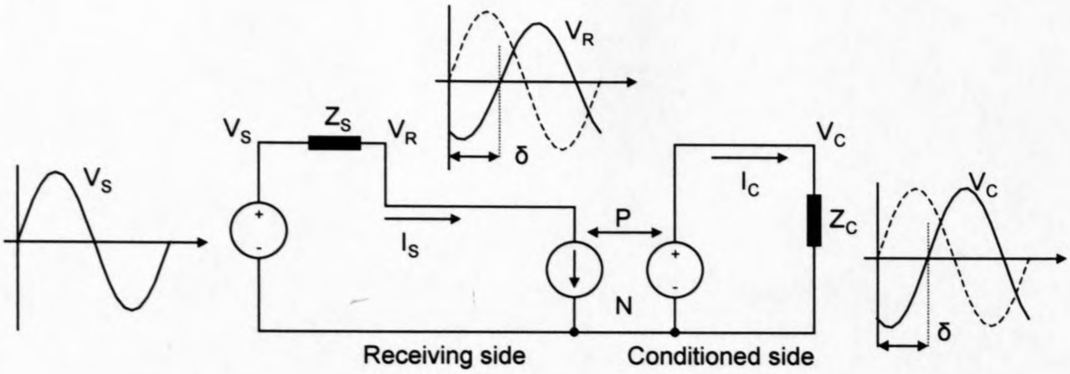


Fig. 42: Single-line diagram illustrating voltage regulation with the EVR [24]

It is important to realise that for both the electronic voltage converter and autotransformer voltage regulator, the receiving-end current must increase to boost the voltages in order to sustain the same power demand on the conditioned side. An autotransformer also has to transfer the reactive power required by the load, but the EVR converter isolates the load's reactive power demand from the receiving side.

This increased LV line current required for regulating the voltage to within limit can be calculated either through determining a constant power relationship as in equation (3.2) and (3.3) [24] or using network parameters as shown in equation (3.5) [42]:

$$P_{in} = \frac{P_{out}}{\eta}$$

$$\therefore V_{in} I_{in} = \frac{V_{out} I_{out}}{\eta} \tag{3.1}$$

$$\Rightarrow I_{in} = \frac{V_{out} I_{out}}{V_{in} \eta} \qquad \text{(single-phase)} \tag{3.2}$$

$$\Rightarrow I_{in} = \frac{V_{out} I_{out}}{3 V_{in} \eta} \qquad \text{(three-phase)} \tag{3.3}$$

Thus the input stage is de-rated by the percentage of voltage drop to be compensated for. The design of the input stage of the EVR has been changed to take this increase in current rating into account.

With reference to Fig. 42, the receiving voltage V_R is calculated as:

$$V_R = V_S - I_S Z_S \tag{3.4}$$

Thus from equation (3.1) with η = 1, equation (3.5) can be derived

$$(\times I_S) \Rightarrow V_R I_S = P = V_S I_S - I_S^2 Z_S$$

$$\Rightarrow I_S = \frac{V_S - \sqrt{V_S - 4 Z_S P}}{2 Z_S} \tag{3.5}$$

The increased line current drawn to maintain the load power causes an increased voltage drop across the line. Therefore the conditioned voltage can only be regulated from a receiving-end voltage of not more than 60% of the nominal voltage and higher [24].

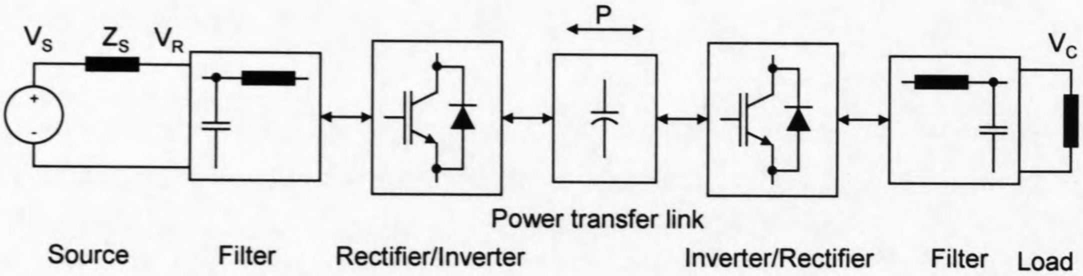


Fig. 43: Schematic of the input and output stages of EVR

It is also possible to export reactive power to the sending side so as to limit the effect of this increased current drawn on the voltage drop of the upstream network. However, due to the small reactance (*X*) to resistance (*R*) ratio ($X/R = 0.088 / 0.868 = 0.1$) of standard 35 mm^2 aerial bundled conductor, which in turn determines the phase shift angle, there is no added benefit for leading reactive power.

The effect of the increased line current drawn to maintain the load power that causes an increased voltage drop across the line is further discussed in section 3.3.7.1.

The design details of the electronic voltage regulator are described in full in [53] and a brief summary of the technical specifications is attached in Appendix B.

3.3.3 Cost benefits of increased input voltage at point load

In order to quantify the importance of optimising the load reach of LV feeders, with maximum available transformer secondary voltage, a study of LV network expansion cost for various sending-end voltages can be done. The voltage compensation for this study was achieved by means of an autotransformer voltage regulator on the MV network. The study, recently performed by Distribution Technology (DT), on the costs involved due to different allowable LV feeder volt drops for three different stand size designs for electrification networks yielded the following results [8]:

DT calculated the cost per connection for allowable LV voltage drops of 5% to 15%. The LV is permitted to drop to 15% if the transformer no-load voltage at system minimum voltage is 5% above nominal. Table 16 shows the benefit in cost per connection for the three stand sizes relative to the 5% voltage drop case. The table indicates that, with a base of R2,100 per connection for 3900 m^2 stands, a saving of R300 is possible if the incoming MV voltage were to be increased from 95% to 105%. This saving is dependent on the stand size and is increased to 20% or R585 per connection for large stand sizes.

Table 16: Benefits of increasing MV input voltage [8]

LV Volt drop	5%	7.50%	10%	12.50%	15%
Case A (3846 m^2)	R 2,100	R 1,976	R 1,908	R 1,840	R 1,800
% Saving	0.00	5.90	9.14	12.38	14.29
R saving	R 0	R 124	R 192	R 260	R 300
Case B (7225 m^2)	R 2,944	R 2,592	R 2,466	R 2,428	R 2,359
% saving	0.00	11.96	16.24	17.53	19.87
R saving	R 0	R 352	R 478	R 516	R 585
Case C (1648 m^2)	R 1,537	R 1,402	R 1,366	R 1,336	R 1,305
% saving	0.00	8.78	11.13	13.08	15.09
R saving	R 0	R 135	R 171	R 201	R 232

From the above (refer Table 16) it is clear that huge savings are possible due to cost savings on LV network expansion as a direct result of a strong MV or LV transformer voltage. The

LV network can now be optimally designed. This is especially true for long MV networks supplying low-density (large stand sizes) townships.

3.3.4 Three-phase EVR as LV voltage regulator

A similar study can be done to determine the optimal number of connections required (as above) to offset the capital outlay of an autotransformer voltage regulator for a group of transformers as compared to an EVR per transformer. The study only covers the application of the EVR20 and excludes the possible cost saving of upstream network cost should voltage compensation percentages larger than 15% be applicable up to the full capacity of the EVR40. The EVR has to cost compete on a cost/kVA base with the mechanical autotransformer voltage regulator (MVR), the latter being the traditional means of compensation. Proportionally the kVA rating of an autotransformer voltage regulator is higher by far; thus the focus has to change to smaller capacity applications.

Fig. 44 illustrates that a break-even point does exist when costs are compared between a 100 A three can 11 or 22 kV voltage regulator (closed delta) and EVR devices of various sizes. The capacities of the various EVR devices were so chosen as to match standard distribution pole-mounted transformer sizes. As was proposed in section 3.3.1.1, the three-phase EVRs should be positioned on the secondary side of pole-mounted distribution transformer structures. In order to achieve the maximum cost benefit, the transformer zones at the end of long MV feeders supplying small to medium sized point loads (24 kVA, 48 kVA and 75 kVA) should be targeted. The latter sizing was so chosen as to match the overload capacity of single-, dual- and three-phase LV distribution transformers. Typically a transformer of 50 kVA (75 kVA overload) capacity can supply up to 180 customers.

Similar philosophies as applied to MV network support will now be further explored to identify opportunities on the LV network for the EVR application.

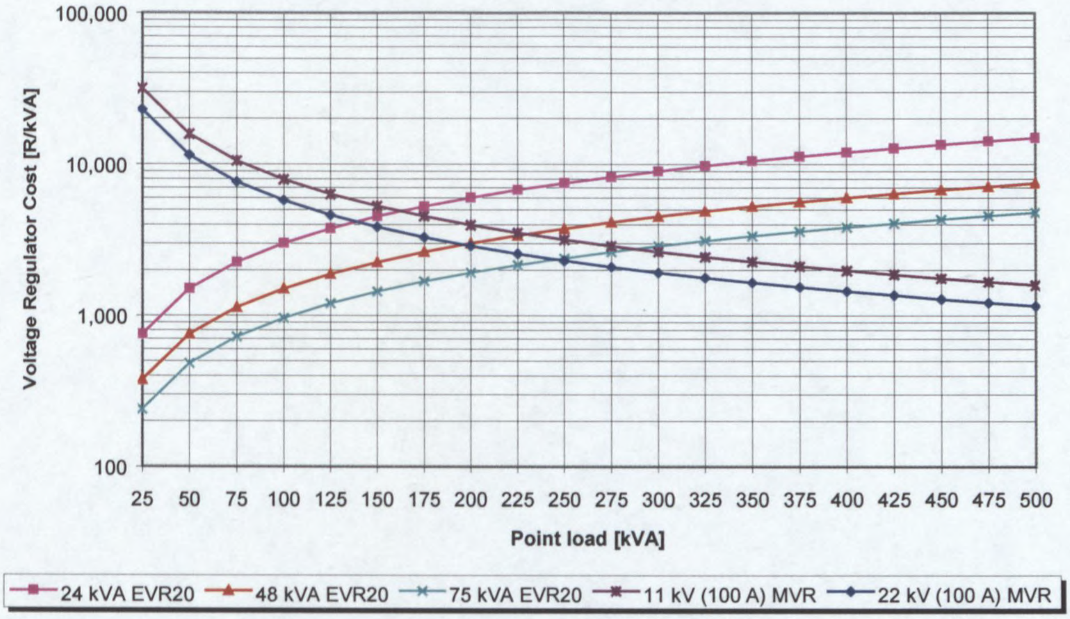


Fig. 44: Voltage regulation cost (MVR vs EVR)

3.3.5 Single-phase EVR as LV voltage regulator

In a situation where a new customer or group of customers, connected to a radial LV feeder, is likely to cause voltage regulation problems at the end of the feeder, the ideal application of the single-phase EVR arises. The situation described is not unfamiliar in township layouts in rural areas. Again as in the case described in section 3.2, feeder strengthening can be avoided with obvious cost benefits. In deciding upon standard power ratings of the single-phase EVR, one has to consider first of all the standard supply options offered by Eskom to its low-usage residential customers.

The "Homelight" range of tariffs is applicable to single-phase supplies in areas designated by Eskom as rural or low density [3]. The tariff has different energy rates based on the supply capacity required and provides for a subsidy to low-usage customers (refer Table 17).

Table 17: Supply options to low-usage residential customers

Technology	Service
Non-grid (solar home systems)	Lights, small TV and radio
Grid, 2.5 Amp	Lights, TV, radio and limited small

	appliances
Grid, 20 Amp	Most electrical requirements but load must be balanced
Grid, 60 Amp	All electrical requirements can be met – adequate for a small business

In this context the non-grid solar home system (SHS) should be seen as "*a basic electricity service*" to be supplied to households in rural areas that cannot be connected to the grid within acceptable cost parameters. The cost associated with supplying these basic needs (less than 5 kWh per day) by means of a photovoltaic system compares favourably with the cost associated with a 2 km grid extension [34].

The 2.5 Amp current limited supply is the basic service for the poorest sector, where grid extension is feasible. The availability of this tariff option, combined with the alternative MV and LV supply technologies already discussed, allows settlements of low density to be electrified by bringing the average cost per connection to within the current cost targets.

As was shown in section 3.3.1 various application opportunities for the EVR were identified in order to further enhance the success of this basic service supply option.

3.3.6 Capacity rating of the single-phase EVR

Voltage drop is a function of the ADMD (After Diversified Maximum Demand), diversity, unbalance and network impedances. LV voltage drop calculations are done through the use of two methods. The first is empirical calculation methods or the more recent method adopted by Eskom, the Herman Beta statistical method, which models loads as being stochastic.

Table 18: Approximate relationship between customer circuit-breaker size, BDMD and ADMD [48]

Customer circuit-breaker size [A]	Before diversified maximum demand (BDMD) [kVA]	After diversified maximum demand (ADMD) [kVA]
2.5	0.6	0.2
20	4.5	1.5
60	13.8	4.6

In using the empirical calculation methodology, two correction factors are normally applied to attempt to correct the statistically worst condition with some degree of confidence. One factor is the unbalanced voltage correction factor (UCF) and the other is called the loss of diversity correction factor (DCF), which attempts to model the effect of having less than 1000 customers and the associated ADMD. The latter technique was applied to accurately size the rating required for the single-phase EVR in various application modes. Results are shown in Table 18 and Table 19.

Table 19: Total kVA demand of LV supply options

		Customer circuit-breaker size					
		2.5 A		20 A		60 A	
Number of customers	Loss of diversity (DCF)	BDMD	Total demand [kVA]	BDMD	Total demand [kVA]	BDMD	Total demand [kVA]
1	3.00	0.60	0.6	4.50	4.5	13.80	13.8
2	2.00	0.40	0.8	3.00	6.0	9.20	18.4
3	1.67	0.33	1.0	2.50	7.5	7.67	23.0
4	1.50	0.30	1.2	2.25	9.0	6.90	27.6
5	1.40	0.28	1.4	2.10	10.5	6.44	32.2
6	1.33	0.27	1.6	2.00	12.0	6.13	36.8
7	1.29	0.26	1.8	1.93	13.5	5.91	41.4
8	1.25	0.25	2.0	1.88	15.0	5.75	46.0
9	1.22	0.24	2.2	1.83	16.5	5.62	50.6
10	1.20	0.24	2.4	1.80	18.0	5.52	55.2
20	1.10	0.22	4.4	1.65	33.0	5.06	101.2
30	1.07	0.21	6.4	1.60	48.0	4.91	147.2
40	1.05	0.21	8.4	1.58	63.0	4.83	193.2
50	1.04	0.21	10.4	1.56	78.0	4.78	239.2
60	1.03	0.21	12.4	1.55	93.0	4.75	285.2
70	1.03	0.21	14.4	1.54	108.0	4.73	331.2
80	1.03	0.21	16.5	1.54	123.0	4.72	377.2
90	1.02	0.20	18.4	1.53	138.0	4.70	423.2
100	1.02	0.20	20.4	1.53	153.0	4.69	469.2
200	1.01	0.20	40.4	1.52	303.0	4.65	929.2
300	1.01	0.20	60.6	1.51	453.0	4.63	1389.2

From Table 19 it is clear that for all 2.5 A connections the single-phase EVR mounted in the 2-way service connection box should be rated at 0.8 kVA, 1.2 kVA for the 4-way application and likewise 2 kVA for the 8-way. Most supplies in low-density areas would require only 2- or 4-way service connection boxes with an average of 2 to 3 customers connected from them. As previously mentioned, the EVR lends also itself ideally to an alternative network upgrade philosophy, should the existing customers supplied require an upgrade to 20 A connections. In this scenario either the rating of the 2-way service connection box-mounted EVR has to increase to 6 kVA or compensation can be achieved by means an ED-mounted EVR with a 4.5 kVA capacity rating. In order to compare the cost effectiveness of this alternative upgrade path, the cost associated with conventional LV network strengthening has to be evaluated and compared to the EVR. Refer to section 3.3.8 for more detail regarding LV network upgrade philosophies.

3.3.7 Cost benefit analyses of the single-phase EVR

As discussed in sections 3.3.1.2 and 3.3.1.3 it is proposed that the single-phase EVR be positioned either in the service connection box or electricity dispenser. Both applications can have distinct advantages on the cost saving of network infrastructure for LV feeder extensions beyond 500 metres or service connections beyond 40 metres. In order to investigate these two options, two models are presented as case studies.

3.3.7.1 "Stretching" the LV feeder length beyond 500 m

A typical MV / LV network layout of an electrification project is presented in Fig. 45. Only two transformer zones are shown.

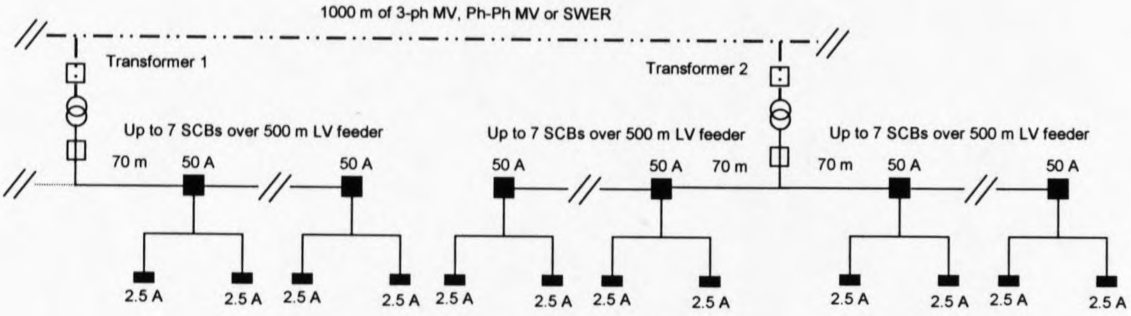


Fig. 45: MV to LV network overlay for two transformer zones

The current design practice would be to install the second zone (transformer 2) should the LV feeder length exceed 500 m. This second zone can be avoided if the feeder length is extended by a further 1000 m (1500 m in total) and voltage compensation is achieved by means of EVRs positioned at each service connection box of the extended portion. As there would be no saving on the LV feeder cost, the only saving would be that on the MV line extension and pole-mounted transformer installation. It is further assumed that the service connection boxes are positioned at each pole position equivalent to the ruling span of the LV bundled conductor - 70 metres in this case. The typical dual-phase LV feeder distribution cost for 35 mm^2 aerial bundled conductors are presented in Table 20. In order to complete the cost comparison exercise, the MV line extension and transformer installation costs were based on national averages [4] and the EVR costs as presented in Table 13 (EVR20-3 and EVR40-3). The results of this study are shown in Fig. 46. It is important to realise that the effect of upstream compensation required as a result of the increased current drawn by the EVRs is still ignored at this stage.

Table 20: Typical dual-phase LV feeder cost per metre – New vs Upgrade

Description	New [R/m]	Upgrade [R/m]	Comments
Aerial bundled conductor (3C XLPE 35mm^2)	8.00	8.00	String second bundle as part of upgrade
9m wood pole (160mm Top Diameter)	5.23	1.73	Extras poles due to wind and weight load
Structure hardware	0.60	0.60	
LV stays	0.68	0.68	
Service connection box (1 - 4)	2.19	0	
10% contingency	1.67	1.10	
Labour	11.03	7.27	60% of material
Total	**29.40**	**19.38**	

The results indicate that the LV feeder extension combined with EVRs per service connection box is the most cost effective means of LV feeder design as compared to a MV SWER extension. This break-even point lies at just over 1000 m with total feeder length of 1500 m. The graphs also shows that any other MV line technology (phase-phase and three-phase) in excess of a 1500 m feeder length is more expensive, although it must be remembered that the maximum limit is determined by fault level and effective protection co-ordination. These results are also in line with the LV feeder protection grading limitation of a 35 mm^2 aerial bundled conductor with a 63 A upstream and 40 A downstream fuse. This limit is set at 1900 m (refer Table 23).

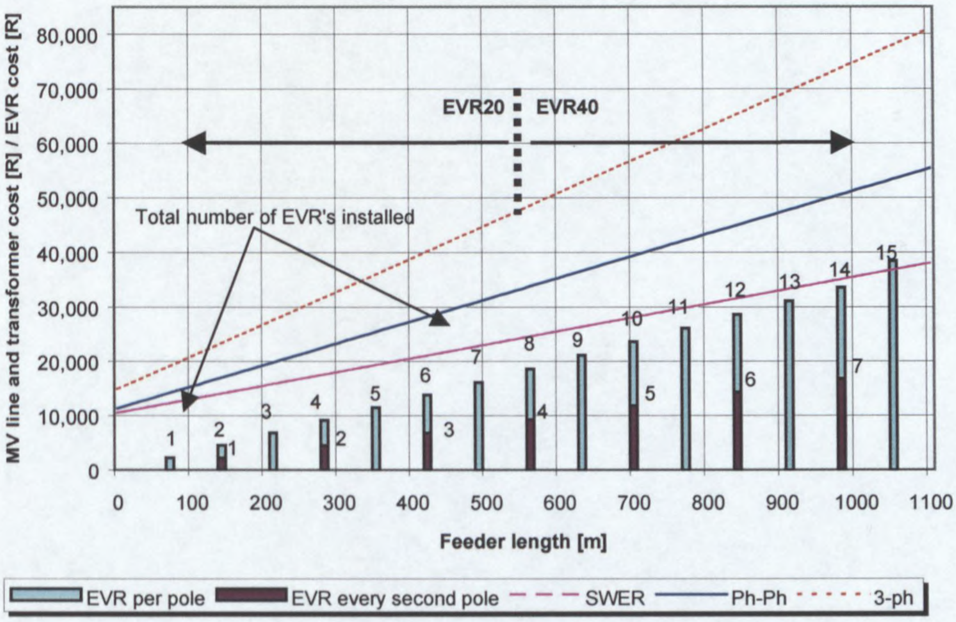


Fig. 46: Cost break-even for MV network extension vs LV network extension & EVR (SCB-mounted)

The sensitivity of an EVR only on every second pole was also tested. This would typically represent the design of a LV network with service connection boxes positioned every 140 metres in areas with lower density.

A typical single-line diagram depicting the maximum load reach of a 35 mm^2 LV aerial bundled conductor with domestic type constant current loads of 2.5 A, two per service connection box and spaced at 70 metre intervals is shown in Fig. 47. The maximum length (1,540 m) of the feeder in this case is determined by the LV protection grading requirements (refer section 3.3.10 and 3.3.11). The voltage regulation limit is ignored as it is assumed that EVRs will be installed at node points RM6 through to RM24 (total of 19) to compensate for the voltage drop.

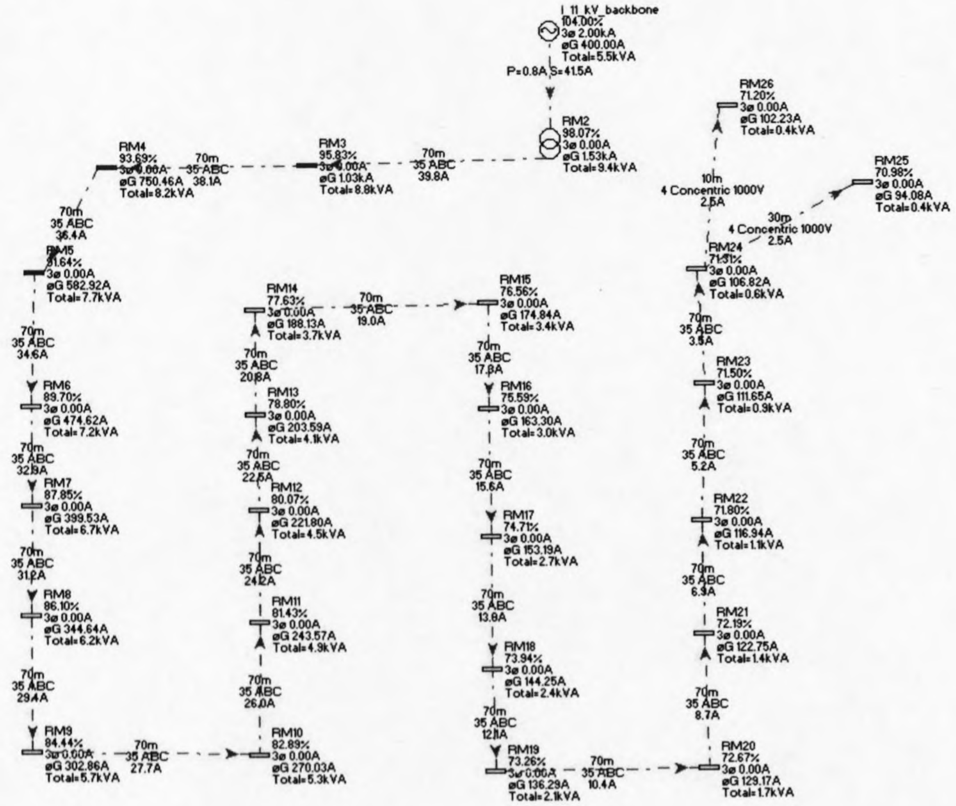


Fig. 47: Single-line diagram depicting maximum load reach of 35 mm^2 ABC

This total is in excess of the cost break-even point that limits the total number to 14 (refer Fig. 46) at an equivalent distance of 1,500 m. The reason is that the upstream network (first 500 m) also requires compensation.

A further load reach-limiting factor is the effect of further upstream compensation that is required as a result of the increased current drawn by the EVRs to compensate for the reduced input voltage (refer section 3.3.2). In order to simulate this, all node points were assumed to be at 0.8 p.u. voltage, and from equation (3.2) all loads was scaled to increase by 25%.

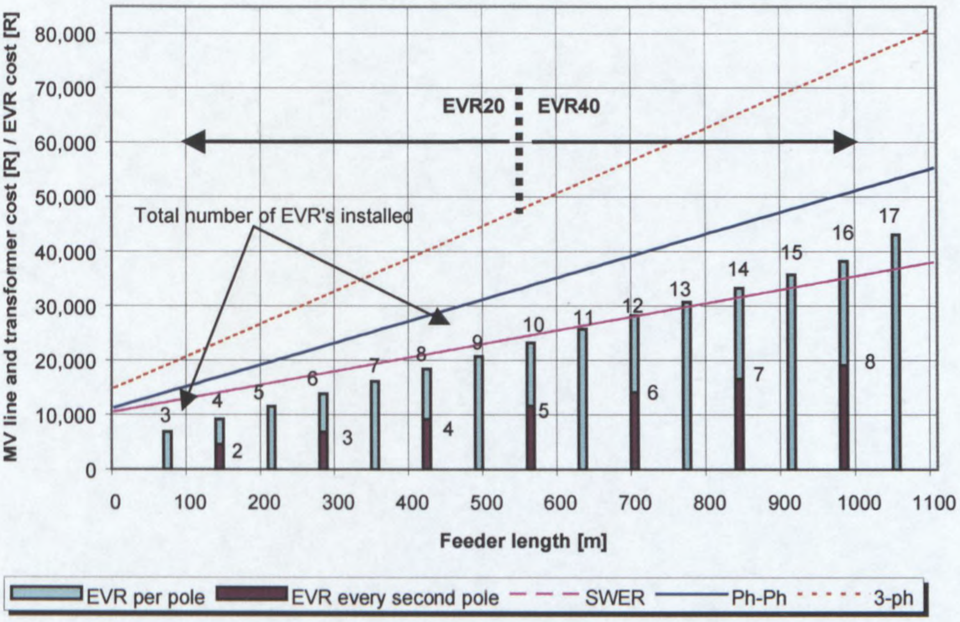


Fig. 48: Additional EVR cost due to upstream compensation required

The cost break-even point for this analysis of additional compensation that is required for upstream loads is shown in Fig. 48 and a single-line diagram depicting the maximum load reach under this condition in Fig. 49.

The results show that, up to a total of 12 EVRs installed at the node points RM7 through to RM18 that in turn relates to a load reach distance of 1,200 m (700 m + 500 m), it would always be more cost effective to extend the LV network than to create a new transformer zone. This limit is also in line with the criteria set by effective protection co-ordination with a 60 A upstream fuse (refer Table 23).

Again as was stated earlier, should the service connection density be even lower and a service connection box required on every second pole (140 m), the load reach can easily be extended to the maximum protection co-ordination limit of a mid-way 40 A fuse, i.e. 1900 m. Thus effectively the load reach of a 35 mm^2 ABC feeder with 2.5 A service connections, two per service connection boxes spaced at 70 m intervals, is limited to only 1,200 m due to the upstream compensation that is required as a result of the increased input current drawn by the EVRs.

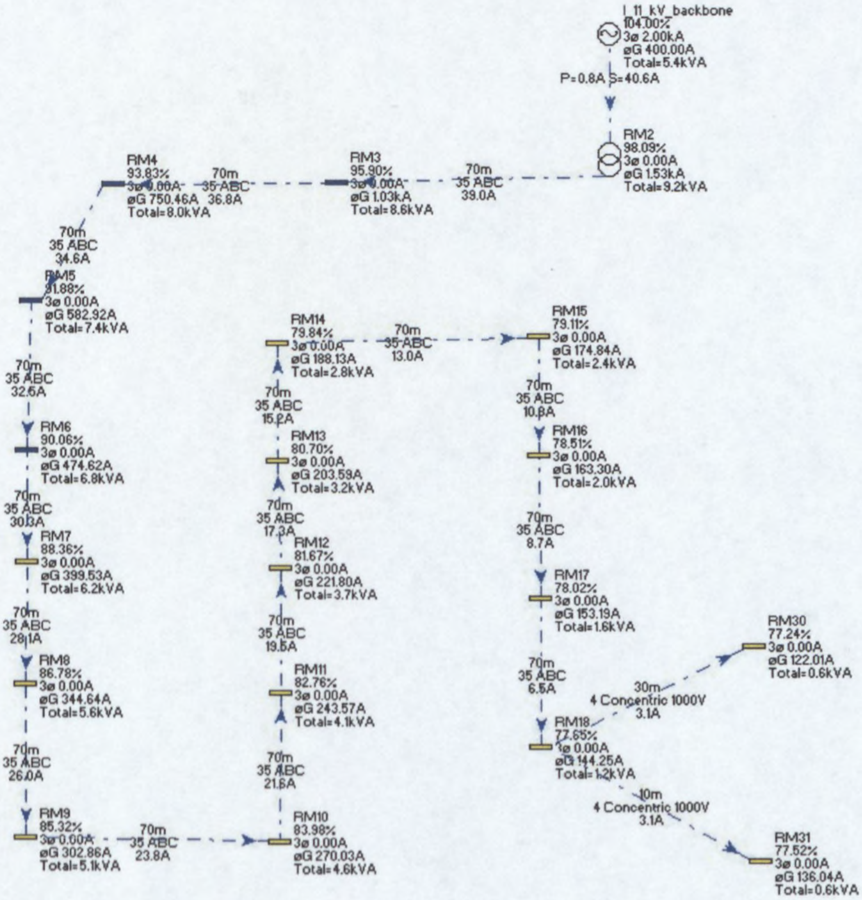


Fig. 49: Single-line diagram depicting maximum load (25% increase) reach of 35 mm^2 ABC

3.3.7.2 "Stretching" the LV service connection length beyond 40 m

A typical LV feeder with service connection is shown in Fig. 50. It is standard design practice to allow for up to 3% as a volt drop window for service connections and up to 15% for the complete LV portion (transformer secondary terminals to meter) [35]. This limitation and other design criteria such as utilisation of service connection boxes, the utilisation of stubby poles and minimum fault current to trip 50 A circuit breaker in SCB, have "traditionally" limited the service connection feeder length to 40 metres. However, there are exceptions to the rule in the form of single-point extensions that are remote from "grouped" settlements.

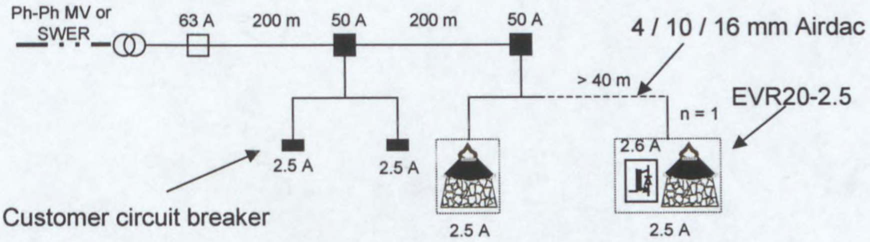


Fig. 50: Service connection options for remote customers

Several options exist to connect these remote single points to the grid. In order to evaluate these options one first has to consider typical LV network extensions costs as presented in Table 21 and compare the results to extensions with voltage compensated (EVR20-2.5) extensions with smaller conductor sizes. The results of this study are shown in Fig. 51 and Fig. 52.

Table 21: Typical LV service connection cost per metre > 40 metres (excl. ED)

Description	$4\ mm^2$ [R/m]	$10\ mm^2$ [R/m]	$16\ mm^2$ [R/m]	Comments
Airdac	3.93	5.74	10.58	
Service poles and hardware	3.23	3.20	3.20	Spaced at 40 m intervals
10% contingency	0.72	0.89	1.38	
Labour	4.72	5.90	9.10	60% of material
Total	**12.6**	**15.73**	**24.26**	

In order to consider all technical compliance criteria, the standard volt drop limits per conductor size (to fall within volt drop window set) and LV protection grading are also shown. The LV protection grading is determined by the minimum fault current required to trip upstream 50 A circuit breaker in the SCB for a phase to earth/neutral fault at the end of the service connection cable or faulty EVR at the meter. The minimum fault current at the SCB was assumed to be 150 A and threshold limit set at the end of the feeder was 90 A with time to trip equal to 200 seconds.

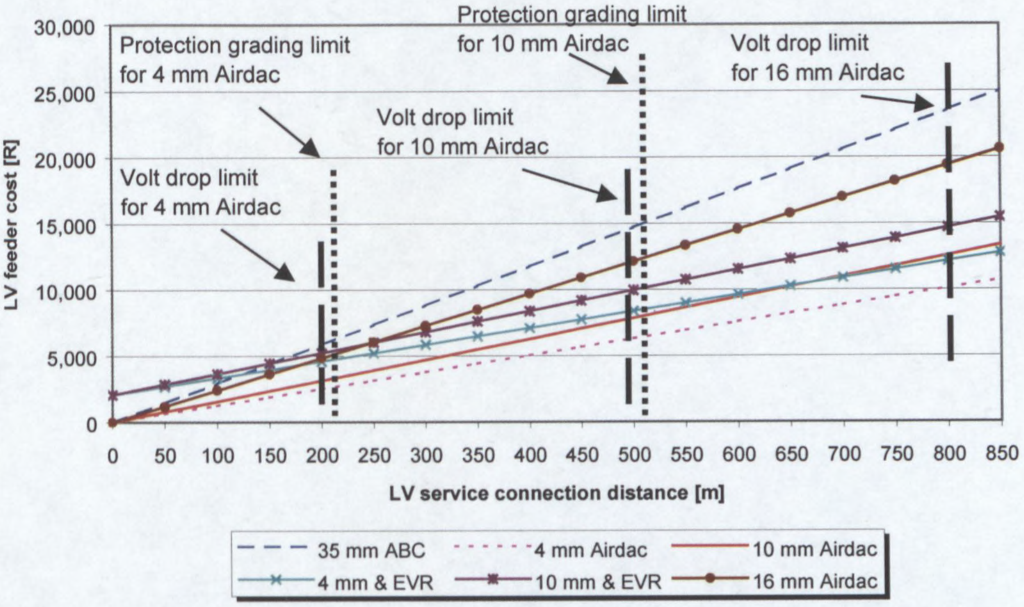


Fig. 51: Cost break-even for 2.5 A LV network extensions

The results of Fig. 51 show that 4 mm^2 Airdac extensions up to 200 m are the most cost effective or in some cases, depending on the sending voltage at the SCB, 10 mm^2 Airdac can be considered (marginal cost difference). All extensions greater than 200 m up to and including 500 m should be done with 10 mm^2 Airdac and similarly 16 mm^2 Airdac for extensions up to 800 m. Within this window (200 to 800 m), the EVR and 4 / 10 mm^2 Airdac combination should not be considered due to LV protection grading problems.

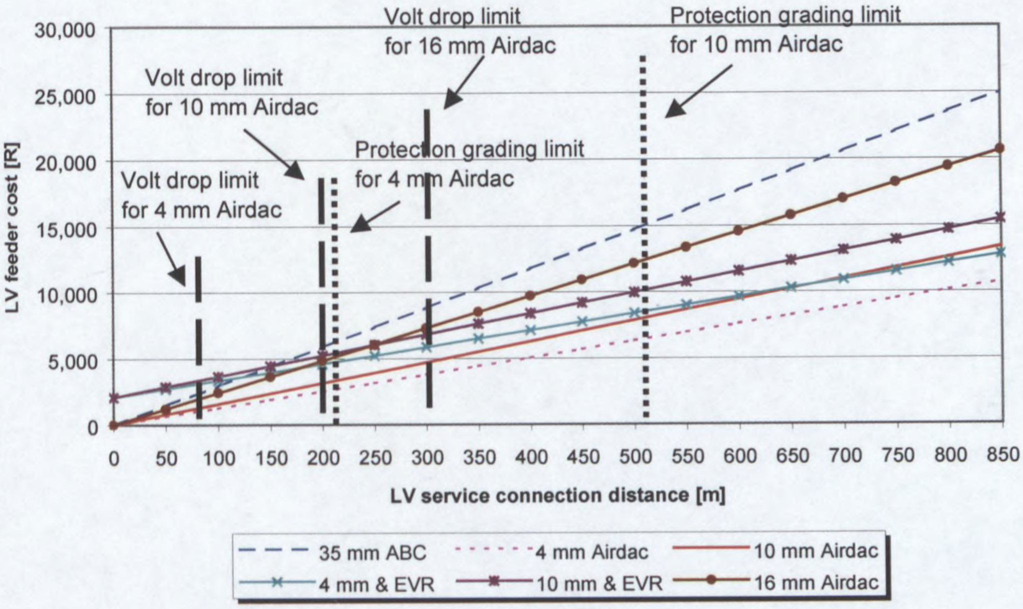


Fig. 52: Cost break-even for 20 A LV network extensions

A very important deduction can thus be made at this point in that the ED-mounted EVR has limited, if any, application opportunities to be considered for initial network design at low ampere ratings (2.5 A). However, it proves to be a cost-effective solution should an increase in supply capacity from 2.5 to 20 A be required for service connection lengths in excess of 200 metres, as shown in Fig. 52.

In summary thus, as discussed in sections 3.3.7.1 and 3.3.7.2, the single-phase EVR proves to be more cost effective in the SCB than ED mode of application, mostly due to its high cost per capacity ratio for smaller loads. *As was proven in section 3.3.7.1, the only cost effective, technically sound solution of expanding grid connected supplies to low density areas (stand sizes greater than 5000 m^2) with service connection boxes spaced at intervals of 140 metres or more, are by means of SCB-mounted EVRs.*

Network planners and designers should thus consider it as an alternative means to increase the load reach of LV feeders. A graphic representation of this philosophy is shown in Fig. 53, indicating the normal and compensated load reach of LV feeders.

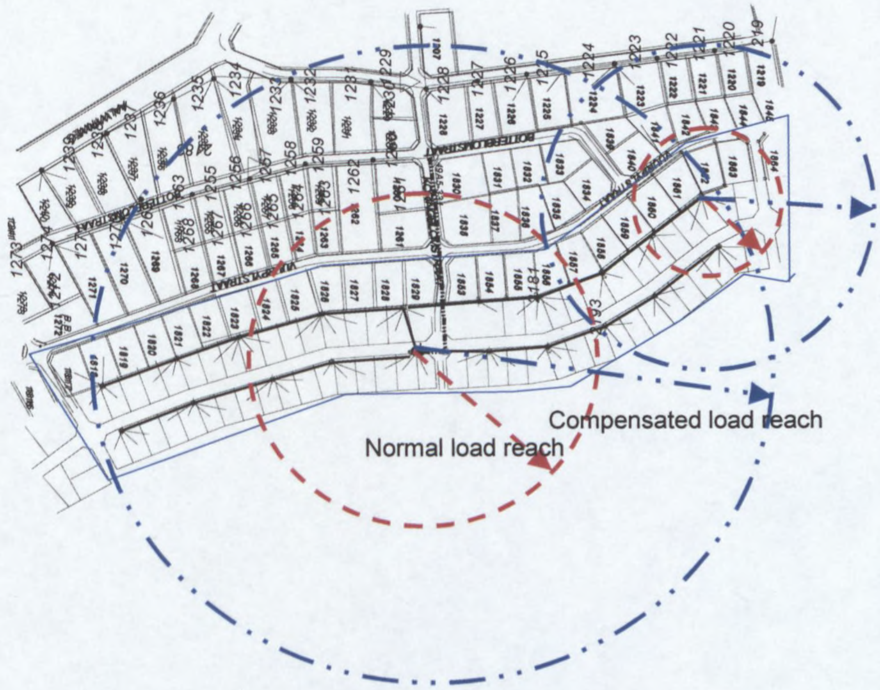


Fig. 53: Effect of EVR on load reach capability of LV feeders

3.3.8 EVR as alternative means for LV feeder upgrade

It is important to realise that network upgrading can only be performed in practical steps that are easily implementable as the networks to be upgraded are energised and are serving customers. As part of the design philosophy applied to specific projects, clear and practical upgrade paths have to be considered and documented. As already pointed out (section 2.3), the planning horizons for electrification networks are associated with a high degree of uncertainty in terms of load forecasting and therefore every attempt must be made to save on initial capital expenditure and to allow for possible upgrading of the network in year 5.

Table 22 presents existing network upgrade paths for low-density networks that are both practical and easily implementable.

Table 22: Existing network upgrade paths for low-density networks

Existing network	Reason for upgrade	Upgrade options
Phase-phase MV or SWER and single-phase LV	LV volt drop and/or transformer overload	• Changing transformer taps • Change transformer to dual-phase LV and add additional

		two-core ABC conductor • Improve MV voltage by means of autotransformer voltage regulator
Phase-phase MV or SWER and dual-phase LV	LV volt drop and/or transformer overload	• Changing transformer taps • Parallel two dual-phase LV transformers and/or add additional three-core ABC conductor • Reduce LV feeder length by extending MV and addition of extra transformer zone • Improve MV voltage by means of autotransformer voltage regulator

As was proven in section 3.3.7, increasing the load reach of LV feeders can be a costly exercise. Again opportunities arise for the EVR as network upgrade tool as an alternative to the stringing of a second parallel connected conductor, thus effectively increasing the conductor size, or the addition of a second transformer zone. Consider a typical LV network case study as presented in Fig. 54. The worst-case scenario exists when customer circuit-breaker sizes are increased at the end of the long feeder. Provided that neither the transformer capacity nor the bundled conductor thermal rating are exceeded, a second parallel feeder would be required to restore the supply voltage back to normal.

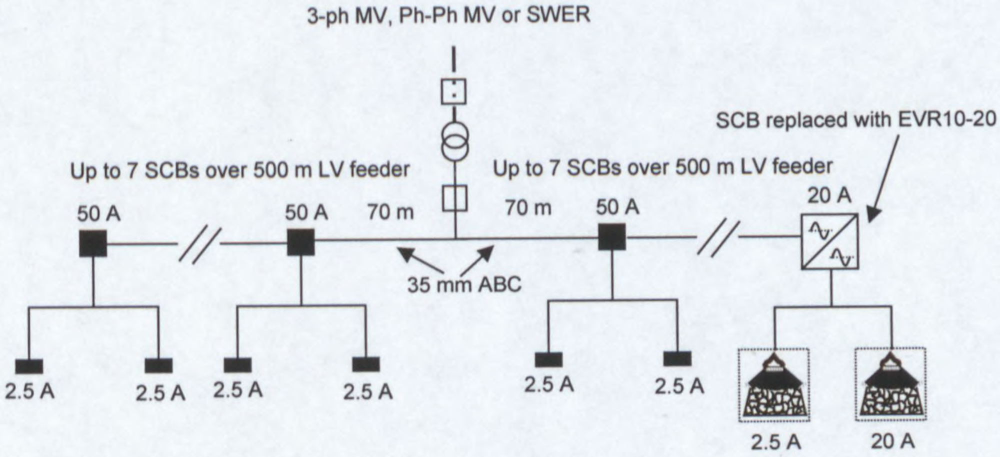


Fig. 54: LV network upgrade application of SCB-mounted EVR

This upgrade would normally only involve the addition of a few extra poles (should this not be already considered in the initial design) due to decreasing weight span, an additional 35 mm^2 conductor and conductor hardware. This additional cost (refer Table 20) versus the installation of one EVR should be compared to determine the cost effectiveness of both options. The results are shown in Fig. 55.

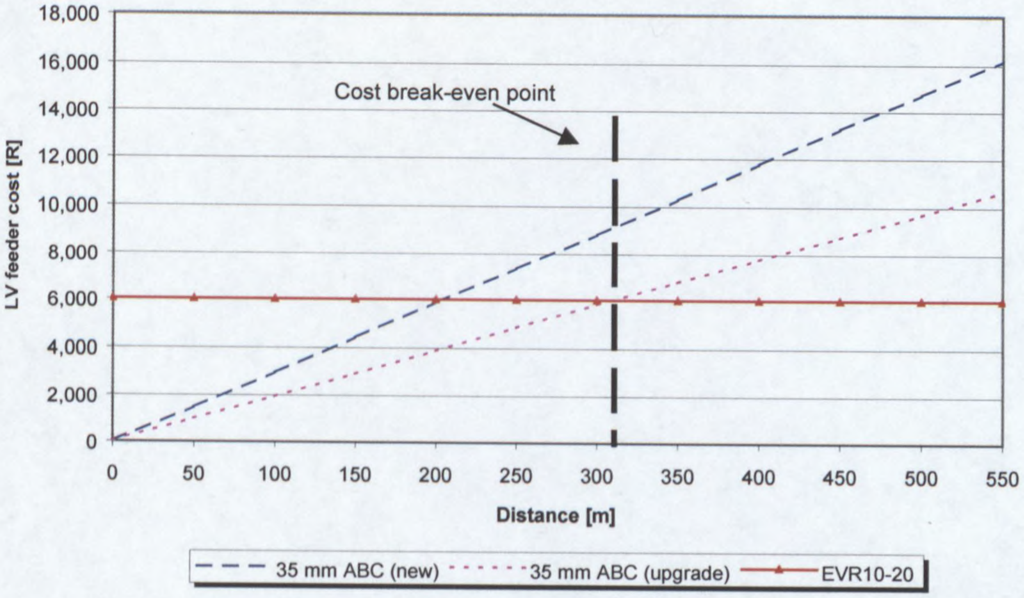


Fig. 55: Cost comparison for LV feeder upgrade

The results show that the EVR can ideally be applied as a "boot strapping" tool for LV feeder upgrades in excess of 300 metres.

Similarly, the cost break-even for the installation of an additional transformer zone can be compared with the study described in section 3.3.7.1 and results shown in Fig. 46.

3.3.9 Dynamic response to sudden load changes

As already discussed in section 3.3.6, the voltage drop on a LV feeder is a function of the ADMD, diversity, unbalance and network impedances. Since only single-phase systems have been considered in the comparisons to date, the effect of unbalance will be ignored. Two methods are currently applied to calculate the effect of both unbalance and diversity on the percentage voltage drop along a feeder: the British and AMEU (Association of Municipal

Electricity Undertakings) methods. Eskom prescribes the AMEU method. The formula for the loss of diversity L is [51]:

$$L = 1 + \frac{2}{N} \tag{3.6}$$

where:

N is the number of consumers, and
2 is a loading factor (assumed to be constant):

A graphic representation of the diversity correction factor (loss of diversity) for up to 100 households is presented in Fig. 56. Also shown is the total demand for number of households at two chosen ADMDs.

It is important to measure the impact of sudden load changes at low diversity levels (small number of households) for various supply capacities and the influence this has on the load current and thus the supply voltage swings. Consider the case study as presented in Fig. 45 and the generic rural electrification design parameters as presented in Table 9. The target benchmark for LV feeder length per connection is 40 m. A 16 kVA transformer would be able to supply at least two to three 500m radial LV feeders, which in turn amounts to between 25 and 40 customers. The equivalent total demands at ADMDs of 0.2 and 0.4 kVA per household are shown in Fig. 56.

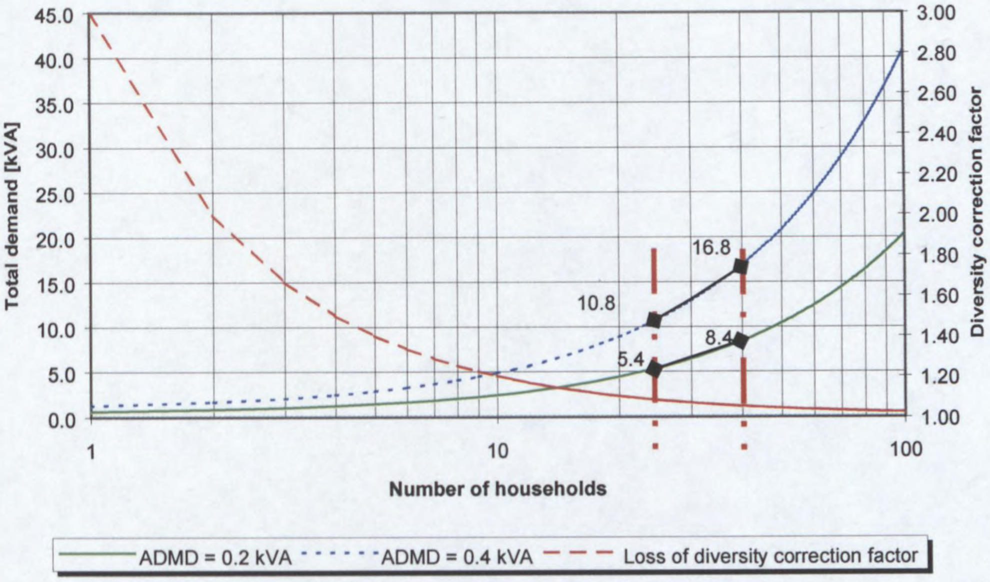


Fig. 56: Approximate relationship between diversity and load fluctuations

It can thus be concluded that "weak" networks (high fault impedance) with a small number of higher-demand customers connected are more susceptible to sudden load changes, which in turn can lead to supply voltage fluctuations on long LV networks (refer Fig. 57).

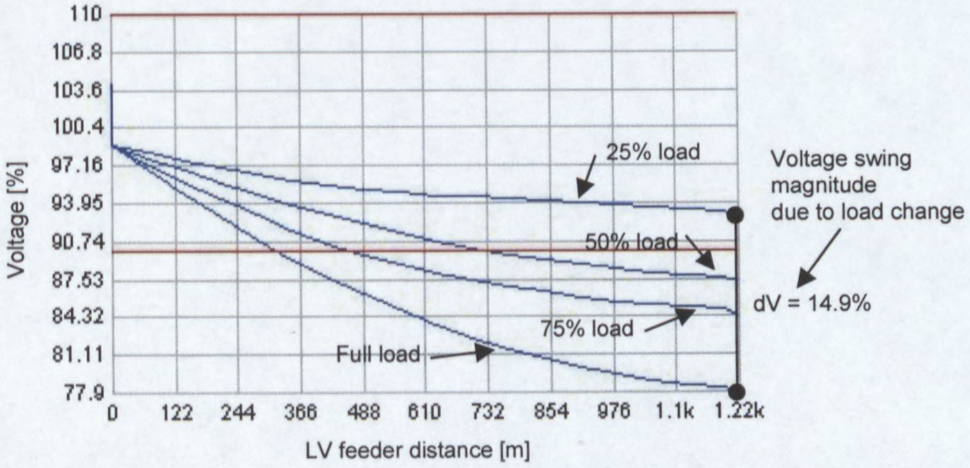


Fig. 57: Voltage swing on long LV feeder due to sudden load changes

Due to the fact that no provision is normally made to compensate for voltage fluctuations at LV voltage levels and the mere fact that the voltage operating window has been drastically increased from ± 10% to +10% and –40% through the introduction of LV voltage regulators, it is of extreme importance that the response time to voltage fluctuations be as short as possible. This requirement basically rules out the use of mechanically switched voltage regulators at low voltage. This type of device normally has a response time of between 10 and 20 seconds as compared to the EVRs capability of dynamic response between 10 to 20 milliseconds.

3.3.10 LV protection philosophy

The importance of LV protection grading has been pointed out it in preceding sections. The reason for stressing this importance can be attributed to the fact that previous restrictions placed on feeder lengths and thus fault impedances were mainly due to the voltage restrictions imposed. With these restrictions now "relaxed" through the introduction of the EVR concept, it is important to review again the philosophies applied. The existing framework presented in [36] will be adopted with changes only applicable due to the increased feeder distances. The standard rating and curve types of Eskom Distribution standardised protection equipment (circuit breakers and fuses) will be left unchanged.

Although a philosophy of rapid LV protection operation is always preferred, it is considered to be more critical for bare-wire systems than ABC systems. In all of the studies shown thus far, only ABC systems were considered due to the fact that operating times of the order of 10s of seconds (typically 10 s to 100 s) should be followed for bare-wire systems. With bare-wire systems there is a much greater probability of a conductor falling to the ground under line fault conditions or due to mechanical failure.

On the other hand, ABC systems require inter-phase or phase-neutral faults to be cleared from the system within the thermal limit (damage curve) of the connected plant. This philosophy further assumes that there is a very low probability of a phase conductor falling to the ground during a line fault or mechanical failure. The result is drastically increased LV feeder distances due to the lower fault levels required to operate upstream protection systems (refer Table 23 and Table 24).

For ease of reference, the extended LV network layout as presented in Fig. 40 will be repeated in Fig. 58.

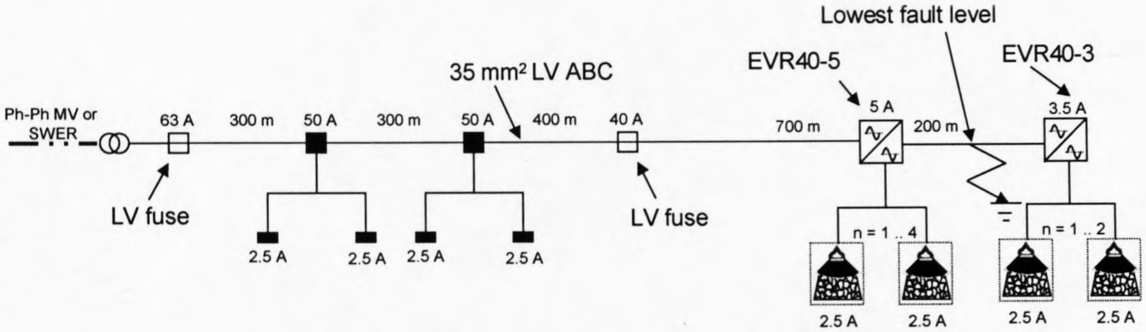


Fig. 58: Typical LV network protection configuration

From [36], Table 23 can be repeated with the addition of the maximum LV conductor length associated with a 40 A fuse.

Table 23: Maximum LV distributor length for ABC (fault level = 1,6 * fuse rating)

Conductor	80 A fuse	63 A fuse	40 A fuse
	Length [m] Fault level = 128 A	Length [m] Fault level = 101 A	Length [m] Fault level = 64 A
35 mm ABC	920	1170	1900

Table 24: Maximum LV distributor length for bare wire (fault level = 100 s min melt time)

Conductor	80 A fuse	63 A fuse
	Length [m] Fault level = 200 A	Length [m] Fault level = 150 A
Squirrel	320	440
Fox	470	650
Mink	810	1100

As can be seen from Fig. 58 and Table 23, the LV distributor length can be increased by a further 900 metres with the application of a downstream 40 A fuse. Due to the introduction of this lower rated fuse to supply remote customers, it is important to realise that the protection co-ordination with the 50 A rated service connection box circuit breakers will be lost. If this is not addressed, it may lead to nuisance tripping and will hamper faultfinding.

However, it is possible to programme the EVR with preset time-current curves in order to achieve protection co-ordination between the various over-current protection elements in the LV network.

3.3.11 Protection co-ordination

Fig. 59 shows the characteristic curves (time-current) of the various protection elements (e.g. 63 A fuse / 50 A SCB breaker / 20 A customer breaker / 20 A EVR / etc.) in the LV network, superimposed on the same axis. All possible modes of the EVR with various capacity ratings are also shown. It is imperative for the EVR to "grade" with the rest of the network so as to avoid nuisance tripping.

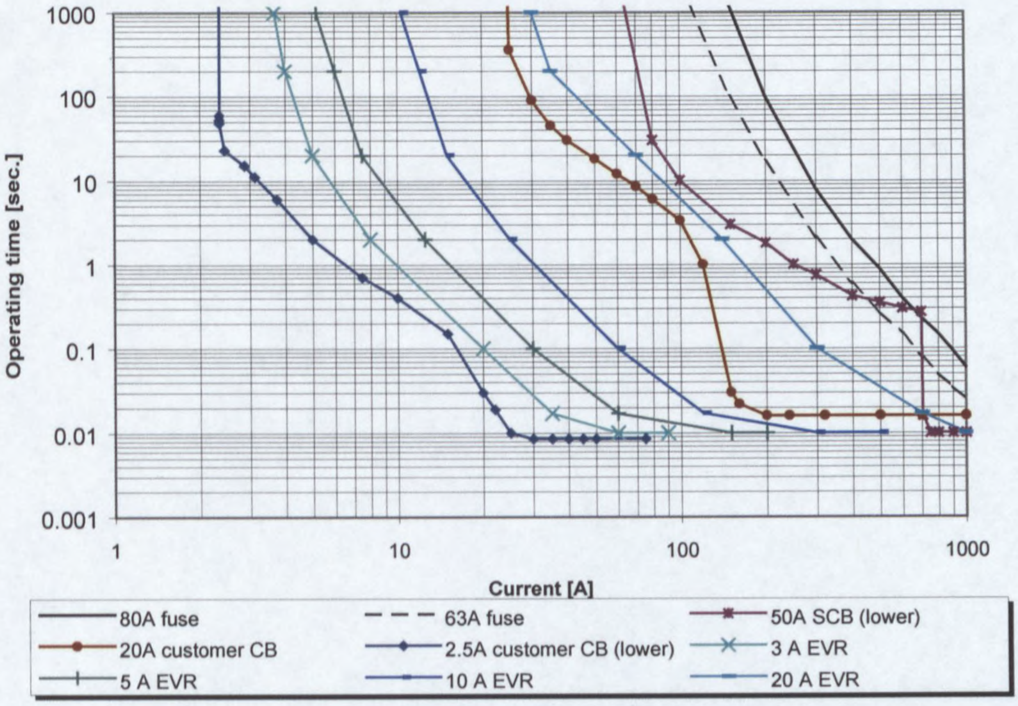


Fig. 59: Fuse protection co-ordination with downstream circuit breakers and EVRs [36]

The 3 A, 7 A and 10 A SCB-mounted EVR application is to grade with the time-current characteristic of the 2.5 A load-limiting circuit breaker at the customer end. However, due to the possible multi-use of the EVR20-20 as both an 8-way service connection box extension with 2.5 A connections as well as its application as upgrade "tool" for a 2-way SCB with at least one 20 A connection, it should emulate the characteristics of the standard 50 A SCB circuit breaker.

It should be noted that standard thermal-magnetic or hydraulic-magnetic type circuit breakers have an instantaneous operating region that begins at approximately 5 times the rated current of the circuit breaker. The time-current characteristics of the EVR were chosen to suit this principal mode of operation.

3.3.12 Effect on CNE earthing philosophy applied

The current earthing practice for LV distributors followed by Eskom Distribution is that of a combined neutral and earth (CNE) system [37]. The system consists of a network whereby the supply is earthed at the source (no earth electrode shall be installed at the customer's premises) and the protective earth and neutral (PEN) conductors are combined and the overall resistance to earth of the LV neutral is limited. This maximum limit (typically 70 Ω for 11 kV primary) is determined by the operation of the upstream MV main earth fault protection in the event of an insulation breakdown between the transformer MV and LV windings.

Due to this, the PEN conductor's integrity through the design, construction, maintenance and operation of the LV distribution system becomes extremely important. It is therefore required that no circuit breakers, isolators, fuses, switches or removable links shall be installed in the earth conductor of the LV supply distributor. The design of the EVR's internal wiring has ensured this compliance. Furthermore, if the PEN conductor is broken, dangerous voltages to earth may exist at the consumer's earth terminal.

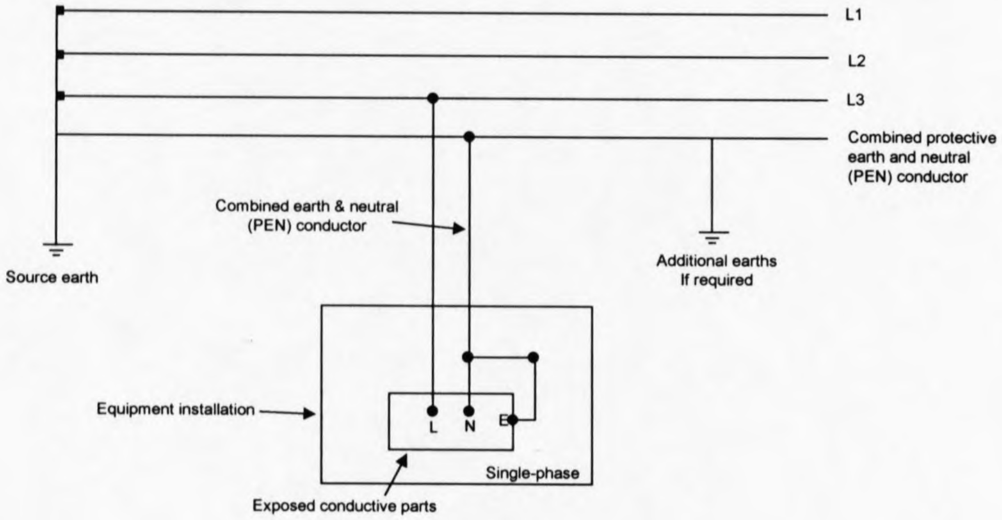


Fig. 60: CNE earthing system [37]

In order to restore the earth leakage operation at the customer's distribution box end, the customer's earthing terminal at the point of supply must be connected to the PEN conductor on the supply side of the circuit-breaker. A typical CNE earthing system is illustrated in Fig. 60.

3.3.13 Appropriate technology index for LV feeders

With reference to the technology comparison technique successfully applied to MV feeders in section 2.7, the ATI for long LV feeders with voltage compensation by means of EVRs will be determined. As listed in Table 9, most LV networks make use of 35 mm^2 ABC as the main LV backbone with 4 mm^2 concentric Airdac for the service connections. In order to increase the load reach of the LV feeder, the conductor size could have been increased compared to the addition of EVRs on a 35 mm^2 ABC feeder. In order to determine the optimum solution, the ATI technique was followed. Examples of the spreadsheets that were compiled to calculate the overall ATI of each study per project, are provided in Appendix A.

Table 25: Typical dual-phase LV feeder cost per metre – New

Description	New [R/m]
Aerial bundled conductor (3C XLPE 70mm^2)	17
9m wood pole (160mm top diameter)	5.23
Structure hardware	0.60
LV stays	1.37
Service connection box (1 - 4)	2.19
10% contingency	2.64
Labour	17.42
Total	**46.45**

With reference to the example of an MV / LV network as shown in Fig. 45 with LV feeder costs for both ABC sizes (35 and 70 mm^2) as given in Table 20 and Table 25, the ATI of both options was calculated using equation (2.5). The results of this study for two sets of weighting factors are presented in Fig. 61 and Fig. 62.

Table 26: Summary of KPIs and weighting factors for LV feeder options

			KPIs and weighting factors					
			Life-cycle cost [R]		Line cost per ampacity rating [R/km/MVA]		Voltage drop [p.u.]	
Study	Load growth [%]	Annual load factor	w1	K1	w2	K2	w4	K4
1 Fig. 61	3	0.3	0.8	Upper (0) = R115,000 Lower (10) = R30,000 Median (3) = R89,500	0.1	Upper (0) = 400 Lower (10) = 200 Median (3) = 340	0.1	Upper (0) = 0.25 Lower (10) =0.00 Median (3) = 0.18
2 Fig. 62	3	0.3	0.6	Upper (0) = R115,000 Lower (10) = R30,000 Median (3) = R89,500	0.3	Upper (0) = 400 Lower (10) = 200 Median (3) = 340	0.1	Upper (0) = 0.25 Lower (10) =0.00 Median (3) = 0.18

Table 26 provides a summary of the KPIs and weighting factors for the two case studies. The upper (score of 0), lower (score of 10) and median (score of 3) limits for each KPI are as indicated. As both conductor options require compensation in the form of EVRs, the KPI for voltage drop, *K4*, defaults to the top score of 10 for both options. The sensitivity of the weighting factors on the total ATI score is clearly noticeable in Fig. 61 and Fig. 62.

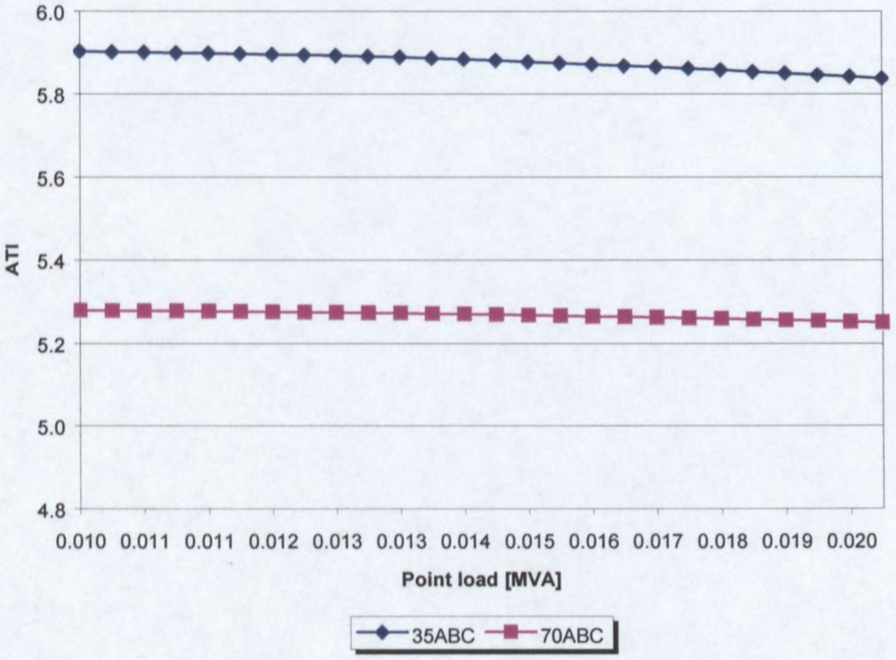


Fig. 61: ATI of compensated LV network with weighting factors (0.5, 0.1, 0.4)

The results of Fig. 61 indicate that with life-cycle cost (sum of capital cost and losses) being weighted the most important (50%), the 35 mm^2 ABC feeder option would be the best technology choice. This is true even though additional capital costs were incurred with the installation of 3 additional service connection box-mounted EVRs due to the need for more compensation at upstream node points.

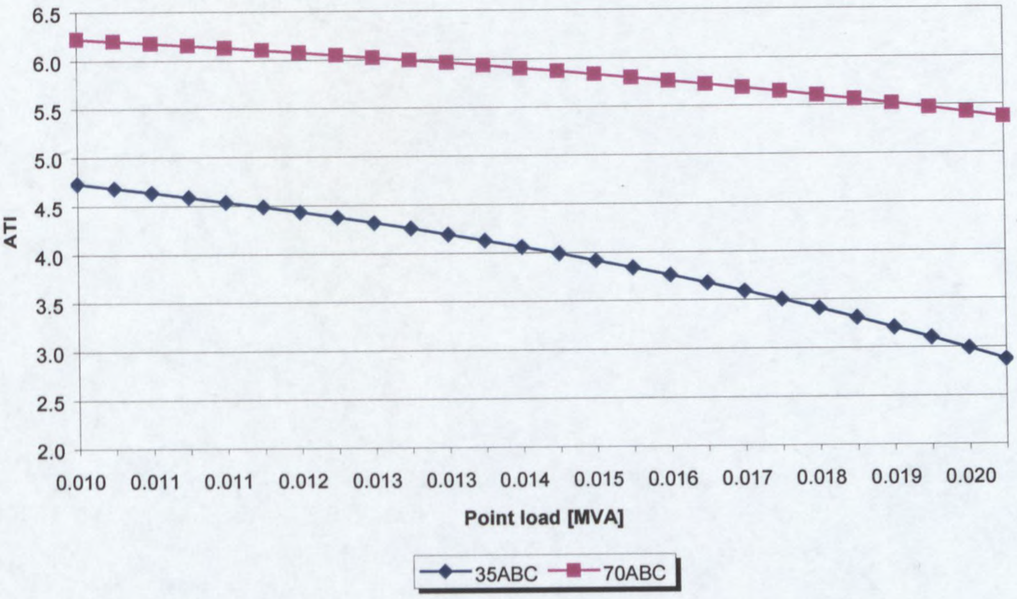


Fig. 62: ATI of compensated LV network with weighting factors (0.3, 0.3, 0.4)

Should the importance of the current carrying capacity be increased from 10 to 30%, the overall rating of 70 mm^2 ABC improves and even out-performs the 35 mm^2 conductor as depicted in Fig. 62. However, due to the nature of the load being only lightly loaded networks initially, this result should only be considered as a possible upgrade path as compared to the introduction of a second transformer zone. The only difference is that a second 35 mm^2 conductor would be connected in parallel to the existing conductor and not restringing with a 70 mm^2 conductor.

This study concludes the section of the EVR application. In the next section, focus will be given to cost effective supply- and end-use technologies in providing single-phase supplies to rural areas, whilst still maintaining the ability to supply small to medium sized motor loads.

3.4 Single-phase supplies in rural areas

Eskom is increasing its rural customer base by providing them with the option of single-phase electricity for agricultural farming activities in the form of phase-phase MV line extensions off three-phase backbone systems or the building of SWER networks. This arrangement allows Eskom to provide electricity to its customers at a reduced cost (lower monthly basic charge). These customers often develop the need to operate medium to large electrical motors for the sole purpose of water pumping and mixing / milling activities. At this point the customer has the choice to request a three-phase supply at a substantial cost or employ single-phase technology at a fraction of the cost. The onus is on the customer to determine his requirements and compare both costs before selecting the option that meets his needs.

3.4.1 Conversion to electric motors

The opportunity now exists even more than ever before to evaluate some of the farming activities such as the mixing and milling of animal feed on the farm that were traditionally performed by means of a diesel tractor and hammer mill combination. Many studies that were previously conducted by Agrelek, Eskom's free advisory service to farmers, have proven that an electric hammer mill can save the farmer as much as 60% on milling costs (capital costs included) [38]. A simple cost study can be carried out to evaluate the energy cost saving on diesel versus electricity. The results are given in Table 27.

Table 27: Energy cost comparison of diesel and electricity

Energy source	Energy content per unit [kWh]	Energy cost per unit [R / unit]	Process efficiency [%]	Cost per kWh [R / kWh]
Diesel	10.7 per litre	3.30 per litre	30	1.03
Electricity	1	0.22 per kWh	90	0.24

The results show that electrical energy is by far (ratio of more than four times) the most cost-effective form of energy when compared to diesel fuel. These activities (milling and mixing of animal feed) combined with other higher power needs, such as irrigation, makes it imperative for the successful farmer to be supplied with cost-effective line technologies off the Eskom network.

3.4.2 Meeting the needs of high power loads

The power requirements for irrigation purposes are often overestimated, resulting in the false impression that a three-phase supply is the minimum supply required. Incorrect sizing of the motor loads and those standard sizes that industry offers further aggravates this wrong perception. The motor power rating for a pump is given by:

$$P[kW] = \frac{9.8 \times \mathit{flow\ rate}\,[m^3/s] \times \mathit{pump\ head}\,[m]}{\mathit{Efficiency}\,[pu]} \tag{3.7}$$

One can clearly deduce from (3.7) and Fig. 63 that, for example, if a flow rate of 10 000 litres per hour at a borehole depth of 45 metres (typically 30 to 60 metres in Karoo region) is required, a motor rating of only 1.5 kW is needed.

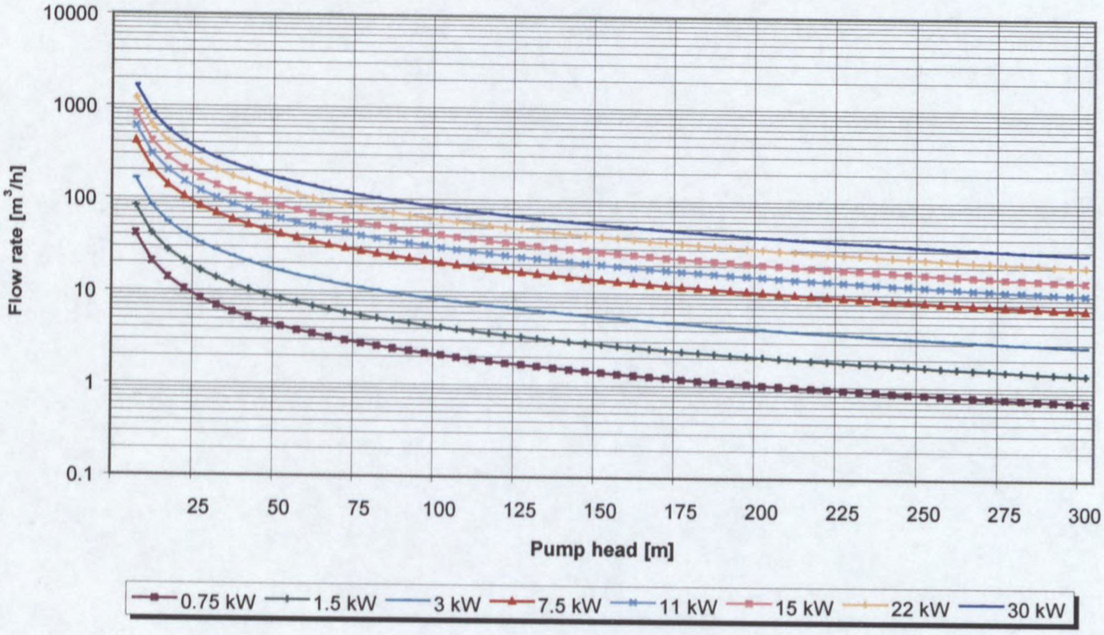


Fig. 63: Electric motor and water pump characteristics

However, there are farming activities such as operating hammer mills that do require higher motor ratings. These requirements can be met in the following ways [26]:

- Large-size single-phase motors (> 2.2 kW)
- Static and rotary phase converters to supply three-phase motor loads
- Power electronic single- to three-phase converters
- Written-pole synchronous motors (not discussed as technology, as it is not supported locally and the imported motor cost is very high).

In order to get a good understanding of these exact capacity needs, a table was compiled listing typical hammer mill models with their power requirements and work capacity ratings as shown in Table 28. Three different end-use technologies were also compared, i.e. large single-phase motor (22 kW) supplied off dual-phase LV network, standard rewound three-phase motor with electronic phase converter (22 kW) supplied off dual-phase LV network and two standard three-phase motor sizes (37 and 45 kW) supplied off three-phase LV network.

Table 28: Typical hammer mill and electric motor installation capacities

	Cost of hammer mill (model) and motor size installation [R]			
	M16 & 22 kW Single-phase	M16 & 22 kW Three-phase	PC24 & 37 kW Three-phase	M36 & 45 kW Three-phase
Hammer mill	7,100	7,100	9,500	12,100
Electric motor	19,004	2,819 (rewound)	13,670	15,930
Phase converter	Not required	11,600	Not required	Not required
Star-delta starter	Not required	Not required	2,595	2,990
Frame and pulleys	1,750	1,750	2,200	2,400
Total Price	27,854	23,269	27,965	33,420
	Work capacity [Ton / h]			
Maize meal	1	1	1.5	2
Broken mealies	8	8	12	15
Lucerne	2	2	4	6

Typical hammer mill and electric motor installation costs are provided in Table 28. The table shows that even for direct end-use technology comparisons the total installation price and capacities are within the same range. The only implication would be that in certain cases the production rate is halved. Then again, when compared to the major saving on supply technology cost, this penalty is negligible.

3.4.3 Large-size single-phase motors

The development of high-power single-phase electric motors has eliminated the need for costly three-phase power to be provided to those customers who require high-power electric motors. Single-phase motors up to 22 kW with favourable starting torque characteristics are now readily available [30].

The single-phase motor uses a split-phase winding and a capacitor-start, capacitor-run technique to start the motor. The split-phase winding has two components which are referred to as the main and auxiliary winding, while the two sets of capacitors are used for starting and running respectively. An added benefit of the capacitors is that the power factor of the machine always operates close to unity, which results in less current drawn by the machine. This means lower operating costs for customers paying for peak kVA consumed.

Single-phase motors have previously been available in sizes up to 7.5 kW, but this has now been increased to 22 kW with the development of the high-power motor (refer Fig. 65).

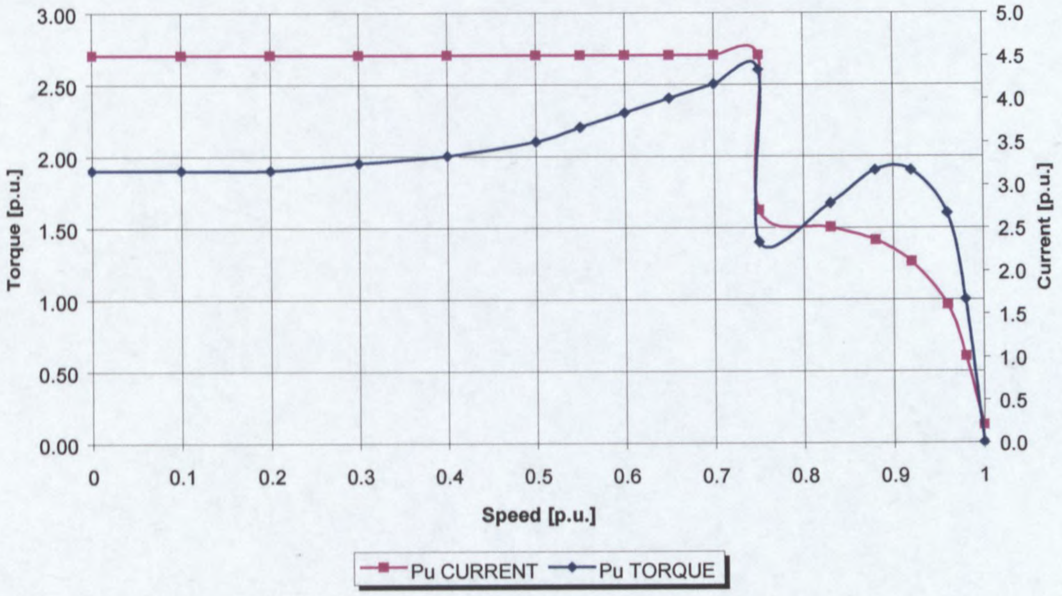


Fig. 64: Typical speed torque curve of a 22 kW single-phase motor [30]

The single-phase 22 kW motor has a starting torque of 261 N.m and a run-up torque of 1.8 p.u (refer Fig. 64). This compares favourably with that of a similarly rated three-phase motor. Furthermore, the motor has been designed for dual-phase low-voltage applications so that the power transferred across it is greater than would be the case with single-phase. A secondary benefit is a reduction in the voltage drop between the distribution transformer and the motor terminals.

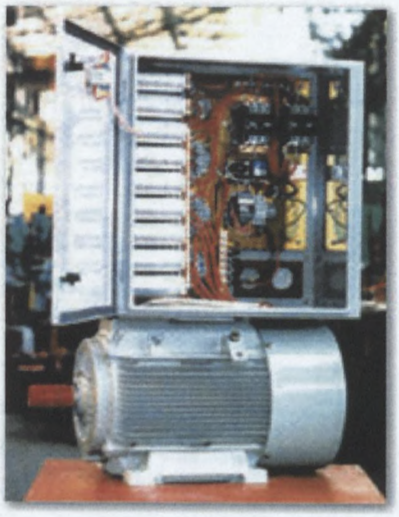


Fig. 65: Large-size single-phase motor and starter (22 kW) [30]

More detail on the commercially available *Alstom* large size single-phase motors is attached in Appendix E.

3.4.4 Static and rotary phase converters to supply three-phase motor loads

Single- to three-phase converters allow three-phase motors to operate off single-phase supplies. Units in the range of 0.2kW to 165 kW are available. The output of the static and rotary converter is 230 V phase-phase and requires a step-up transformer to obtain 400 V.

3.4.4.1 Static phase converter

The static phase converter is the most cost-effective system and uses capacitors to induce voltage and current to the un-energised phase of the motor. The static converter is only capable of operating a single-speed, non-reversing three-phase motor. The three-phase motor and the static converter that is used to operate the motor must both have the same power rating. The three-phase motors that operate via static converter must be derated. The absence of a true generated phase to the motor results in the loss of power. Typical sizes of the static converter are 0.2 kW to 37.5 kW.

Main disadvantages of static converters are:

- The output of the static converter is not balanced;
- The noise and vibration of the motor are higher with the static converter;
- The static converters are designed for single-motor applications;
- Static converters are generally suited for applications requiring a low starting torque, e.g. machine tools.

3.4.4.2 Rotary phase converter

The rotary converter was developed 35 years ago and consists of a rotating machine using a single-phase source to generate a three-phase output (refer Fig. 66). The machine is started as a single-phase motor using extra starting capacitors and is switched-out when the motor reaches operating speed. A field is induced in the squirrel-cage rotor. The prime mover of the rotor is the single-phase supply, as this drives the rotor in motoring mode. The rotating magnetic field, coupled to the rotor, induces voltages in the extra stator windings (120° shift). The resultant effect is that of a three-phase voltage generator.

In addition, the sum of the motors operated as a rotary converter would be substantially higher than the largest motor rating of the converter. This is made possible as each motor in turn acts as a converter. The motor that is started later in the system has a higher starting torque. So the largest motor can, if necessary, be started last.

Features of the rotary converter are [23]:

- Rotary converters are suited to rotating and non-rotating loads;
- A single converter can operate multiple motors of different power ratings. In addition, the sum of the motors operated could be substantially larger than the largest motor rating of the converter;
- Under full load conditions, the output of the converter is balanced across all three phases;
- The output of the converter is suitable from a fraction of a kW up to the converter rating, with no adjustment required at the converter in order to suit the load;
- The total kW capacity may reach 1.5 to 2 times the largest motor size.

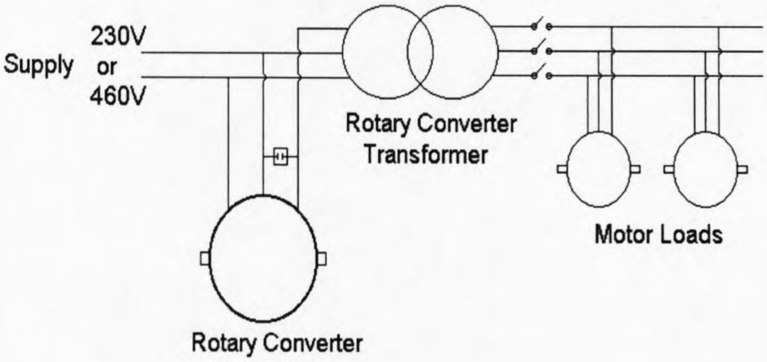


Fig. 66: Rotary phase converter concept [41]

3.4.5 Power electronic single- to three-phase converters

The electro-mechanical phase converters described in the preceding section as well as electronic phase converters (EPC) are means of supplying a three-phase voltage from a single-phase supply. These technologies combined with the large-size single-phase motors are cost-effective end-use technologies to meet the needs of medium-power loads (up to 30 kW) of the farming industry in rural areas.

3.4.5.1 Field installations

One of the recent, very successful installations of three EPCs installed at a pilot site on the farm Alexanderkraal in the Karoo is shown in Fig. 67. The pilot site chosen offered an ideal application of the EPC since the farmer previously generated (diesel generator sets) his own three-phase supply and operated a three-phase MV and LV network. However, it was not cost effective for this particular farming community to be supplied with three-phase Eskom grid power due to its remoteness and SWER was the only cost-effective supply technology possible. That unfortunately left the farmer with the dilemma of having acquired three-phase motors (2*11 kW and 1*5.5 kW) already and it wasn't possible to connect them to the SWER single-phase supply. Installing EPCs at each motor load solved this problem. Optimum use (paralleling of all three motor loads onto one drive) of the drive capacity was unfortunately not possible due to the long distances between each borehole.

Fig. 67: 32 kVA single- to three-phase converter installed in stubby kiosk

This end-use technology made it possible for the farmer to continue with his normal farming activities whilst still maintaining a good balance in terms of operating and maintenance costs. As already proven in section 3.4.1, major savings on operating cost can be achieved.

3.4.5.2 EPC concept

The development of the electronic phase converter was specifically focused on addressing this possible market niche. The capacity rating, input voltage, protection system and control logics were standardised, knowing that the Eskom standard dual-phase LV transformer has a rating of 32 kVA and the typical motor loads would not exceed 30 kW (on average 7.5 and 11 kW) [30]. Furthermore, it is also possible to raise direct bus voltage sufficiently to meet these higher power ratings due to the phase-phase LV input voltage of 460V. This in turn relates to lower starting currents and less voltage drop over the supply cable. Thus the very stringent requirement of ensuring that the voltage at the motor terminals does not drop below 85% of nominal for motor starting conditions becomes less important and higher network source impedances are allowed. A schematic of the supply and end-use technologies for the EPC application is shown in Fig. 68.

Due to the soft-starting capabilities (voltage and frequency control) of the EPC, no current-limiting starters (e.g. star-delta starters) are required and direct-on-line starting is possible.

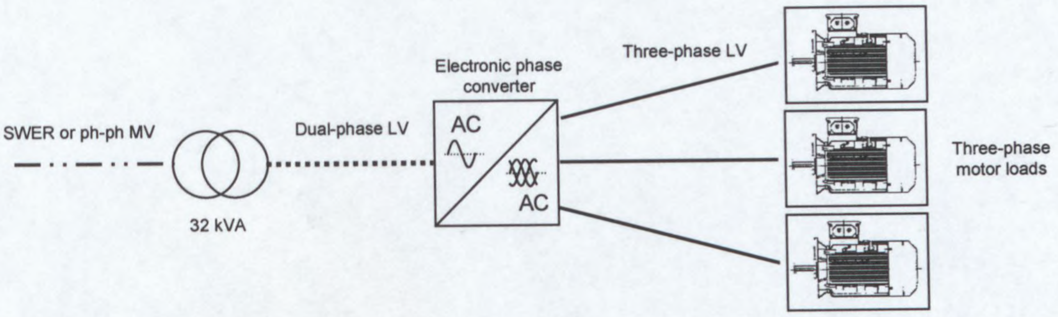


Fig. 68: Schematic of supply- and end-use technologies

The converter has a current rating of approximately 70 A_{RMS}. A 30 kW motor is started by slowly increasing the speed of the motor by changing the frequency and voltage supplied to the stator winding. Due to the fact that torque is independent of frequency, it is possible to start the motor at any required torque level up to the rated torque (196 Nm) of the motor (refer Fig. 69).

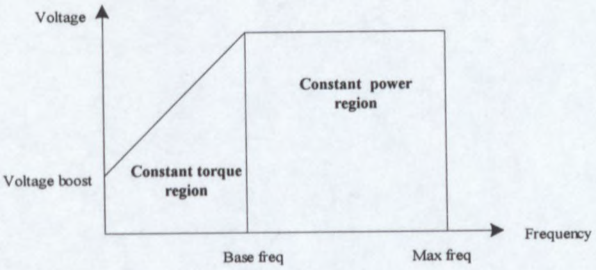


Fig. 69: Scalar control of three-phase induction motor [52]

This ability is of extreme importance as it is now possible to overcome the initial load torque without the need to drastically increase the starting current. In order to "force" the current through the series impedance, the machine is started at an initial offset voltage. Should the delivered torque increase to more than twice the rated torque, thus impeding on the limit of the pull-out torque of the motor, the drive (converter) will trip. The converter has sufficient capacity in terms of current (limited to its rating) and the rectified dual-phase input voltage provides sufficient bus voltage to "force" the current. It is for this very reason that it is not possible to connect the EPC to a single-phase LV supply.

Table 29: Standard (STD) three-phase and large single-phase (LSP) motor ratings [55]

Rated output [kW]	Rated full load current [A]		Rated torque [Nm]		Rated efficiency at full load [%]		Power factor at full load [p.u.]		Locked rotor current [p.u.]		Locked rotor torque [p.u.]		Pull out torque [p.u.]	
	STD	LSP	STD	LSP	STD	LSP	STD	LSP	STD	LSP	STD	LSP	STD	LSP
4	8.7	10	26.8	26.3	83	85	0.80	0.98	6.5	5.5	2.5	2.2	3.0	1.9
7.5	15.5	20	50.1	49.4	86	85	0.81	0.98	6.5	4.5	2.6	1.9	3.3	1.7
11	22.5	32	72.5	71.7	88	87	0.85	0.98	6.45	4.5	2.4	1.9	2.6	1.9
22	43.5	56	144	142	91	89	0.80	0.97	7.65	4.5	2.45	1.9	2.90	1.9
30	58	N/A	196	N/A	91.5	N/A	0.86	N/A	6.9	N/A	2.55	N/A	2.60	N/A

Table 29 allows a direct comparison of motor ratings (large single-phase and standard three-phase). From the table it is clear that the ratings of the large single-phase motors compare favourably with those of standard three-phase motors. The table also provides details regarding direct-on-line starting currents for various three-phase motor sizes. The EPC provides the ability for three-phase motors to be started at low initial current and torque levels (< 1 p.u.), as this is mostly determined by the load and not by the inertia of the rotor. There is no need for the run-up torque to exceed the rated torque of the motor as the speed is gradually increased in order to overcome the rotor inertia.

Furthermore, automatic restart of the motor following short duration power outages is also possible as this function forms part of the contactor control circuitry.

The design details of the electronic phase converter are fully covered in [52] and a brief summary of the technical specifications are attached in Appendix C.

3.4.5.3 Cost comparison to large single-phase motor

In order to compare the direct costs of the two end-use technologies (large single-phase motor / starter combination and the EPC and new / rewound three-phase motor) with the three-phase motor and starter being used as benchmark, Fig. 70 was compiled. Detailed costs are summated in Appendix F. From the graph it is clear that at lower ratings (≤ 7.5 kW) the large single-phase motor and starter combination would be the most cost-effective technology to be offered to the customer. This can mostly be attributed to the fact that the capacity rating of the EPC was initially focussed on the maximum possible rating of a dual-phase transformer. However, as is the case with the rotary phase converters, more than one motor load can be connected to a single EPC (refer Fig. 68), thus effectively reducing the cost by more than half.

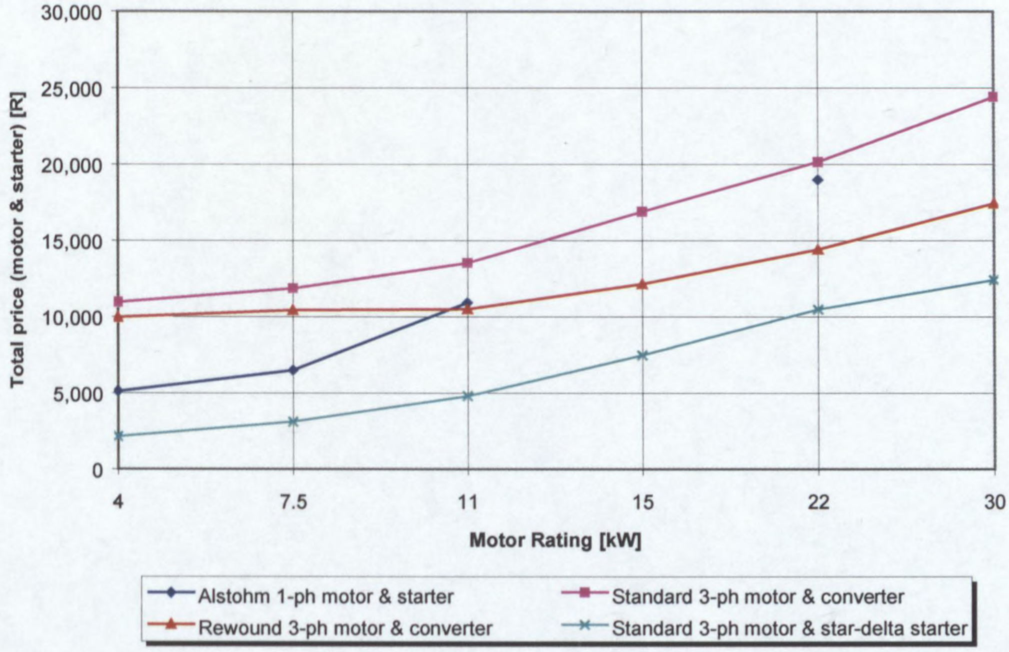


Fig. 70: Electric motor and starter price comparison

Table 30 compares the price of the mentioned end-use technologies to the cost associated with providing the MV supply. Again the cost associated with a standard three-phase supply (R60 / m) and three-phase motor and starter was used as benchmark. The MV line technologies costs are as discussed previously in section 1.3.

By comparing the cost associated with a standard three-phase motor and starter (normally much cheaper than either the EPC or large single-phase motor installation) and the cost for providing the power supply with the alternative motor or converter technology and its supply technology, it is possible to determine a cost break-even point measured in equivalent MV line length.

Table 30: Supply- and end-use technology cost comparison for medium-capacity motor loads [41]

				Equivalent line length [m]			
Installation cost [R]				Large 1ϕ motor and starter		EPC and rewound 3ϕ motor	
Motor rating [kW}	Large 1ϕ motor and starter	EPC and rewound 3ϕ motor	3ϕ motor and starter	ph-ph	SWER	ph-ph	SWER
4	5,130	9,969	2,161	148	85	390	223
7.5	6,515	10,423	3,121	170	97	365	209
11	10,918	10,488	5,964	248	142	226	129
22	19,004	14,419	10,494	426	243	196	112

For example, if the 22 kW motor load option is chosen, the cost difference to a 3ϕ motor / starter combination compared to the EPC option would be R3,925 (R14,419 – R10,494). In turn the supply line technology (say, SWER vs three-phase MV) cost difference would be R35 / m (R60 / m – R25 / m). This comparison amounts to an equivalent supply line break-even distance of 112 m (R3,925 / R35 per metre). The table has been completed to indicate the rest of the comparisons.

A very important deduction can be made from the above, namely that very short equivalent line lengths (100 to 400 metres) for these alternative supply line technologies are required to counter the additional cost associated with the end-use technologies for medium-capacity motor loads. However, it should be noted that the SWER line technology costs have been averaged and are only cost-effective for supply line distances greater than 10 kilometres. Similarly the cost effective load reach ability of phase-phase MV is limited to distances up to 10 kilometres when compared with SWER (refer section 2.5.3).

3.5 Summary

This chapter initially focussed on the concepts of power system conditioning and motivated the reasons for choosing transistor-based, in-line voltage regulators and phase converters. Comparative studies were then performed to identify possible application opportunities for these devices. At the same time the influence on network integration parameters such as dynamic response to sudden load changes, LV protection co-ordination and earthing methods, were investigated.

It has been shown that alternative line technologies in combination with the EVR device can be one of the long-awaited hybrids of technology applications that can broaden the scope of possible network solutions. The Distribution Network Planner now has more options to investigate, although as indicated, this still requires careful planning as the applications are not as simplistic as they may seem at first glance. It is also possible to apply the EVR device as a "boot strapping" tool for network upgrades in excess of 300 metres. Further savings are possible should better cost per capacity ratios be achieved in the industrialisation phase of the EVR.

It was also concluded that the single-phase EVR proves to be more cost-effective in the SCB than ED mode of application, mostly due to its high cost per capacity ratio for smaller loads and should thus be considered as an alternative means to increase the load reach of LV feeders. As was proven, the only cost effective, technically sound solution of expanding grid connected supplies to low-density areas (stand sizes greater than 5000 m^2) with service connection boxes spaced at intervals of 140 metres or more, is by means of SCB-mounted EVRs. Furthermore, the transformer-mounted EVR is the most cost effective means of MV voltage regulation for small- to medium-sized point loads (four 24 kVA (single-phase LV), four 48 kVA (dual-phase LV) or three 75 kVA (three-phase LV) units), when compared with an autotransformer voltage regulator.

The needs of rural agricultural customers for three-phase supplies to motor loads were also addressed and it was shown that the cost "penalty" in providing an end-use bridging technology is nullified with the major savings in MV line cost.

The first prototype EVR (5 kVA capacity) has just been completed by the University of Stellenbosch (refer Fig. 71). The EVR is currently undergoing functional tests to the requirements as stipulated by this thesis. Further development work will be focussing on the correct sizing, housing design, operator interface, surge protection and maintenance friendly plug-in interface systems as to assist with faultfinding and repairs.

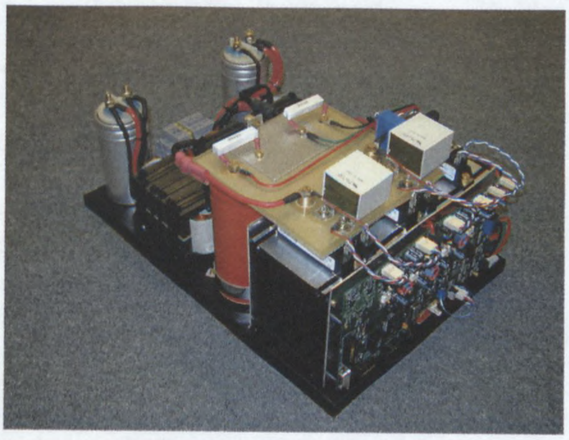


Fig. 71: EVR40-20 (5 kVA single-phase electronic voltage regulator)

A similar product to the EVR, though not a power electronic device (electro-mechanically switched transformer tap positions), is currently commercially available. The so-called electronic voltage stabiliser from *Clearline* has managed to reduce its cost to R1,000 / kVA. It is estimated that through mass production the EVR can be manufactured at an even lower price with higher degrees of reliability, as no mechanical switching components are required. More detail on the electronic voltage stabiliser from *Clearline* is provided in Appendix D.

Due to the unique application opportunities of the electronic voltage regulator in support for voltage control on long LV networks, a patent application was completed and is currently being evaluated for possible registration.

Finally, a paper on electronic voltage regulation of MV and LV power distribution networks was written and is due for publication in the November / December 2000 issue of "Energize"[54].

Chapter 4

Conclusions

This final chapter comments on the work presented in the thesis. It starts with the specific contributions made by this study, followed by a summary of concluding remarks. Finally the thesis ends with some suggestions for possible future research.

4.1 Contributions made by this study

- *A survey was conducted to determine the greatest challenges for the electricity supply industry for the next decade.* Chapter 1 started with the background to one of the main problems Eskom and municipalities currently face, i.e. electrification of a vast number of households and specifically in the deep rural areas. The challenge for the electricity suppliers is to bring electricity to these people, specifically those in the rural areas, where more than 50% (2 million) of the dwellings are not electrified. An idea of the cost implications was given and it was indicated that a paradigm shift from using three-phase high-capacity lines to single-phase lines is crucial.

- *Defining current cost targets and identification of possible cost-saving opportunities.* The first objective was to identify possible cost-saving opportunities for rural electrification with a specific focus on low population density (<200 stands per square kilometre) and low power consumption (2.5 A load limiting supplies) areas. The second objective was to address the needs of customers requiring three-phase supplies in remote rural areas for agricultural farming activities.

- *Stretching the load reach abilities of MV and LV lines by increasing the voltage regulation margin from ± 10% to ± 40%.* Chapter 2 focused on line technologies and addressed issues of importance for "stretching the network" beyond previously set design criteria.

- *Developing practical application opportunities for electronic voltage compensation.* Chapter 3 focused on the support of lines stretched beyond their previously accepted limits. One of the main objectives was to identify practical application opportunities of the EVR in support of the existing electrification technology options. These applications were proven to be technically sound and the most cost-effective solution available.

- *Evaluated the implications of network integration parameters such as dynamic response to sudden load changes, LV protection co-ordination and earthing methods.* The importance of dynamic response to voltage changes of the compensating device was highlighted and the use of any mechanical switched voltage regulator was ruled out. In order for the EVRs to meet the protection co-ordination requirements of the LV network, specific preset time-current curves were recommended. The last integration parameter investigated was to ensure that the continuity of the PEN conductor is never interrupted.

- *A technology index was developed to compare various line technologies and to rank each technology relatively on a per project basis.* The result of this contribution was the ATI model, which was developed to aid as an evaluation technique in deciding on the best technology choice for each network supply option.

- *Addressed the customer requirements for three-phase supplies in remote rural areas.* It was proven in Chapter 3 that it is now possible to provide remote rural agricultural customers with single-phase supplies supported by end-use technologies in the form of electronic phase converters that eliminate the need for three-phase supplies.

4.2 Conclusions of this study

- It has been shown that alternative line technologies in combination with the EVR device can be one of the long-awaited hybrids of technology applications that can broaden the scope of possible network solutions. The Distribution Network Planner now has more options to investigate, although as indicated, this still requires careful planning as the applications are not as simplistic as they may seem at first glance. It is also possible to apply the EVR device as a “boot strapping” tool for network upgrades in excess of 300 metres. Further savings are possible should better cost per capacity ratios be achieved in the industrialisation phase of the EVR. It is of utmost importance that all the necessary support to be given by all role-players within Eskom and Industry to ensure that the industrialisation phase of the EVR is made possible within a very short space of time. Without this support the cost saving opportunities identified will go wasted.

It was also concluded that the single-phase EVR proves to be more cost-effective in the SCB than ED mode of application, mostly due to its high cost per capacity ratio for smaller loads and should thus be considered as an alternative means to increase the load reach of LV feeders. As was proven, the only cost effective, technically sound solution of expanding grid connected supplies to low-density areas (stand sizes greater than 5000 m^2) with service connection boxes spaced at intervals of 140 metres or more, is by means of SCB-mounted EVRs. Furthermore, the transformer-mounted EVR is the most cost effective means of MV voltage regulation for small- to medium-sized point loads (four 24 kVA (single-phase LV), four 48 kVA (dual-phase LV) or three 75 kVA (three-phase LV) units), when compared with an autotransformer voltage regulator.

- The needs of rural agricultural customers for three-phase supplies to motor loads were also addressed and it was shown that the cost "penalty" in providing an end-use bridging technology is nullified with the major savings in MV line cost.

- Finally, the ATI model proved that it is possible to develop a technology index to compare various technologies objectively on a per project basis and that realistic results can be achieved. The model is recommended for use by planners for all network option comparisons.

4.3 Possibilities for future studies

The technology reach per load served for the following technologies needs to be determined (refer Fig. 72):

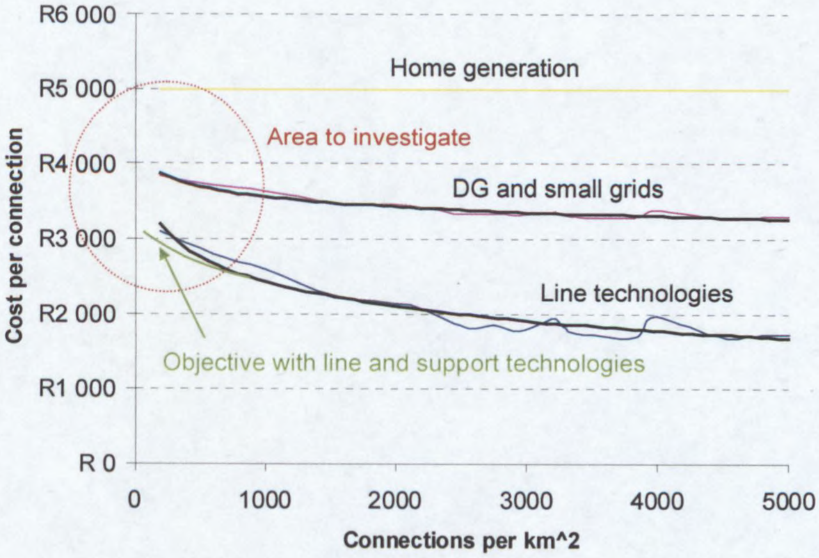


Fig. 72: Technology reach per load served

4.3.1 HVDC "light" (3 kV and above) and DC SWER

In applying this technology, the 10% voltage regulation problem could become something of the past. The inverter at the load end can cater for up to 30 - 40% volt drop with no commutation problems (transistor-based technology).

Another possible solution is DC SWER lines. The advantage is that no telecommunications interference may exist as a result of the ground current. This technology can be combined with special conductor types such as Aluminium Clad Steel (ACS). By making maximum use of this higher steel content, longer line spans can be achieved over undulating terrain, thus reducing costs.

4.3.2 600/1000 V LV networks with EVRs

The impact of changing the transformer secondary voltage to 577 V (phase-neutral) with standard 600/1000 V rated ABC conductors, thus providing a much higher direct bus voltage to the EVR, should be measured. This could increase the load-reach capabilities of supplying higher-demand customers.

4.3.3 Grid-connected DC supplies

The research question to answer is whether it would be cost effective to supply low-demand customers with grid-connected DC power via service connection box-mounted rectifiers. The advantages are 24-hour energy source availability at very low required Ampere ratings. The 12 DC batteries can then also be used as back-up during power outages.

References

[1] RG Stephen, "Business Plan 1999-2003 – Strategies and targets for WUC", 24 July 1998

[2] Eskom, "Eskom's Tariffs & Charges for 1999", January 1999

[3] Eskom, "Eskom's Tariffs & Charges for 2000", January 2000

[4] Eskom, "Eskom's Tariffs & Charges for 1999 – Additional information", January 1999

[5] H. Lee Willis, "Power Distribution Planning Reference Book", 1997, pp 13 - 19

[6] Westinghouse Electric Corporation, *Electrical Transmission and Distribution Reference Book*, East Pittsburgh, Pennsylvania, 1964, pp 270 - 272

[7] P Crowdy, "Technical Bulletin (99TB024) - Operating voltages for power transformers", Eskom Distribution Technology Group, February 1998

[8] P Crowdy, "Technical Bulletin (98TB004) – Effect of MV voltage on cost per connection", Eskom Distribution Technology Group, August 1999

[9] MC Mpye, "Energy losses management directive", Eskom Energy Management Group, April 1999

[10] N.G. Hingorani, RG Stephen, N Sudja, C Nietsch, M Weinhold "Use of Power Electronics for Rural Electrification," Cigré 14-202, Session 1998.

[11] J Jordaan, "Conductor Optimisation", Eskom Transmission Line Technology department, June 1996

[12] Regulation 9 of Electricity Act, 1987 (as amended in January 1996)

[13] J. de Lange, B. Meyer, private discussions

[14] R. Stephen, H.J. Beukes, B. Meyer, private discussions

[15] R. G. Stephen, "Electrification and Innovative Cost reduction Methods," *Electricity and Control*, pp. 7-11, Aug. 1996.

[16] National Electricity Regulator, "Updated Electrification statistics for 1999", Internet Web site: www.ner.org.za/

[17] I.A. Ferguson, "Distribution Standard, Part 1: Planning and design, Section 12: Electrification design - rural", Eskom Distribution Technology Group, February 2000

[18] I.A. Ferguson, "Distribution Standard, Part 1: Planning guidelines, Section 42: Tool - Electrification technology selection", Eskom Distribution Technology Group, January 2000

[19] G. Stanford, "Distribution Specification, Phase conductor for Distribution lines", Eskom Distribution Technology Group, November 1999

[20] G. Stanford, "Distribution Standard, Part 6: Sub-transmission lines, Section 2: Conductors", Eskom Distribution Technology Group, September 1999

[21] G. Stanford, "Eskom Standard, Determination of conductor current ratings in Eskom", Eskom Distribution Technology Group, June 2000

[22] N.G. Hingorani, "Flexible AC Transmission", IEEE Spectrum, pp 40 – 45, April 1993

[23] T. Leibold and J. Marx, "Field test report: roto-phase converter," 18 February 1998.

[24] W. Swiegers, H.J. Beukes, G.B. Lee, C. Barnard and J.H.R. Enslin, "Industrialisation of power electronic devices for USE applications," *ESKOM TRI Final Research Report TRR/E/97/EL246,* March 1999.

[25] R. Smit, Private discussions on distribution planning.

[26] D. Padyachi, Private discussions on distribution technologies.

[27] H.J. Geldenhuys, Private discussions on line technologies.

[28] B. McLaren, Private discussion on current electrification indicators pertaining to Eastern Cape (Transkei)

[29] NRS 048, "Electricity supply - quality of supply," South African Bureau of Standards, Pretoria, 1996.

[30] D. Steenkamp, "Large Single Phase Squirrel cage Induction motors", Alstom SA, 2000

[31] "White Paper on Energy Policy for the Republic of South Africa", December 1998

[32] IEC 60354, "Loading guide for Oil-immersed Transformers" International European Committee, 1991

[33] W. Swiegers, H.J. Beukes, G.B. Lee and J.H.R. Enslin, "Industrialisation of power electronic devices for USE applications," ESKOM TRI Research Report RES/RR/99/00138, October 1999

[34] W.J. Cowan, "RAPS Design Manual", EDRC, University of Cape Town, 1995

[35] I.A. Ferguson, "Distribution Standard, Part 1: Planning Guidelines, Section 27: Voltage drop apportionment", Eskom Distribution Technology Group, February 2000

[36] G.A. Whyte, "Distribution Standard, Part 3: Low voltage reticulation, Section 4: Low voltage protection philosophy for low consumption areas", Eskom Distribution Technology Group, August 1997

[37] S.J. van Zyl, "Distribution Standard, Part 2: Earthing, Section 1: MV and LV reticulation earthing", Eskom Distribution Technology Group, July 1999

[38] Agrelek case study, "Electrical milling and mixing of animal feed", Eskom Distribution, March 1993

[39] G.K. Vosloo, "Kylemore Distribution Network Development Plan", 22 April 1999

[40] R.F. Smit, "Models on comparison of conductor costs and losses", 5 July 1999

[41] H. J. Geldenhuys, "Presentation on Large motors an single phase supplies", 3 July 1993

[42] S. Thiel, "The Universal Semiconductor Concept", Masters thesis, University of Stellenbosch, page 33, 1998

[43] T.J.E. Miller, "Reactive Power Control in Electric Systems", John Wiley & Sons, New York, 1982

[44] C. Clark, "Distribution Specification for large power transformers up to 132 kV, in the rating range of 2.5 MVA to 80 MVA", Eskom Distribution Technology Group, May 1999

[45] I.J.J. van Aarde, "Distribution Specification for pole-mounted single-phase step automatic voltage regulators with integrated remote communication capability", Eskom Distribution Technology Group, December 1999

[46] R. Branfield, "Distribution Standard, Part 4: Medium voltage reticulation, Section 0: General information and requirements for overhead lines up to 33 kV with conductors up to Hare/Oak", Eskom Distribution Technology Group, September 1998

[47] D.R. Theron, "Distribution Specification for oil-immersed power transformers up to 2 MVA and 33 kV", Eskom Distribution Technology Group, November 1998

[48] I.A. Ferguson, "Distribution Standard, Part 1: Planning Guidelines, Section 28: Book – LV feeder voltage drop calculation methods", Eskom Distribution Technology Group, February 2000

[49] Dr J. Beukes, Prof J.H.R. Enslin, R Stephen, "Distribution Planning and Design course – course notes (part 1)", October 1999

[50] D. Ramsbottom, "Jagersbos Planning Report", 13 January 2000

[51] NRS 034-1, "Electricity distribution – guidelines for the provision of electrical distribution networks in residential areas, Part 1: Planning and design of distribution", South African Bureau of Standards, Pretoria, 1992.

[52] J.J. Serdyn, "Design of the Electronic Phase Converter", Power Electronic Group, Department of Electrical Engineering, University of Stellenbosch, February 2000

[53] J.J. Serdyn, "Design of the Electronic Voltage Regulator", Power Electronic Group, Department of Electrical Engineering, University of Stellenbosch, November 2000

[54] B. Meyer, H.J. Beukes and R. G. Stephen, "Electronic voltage regulation of MV and LV power distribution networks", *Energize*, November 2000.

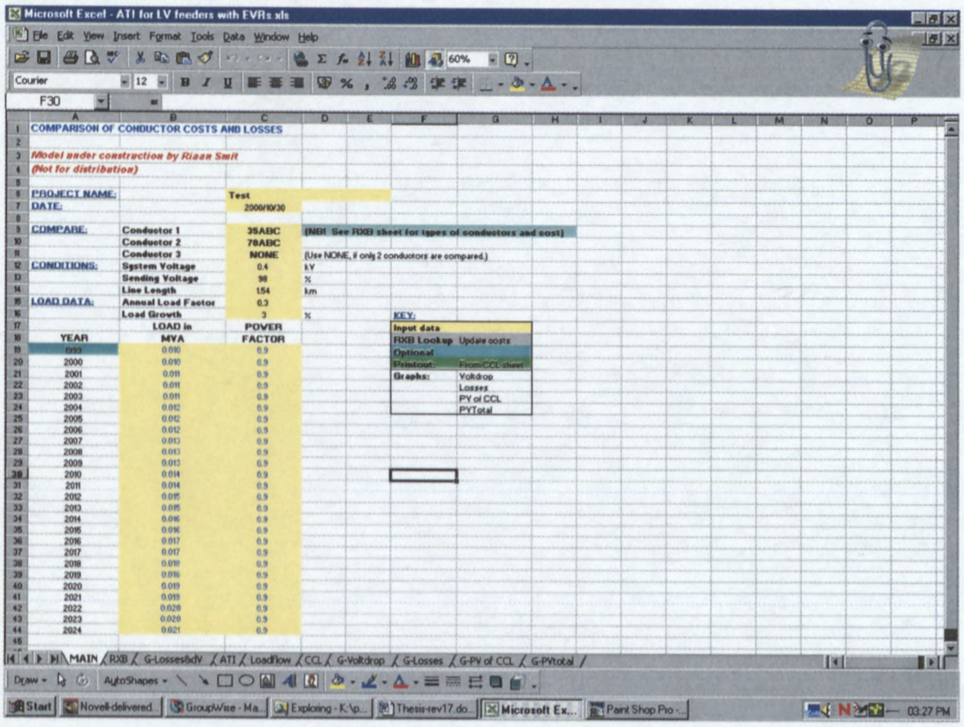
[55] Alstom, "Electrical Machines Price List", September 1999

[56] IEC 61089, "Round wire concentric lay overhead electrical stranded conductors", 1991

Appendix A

ATI studies

An example of the main data input sheet for load flow and ATI studies is presented in Fig. 73. As can be seen, up to three line types can be compared and the influence of both load growth over the lifetime of the project and the load factor can be set.



COMPARISON OF CONDUCTOR COSTS AND LOSSES

Model under construction by Riaan Smit
(Not for distribution)

PROJECT NAME:		Test	
DATE:		2000/10/30	
COMPARE:	Conductor 1	35ABC	(NB! See RXB sheet for types of conductors and cost)
	Conductor 2	70ABC	
	Conductor 3	NONE	(Use NONE, if only 2 conductors are compared.)
CONDITIONS:	System Voltage	0.4	kV
	Sending Voltage	98	%
	Line Length	1.54	km
LOAD DATA:	Annual Load Factor	0.3	
	Load Growth	3	%

YEAR	LOAD in MVA	POWER FACTOR
1999	0.010	0.9
2000	0.010	0.9
2001	0.011	0.9
2002	0.011	0.9
2003	0.011	0.9
2004	0.012	0.9
2005	0.012	0.9
2006	0.012	0.9
2007	0.013	0.9
2008	0.013	0.9
2009	0.013	0.9
2010	0.014	0.9
2011	0.014	0.9
2012	0.015	0.9
2013	0.015	0.9
2014	0.016	0.9
2015	0.016	0.9
2016	0.017	0.9
2017	0.017	0.9
2018	0.018	0.9
2019	0.018	0.9
2020	0.019	0.9
2021	0.019	0.9
2022	0.020	0.9
2023	0.020	0.9
2024	0.021	0.9

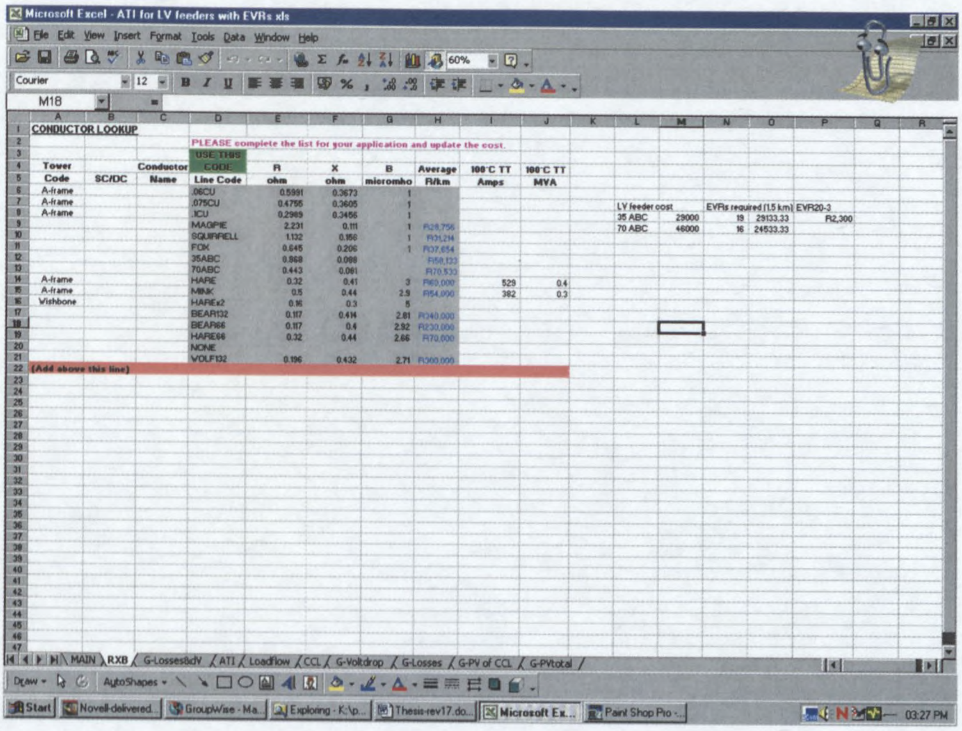
KEY:

Input data	
RXB Lookup	Update costs
Optional	
Printout:	From CCL sheet
Graphs:	Voltdrop Losses PV of CCL PYTotal

Fig. 73: Main data input sheet for ATI model

The model was also written as to perform comparisons of line technologies at any voltage level, load size and overall line length.

The second data input sheet is shown in Fig. 74. This sheet allows the user to add or update the specific network parameters and capital cost pertaining to the line technologies to be compared. Provision is also made to add the capital cost associated with the voltage-compensating device.



Microsoft Excel - ATI for LV feeders with EVRs.xls

CONDUCTOR LOOKUP

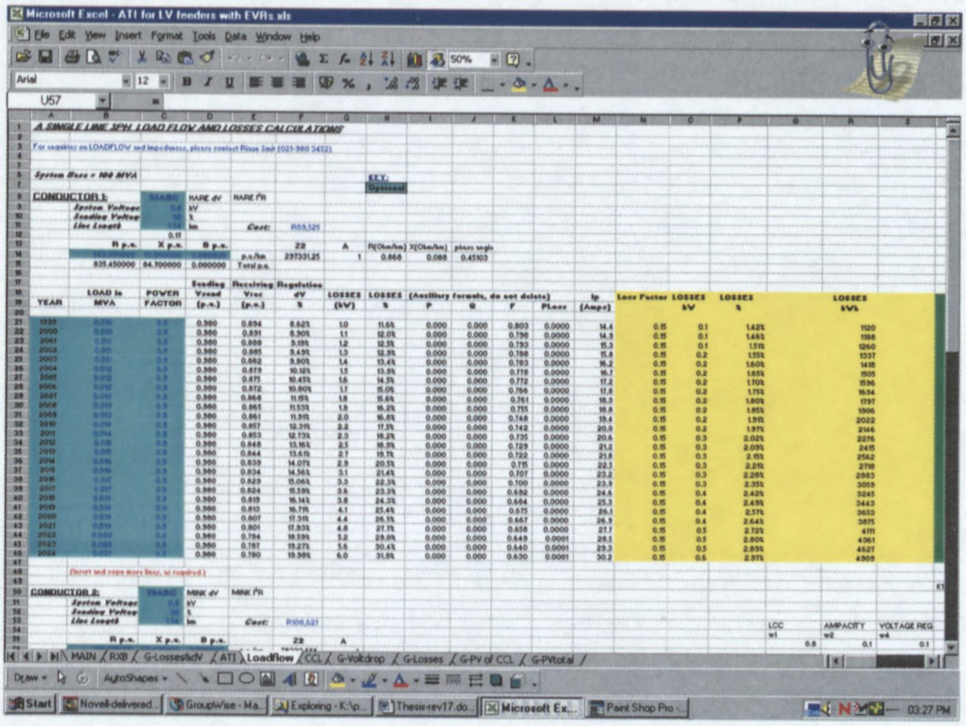
PLEASE complete the list for your application and update the cost.

Tower Code	SC/DC	Conductor Name	USE THIS CODE Line Code	R ohm	X ohm	B micromho	Average R/km	100°C TT Amps	100°C TT MVA
A-frame			.06CU	0.5991	0.3673	1			
A-frame			.075CU	0.4755	0.3605	1			
A-frame			.1CU	0.2989	0.3456	1			
			MAGPIE	2.231	0.111	1	R28,756		
			SQUIRRELL	1.132	0.156	1	R31,214		
			FOX	0.645	0.206	1	R37,654		
			35ABC	0.868	0.088		R58,133		
			70ABC	0.443	0.081		R70,533		
A-frame			HARE	0.32	0.41	3	R60,000	529	0.4
A-frame			MINK	0.5	0.44	2.9	R54,000	382	0.3
Wishbone			HAREx2	0.16	0.3	5			
			BEAR132	0.117	0.414	2.81	R340,000		
			BEAR66	0.117	0.4	2.92	R230,000		
			HARE66	0.32	0.44	2.66	R70,000		
			NONE						
			WOLF132	0.196	0.432	2.71	R300,000		

(Add above this line)

LV feeder cost		EVRs required (1.5 km)		EVR20-3
35 ABC	29000	19	29133.33	R2,300
70 ABC	46000	16	24533.33	

Fig. 74: Line parameters and compensating device data input sheet for ATI model



Microsoft Excel - ATI for LV feeders with EVRs.xls

A SINGLE LINE 3PH LOAD FLOW AND LOSSES CALCULATIONS

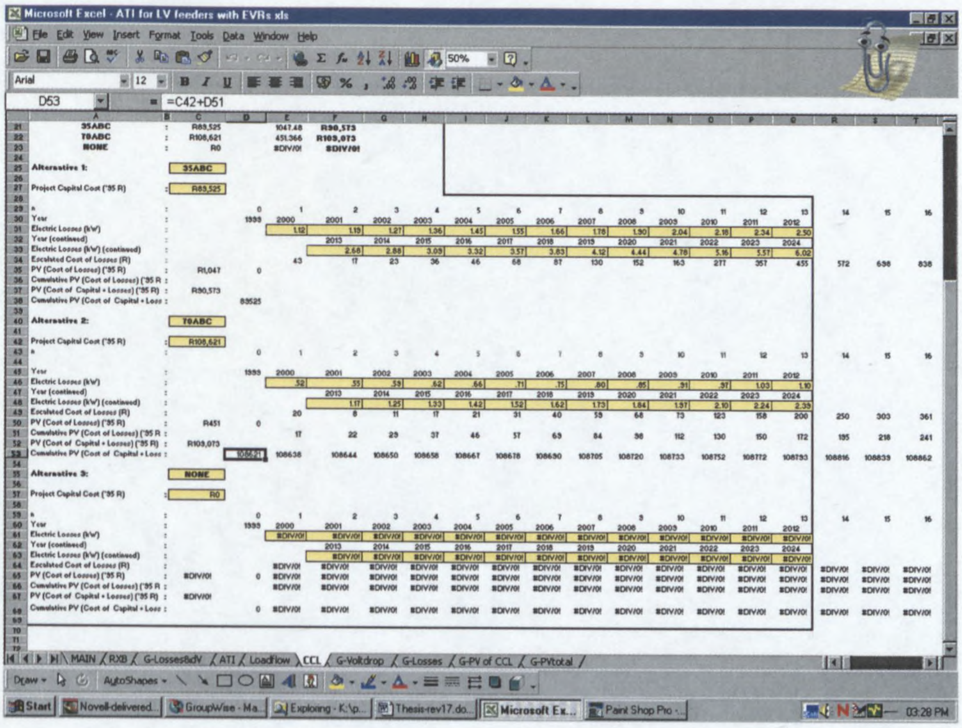
For enquiries on LOADFLOW and impedances, please contact Risse Smit (021-980 3452)

System Base = 100 MVA

KEY: Optional

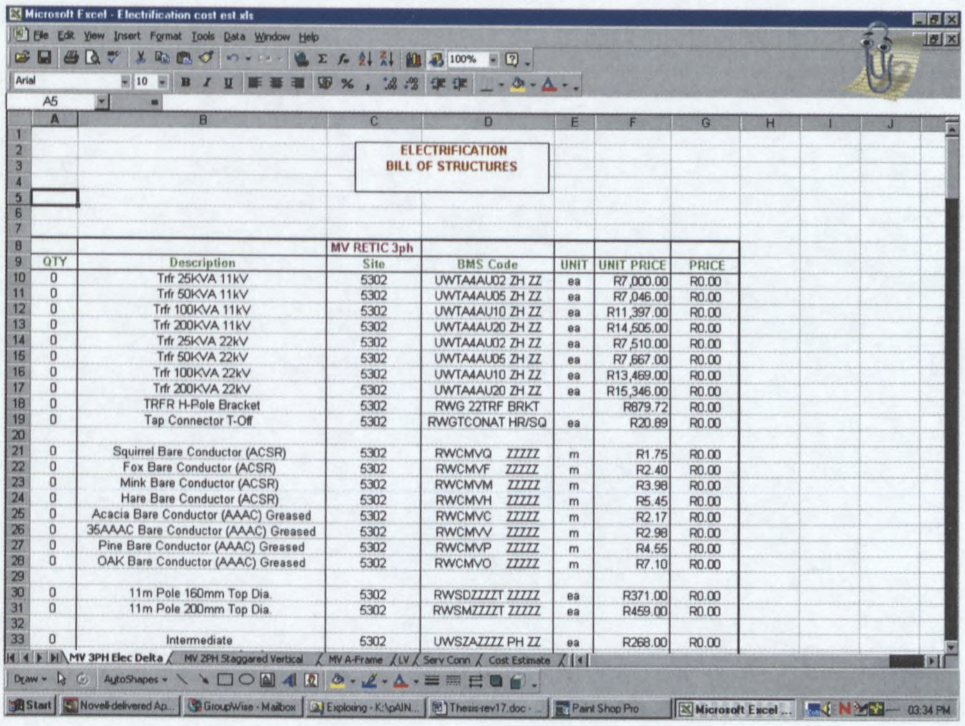
CONDUCTOR 1:

Fig. 75: Load flow results of ATI model



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
21	35ABC	:	R89,525		1047.48	R90,573														
22	70ABC	:	R108,621		451.366	R109,073														
23	NONE	:	R0		#DIV/0!	#DIV/0!														
24																				
25	Alternative 1:		35ABC																	
26																				
27	Project Capital Cost ('95 R)	:	R89,525																	
28																				
29	n	:		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
30	Year	:		1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012			
31	Electric Losses (kW)	:			1.12	1.19	1.27	1.36	1.45	1.55	1.66	1.78	1.90	2.04	2.18	2.34	2.50			
32	Year (continued)	:				2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024			
33	Electric Losses (kW) (continued)	:				2.68	2.88	3.09	3.32	3.57	3.83	4.12	4.44	4.78	5.16	5.57	6.02			
34	Escalated Cost of Losses (R)	:			43	17	23	36	46	68	87	130	152	163	277	357	455	572	698	838
35	PV (Cost of Losses) ('95 R)	:	R1,047	0																
36	Cumulative PV (Cost of Losses) ('95 R	:																		
37	PV (Cost of Capital + Losses) ('95 R)	:	R90,573																	
38	Cumulative PV (Cost of Capital + Loss	:		89525																
39																				
40	Alternative 2:		70ABC																	
41																				
42	Project Capital Cost ('95 R)	:	R108,621																	
43	n	:		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
44																				
45	Year	:		1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012			
46	Electric Losses (kW)	:			.52	.55	.59	.62	.66	.71	.75	.80	.85	.91	.97	1.03	1.10			
47	Year (continued)	:				2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024			
48	Electric Losses (kW) (continued)	:				1.17	1.25	1.33	1.42	1.52	1.62	1.73	1.84	1.97	2.10	2.24	2.39			
49	Escalated Cost of Losses (R)	:			20	8	11	17	21	31	40	59	68	73	123	158	200	250	303	361
50	PV (Cost of Losses) ('95 R)	:	R451	0																
51	Cumulative PV (Cost of Losses) ('95 R	:			17	22	29	37	46	57	69	84	98	112	130	150	172	195	218	241
52	PV (Cost of Capital + Losses) ('95 R)	:	R109,073																	
53	Cumulative PV (Cost of Capital + Loss	:		108621	108638	108644	108650	108658	108667	108678	108690	108705	108720	108733	108752	108772	108793	108816	108839	108862
54																				
55	Alternative 3:		NONE																	
56																				
57	Project Capital Cost ('95 R)	:	R0																	
58																				
59	n	:		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
60	Year	:		1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012			
61	Electric Losses (kW)	:			#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!			
62	Year (continued)	:				2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024			
63	Electric Losses (kW) (continued)	:				#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!			
64	Escalated Cost of Losses (R)	:			#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
65	PV (Cost of Losses) ('95 R)	:	#DIV/0!	0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
66	Cumulative PV (Cost of Losses) ('95 R	:			#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
67	PV (Cost of Capital + Losses) ('95 R)	:	#DIV/0!																	
68	Cumulative PV (Cost of Capital + Loss	:		0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!

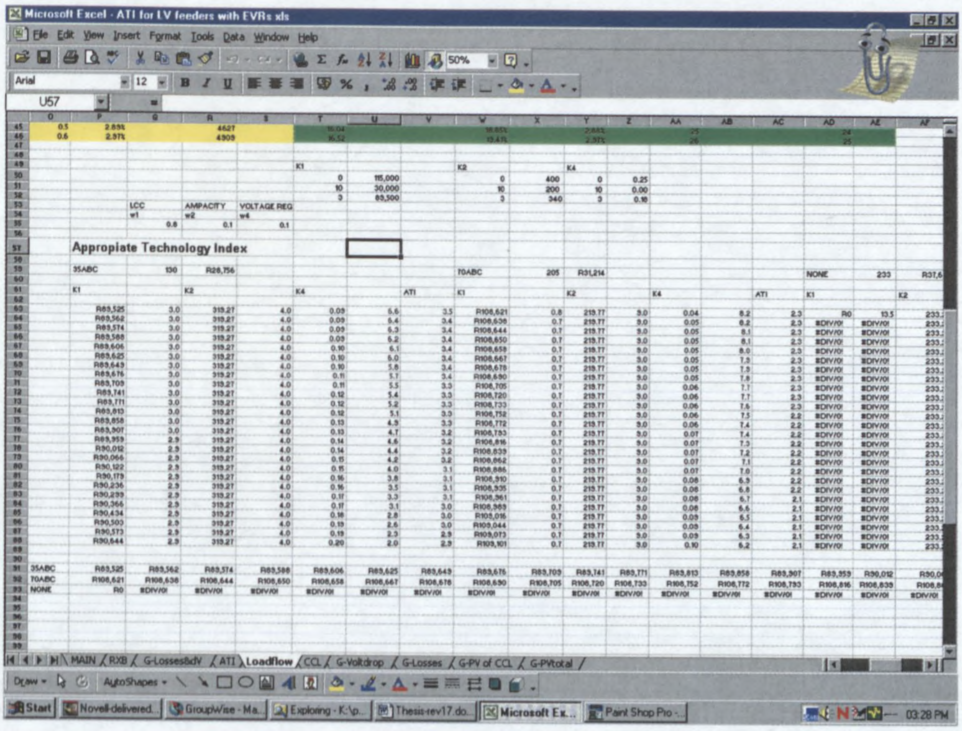
Fig. 76: Cost of losses results of ATI model



ELECTRIFICATION
BILL OF STRUCTURES

	A	B	C	D	E	F	G
8			MV RETIC 3ph				
9	QTY	Description	Site	BMS Code	UNIT	UNIT PRICE	PRICE
10	0	Trfr 25KVA 11kV	5302	UWTA4AU02 ZH ZZ	ea	R7,000.00	R0.00
11	0	Trfr 50KVA 11kV	5302	UWTA4AU05 ZH ZZ	ea	R7,046.00	R0.00
12	0	Trfr 100KVA 11kV	5302	UWTA4AU10 ZH ZZ	ea	R11,397.00	R0.00
13	0	Trfr 200KVA 11kV	5302	UWTA4AU20 ZH ZZ	ea	R14,505.00	R0.00
14	0	Trfr 25KVA 22kV	5302	UWTA4AU02 ZH ZZ	ea	R7,510.00	R0.00
15	0	Trfr 50KVA 22kV	5302	UWTA4AU05 ZH ZZ	ea	R7,667.00	R0.00
16	0	Trfr 100KVA 22kV	5302	UWTA4AU10 ZH ZZ	ea	R13,469.00	R0.00
17	0	Trfr 200KVA 22kV	5302	UWTA4AU20 ZH ZZ	ea	R15,346.00	R0.00
18	0	TRFR H-Pole Bracket	5302	RWG 22TRF BRKT		R879.72	R0.00
19	0	Tap Connector T-Off	5302	RWGTCONAT HR/SQ	ea	R20.89	R0.00
20							
21	0	Squirrel Bare Conductor (ACSR)	5302	RWCMVQ ZZZZZ	m	R1.75	R0.00
22	0	Fox Bare Conductor (ACSR)	5302	RWCMVF ZZZZZ	m	R2.40	R0.00
23	0	Mink Bare Conductor (ACSR)	5302	RWCMVM ZZZZZ	m	R3.98	R0.00
24	0	Hare Bare Conductor (ACSR)	5302	RWCMVH ZZZZZ	m	R5.45	R0.00
25	0	Acacia Bare Conductor (AAAC) Greased	5302	RWCMVC ZZZZZ	m	R2.17	R0.00
26	0	35AAAC Bare Conductor (AAAC) Greased	5302	RWCMVV ZZZZZ	m	R2.98	R0.00
27	0	Pine Bare Conductor (AAAC) Greased	5302	RWCMVP ZZZZZ	m	R4.55	R0.00
28	0	OAK Bare Conductor (AAAC) Greased	5302	RWCMVO ZZZZZ	m	R7.10	R0.00
29							
30	0	11m Pole 160mm Top Dia.	5302	RWSDZZZZT ZZZZZ	ea	R371.00	R0.00
31	0	11m Pole 200mm Top Dia.	5302	RWSMZZZZT ZZZZZ	ea	R459.00	R0.00
32							
33	0	Intermediate	5302	UWSZAZZZZ PH ZZ	ea	R268.00	R0.00

Fig. 77: Line cost structure model for capital investment cost calculation



	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF
45	0.5	2.89%		4627		16.04			18.85%		2.88%		25			24		
46	0.6	2.97%		4909		16.52			13.41%		2.97%		26			25		
47																		
48																		
49						K1			K2		K4							
50						0	115,000		0	400	0	0.25						
51						10	30,000		10	200	10	0.00						
52						3	89,500		3	340	3	0.18						
53			LCC	AMPACITY	VOLTAGE REG													
54			w1	w2	w4													
55			0.8	0.1	0.1													
56																		
57		**Appropiate Technology Index**																
58																		
59		35ABC	130	R28,756					70ABC	205	R31,214					NONE	233	R37,6
60																		
61		K1		K2		K4		ATI	K1		K2		K4		ATI	K1		K2
62																		
63		R89,525	3.0	319.27	4.0	0.09	6.6	3.5	R108,621	0.8	219.77	3.0	0.04	8.2	2.3	R0	13.5	233.
64		R89,562	3.0	319.27	4.0	0.09	6.4	3.4	R108,636	0.7	219.77	3.0	0.05	8.2	2.3	#DIV/0!	#DIV/0!	233.
65		R89,574	3.0	319.27	4.0	0.09	6.3	3.4	R108,644	0.7	219.77	3.0	0.05	8.1	2.3	#DIV/0!	#DIV/0!	233.
66		R89,588	3.0	319.27	4.0	0.09	6.2	3.4	R108,650	0.7	219.77	3.0	0.05	8.1	2.3	#DIV/0!	#DIV/0!	233.
67		R89,606	3.0	319.27	4.0	0.10	6.1	3.4	R108,658	0.7	219.77	3.0	0.05	8.0	2.3	#DIV/0!	#DIV/0!	233.
68		R89,625	3.0	319.27	4.0	0.10	6.0	3.4	R108,667	0.7	219.77	3.0	0.05	7.9	2.3	#DIV/0!	#DIV/0!	233.
69		R89,649	3.0	319.27	4.0	0.10	5.8	3.4	R108,678	0.7	219.77	3.0	0.05	7.9	2.3	#DIV/0!	#DIV/0!	233.
70		R89,676	3.0	319.27	4.0	0.11	5.7	3.4	R108,690	0.7	219.77	3.0	0.05	7.8	2.3	#DIV/0!	#DIV/0!	233.
71		R89,709	3.0	319.27	4.0	0.11	5.5	3.3	R108,705	0.7	219.77	3.0	0.06	7.7	2.3	#DIV/0!	#DIV/0!	233.
72		R89,741	3.0	319.27	4.0	0.12	5.4	3.3	R108,720	0.7	219.77	3.0	0.06	7.7	2.3	#DIV/0!	#DIV/0!	233.
73		R89,771	3.0	319.27	4.0	0.12	5.2	3.3	R108,733	0.7	219.77	3.0	0.06	7.6	2.3	#DIV/0!	#DIV/0!	233.
74		R89,813	3.0	319.27	4.0	0.12	5.1	3.3	R108,752	0.7	219.77	3.0	0.06	7.5	2.2	#DIV/0!	#DIV/0!	233.
75		R89,858	3.0	319.27	4.0	0.13	4.9	3.3	R108,772	0.7	219.77	3.0	0.06	7.4	2.2	#DIV/0!	#DIV/0!	233.
76		R89,907	3.0	319.27	4.0	0.13	4.7	3.2	R108,793	0.7	219.77	3.0	0.07	7.4	2.2	#DIV/0!	#DIV/0!	233.
77		R89,959	2.9	319.27	4.0	0.14	4.6	3.2	R108,816	0.7	219.77	3.0	0.07	7.3	2.2	#DIV/0!	#DIV/0!	233.
78		R90,012	2.9	319.27	4.0	0.14	4.4	3.2	R108,839	0.7	219.77	3.0	0.07	7.2	2.2	#DIV/0!	#DIV/0!	233.
79		R90,066	2.9	319.27	4.0	0.15	4.2	3.2	R108,862	0.7	219.77	3.0	0.07	7.1	2.2	#DIV/0!	#DIV/0!	233.
80		R90,122	2.9	319.27	4.0	0.15	4.0	3.1	R108,886	0.7	219.77	3.0	0.07	7.0	2.2	#DIV/0!	#DIV/0!	233.
81		R90,179	2.9	319.27	4.0	0.16	3.8	3.1	R108,910	0.7	219.77	3.0	0.08	6.9	2.2	#DIV/0!	#DIV/0!	233.
82		R90,236	2.9	319.27	4.0	0.16	3.5	3.1	R108,935	0.7	219.77	3.0	0.08	6.8	2.2	#DIV/0!	#DIV/0!	233.
83		R90,299	2.9	319.27	4.0	0.17	3.3	3.1	R108,961	0.7	219.77	3.0	0.08	6.7	2.1	#DIV/0!	#DIV/0!	233.
84		R90,366	2.9	319.27	4.0	0.17	3.1	3.0	R108,989	0.7	219.77	3.0	0.08	6.6	2.1	#DIV/0!	#DIV/0!	233.
85		R90,434	2.9	319.27	4.0	0.18	2.8	3.0	R109,016	0.7	219.77	3.0	0.09	6.5	2.1	#DIV/0!	#DIV/0!	233.
86		R90,503	2.9	319.27	4.0	0.19	2.6	3.0	R109,044	0.7	219.77	3.0	0.09	6.4	2.1	#DIV/0!	#DIV/0!	233.
87		R90,573	2.9	319.27	4.0	0.19	2.3	2.9	R109,073	0.7	219.77	3.0	0.09	6.3	2.1	#DIV/0!	#DIV/0!	233.
88		R90,644	2.9	319.27	4.0	0.20	2.0	2.9	R109,101	0.7	219.77	3.0	0.10	6.2	2.1	#DIV/0!	#DIV/0!	233.
89																		
90																		
91	35ABC	R89,525	R89,562	R89,574	R89,588	R89,606	R89,625	R89,649	R89,676	R89,709	R89,741	R89,771	R89,813	R89,858	R89,907	R89,959	R90,012	R90,0
92	70ABC	R108,621	R108,636	R108,644	R108,650	R108,658	R108,667	R108,678	R108,690	R108,705	R108,720	R108,733	R108,752	R108,772	R108,793	R108,816	R108,839	R108,8
93	NONE	R0	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
94																		
95																		
96																		
97																		
98																		
99																		

Fig. 78: ATI calculation with weighting parameters

The load flow and cost of losses results are shown in Fig. 75 and Fig. 76. The load flow results provide two inputs to the ATI model, the first being the total losses at various loadings and secondly the voltage regulation. In order to calculate the NPV of the losses over the lifetime of the network the existing financial evaluation model currently in use by Eskom Distribution is utilised.

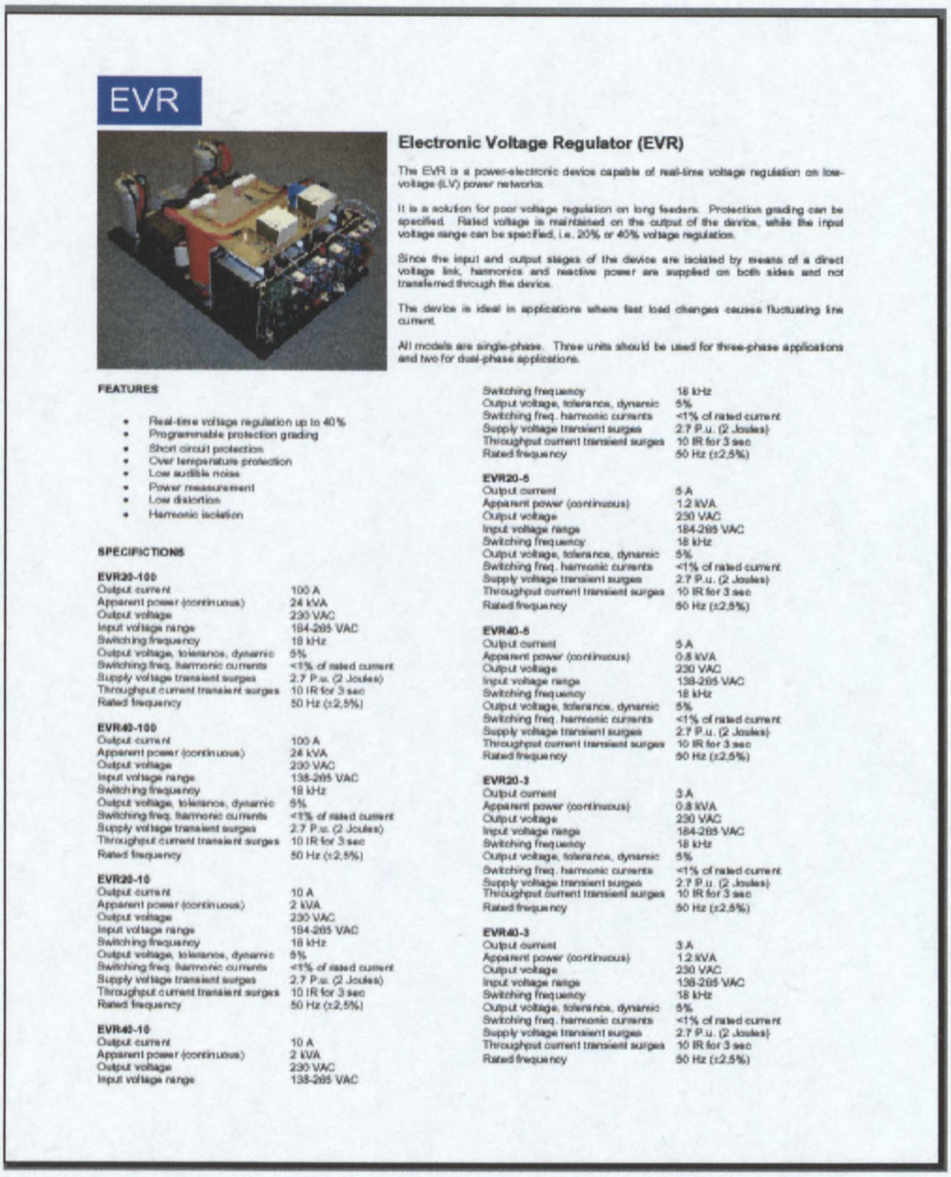
The capital cost for the various line technologies are calculated by means of standard modules in the form of a bill of structures (refer Fig. 77). These modules are installation specific and can be broken down into smaller cells. A typical example of a module would be a 16 kVA pole mounted transformer complete with holding bracket, set screws, surge arrestors, line taps and conductor lugs.

Finally, the ATI can be calculated from the results obtained in the previous mentioned sheets. An example of the ATI calculation results is shown in Fig. 78.

Appendix B

Available products – *US* series of EVR

The technical data sheet of the electronic voltage regulator (EVR) from the *University of Stellenbosch* is shown in Fig. 79. The various capacity ratings and input voltage ranges are as shown.



EVR

Electronic Voltage Regulator (EVR)

The EVR is a power-electronic device capable of real-time voltage regulation on low-voltage (LV) power networks.

It is a solution for poor voltage regulation on long feeders. Protection grading can be specified. Rated voltage is maintained on the output of the device, while the input voltage range can be specified, i.e. 20% or 40% voltage regulation.

Since the input and output stages of the device are isolated by means of a direct voltage link, harmonics and reactive power are supplied on both sides and not transferred through the device.

The device is ideal in applications where fast load changes causes fluctuating line current.

All models are single-phase. Three units should be used for three-phase applications and two for dual-phase applications.

FEATURES

- Real-time voltage regulation up to 40%
- Programmable protection grading
- Short circuit protection
- Over temperature protection
- Low audible noise
- Power measurement
- Low distortion
- Harmonic isolation

SPECIFICTIONS

EVR20-100

Output current	100 A
Apparent power (continuous)	24 kVA
Output voltage	230 VAC
Input voltage range	184-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

EVR40-100

Output current	100 A
Apparent power (continuous)	24 kVA
Output voltage	230 VAC
Input voltage range	138-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

EVR20-10

Output current	10 A
Apparent power (continuous)	2 kVA
Output voltage	230 VAC
Input voltage range	184-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

EVR40-10

Output current	10 A
Apparent power (continuous)	2 kVA
Output voltage	230 VAC
Input voltage range	138-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

EVR20-5

Output current	5 A
Apparent power (continuous)	1.2 kVA
Output voltage	230 VAC
Input voltage range	184-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

EVR40-5

Output current	5 A
Apparent power (continuous)	0.8 kVA
Output voltage	230 VAC
Input voltage range	138-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

EVR20-3

Output current	3 A
Apparent power (continuous)	0.8 kVA
Output voltage	230 VAC
Input voltage range	184-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

EVR40-3

Output current	3 A
Apparent power (continuous)	1.2 kVA
Output voltage	230 VAC
Input voltage range	138-265 VAC
Switching frequency	18 kHz
Output voltage, tolerance, dynamic	5%
Switching freq. harmonic currents	<1% of rated current
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2,5%)

Fig. 79: Technical data sheet of electronic voltage regulator (EVR) from *University of Stellenbosch*

Appendix C

Available products – *US* series of EPC

The technical data sheet of the electronic phase converter (EPC) from the *University of Stellenbosch* is shown in Fig. 80. The various capacity ratings are as shown.

EPC

Electronic Phase Converter (EPC)

The EPC is a power-electronic device capable of real-time phase conversion for machine loads on low-voltage (LV), dual-phase power networks.

It is a solution for three-phase requirements on low cost medium voltage (MV) networks.

The device can only operate at full rating when it is sourced from a dual-phase supply.

The device uses a scalar control algorithm that is fully programmable in field to obtain the best performance from the machine being driven. The rate of start-up can be reduced to such a level that insignificant extra torque is present during this process.

FEATURES

- Single-phase to three-phase conversion
- Programmable start-up and operating conditions
- Short circuit protection
- Over temperature protection
- Low audible noise
- 50% Dip rejection

SPECIFICTIONS

EPC-11

Output current	16 A
Power (continuous)	11 kW
Output voltage	400 VAC
Input voltage range	230 VAC (2)
Switching frequency	5 kHz
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2.5%)

EPC-15

Output current	22 A
Power (continuous)	15 kW
Output voltage	400 VAC
Input voltage range	230 VAC (2)
Switching frequency	5 kHz
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2.5%)

EPC-22

Output current	32 A
Power (continuous)	22 kW
Output voltage	400 VAC
Input voltage range	230 VAC (2)
Switching frequency	5 kHz
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2.5%)

EPC-30

Output current	44 A
Power (continuous)	30 kW
Output voltage	400 VAC
Input voltage range	230 VAC (2)
Switching frequency	5 kHz
Supply voltage transient surges	2.7 P.u. (2 Joules)
Throughput current transient surges	10 IR for 3 sec
Rated frequency	50 Hz (±2.5%)

Ordering information: The EPC can be ordered from the contact persons below. Delivery time is 1 month for single units. The EPC can also be modified to meet a customer's specific specifications.

Developed by:

ESKOM TSI
Private Bag 40175
Cleveland 2022
South Africa

Contact person:
Dayalin Padyachi
Tel: +27 82 415 1467

and

Power Electronics Group
Dept of Electrical Engineering
University of Stellenbosch
Private Bag X1
Matieland 7602
South Africa

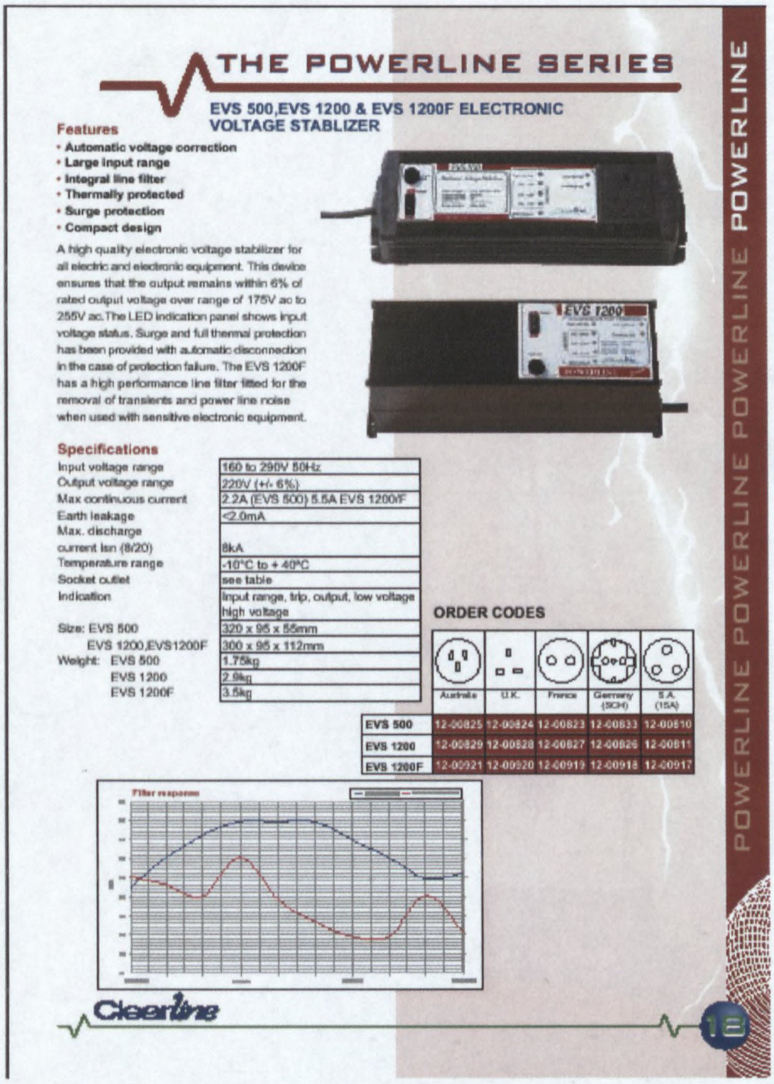
Contact person:
Dr Johan Beukes
Tel. +27 82 5 627 627

Fig. 80: Technical data sheet of electronic phase converter (EPC) from the *University of Stellenbosch*

Appendix D

Available products – *Powerline* series of EVR

The technical data sheet of the electronic voltage stabiliser from *Clearline* is shown in Fig. 81. As can be seen the capacity ratings are very much in line with those proposed for the service connection box mounted EVR.



THE POWERLINE SERIES

EVS 500,EVS 1200 & EVS 1200F ELECTRONIC VOLTAGE STABLIZER

Features

- **Automatic voltage correction**
- **Large input range**
- **Integral line filter**
- **Thermally protected**
- **Surge protection**
- **Compact design**

A high quality electronic voltage stabilizer for all electric and electronic equipment. This device ensures that the output remains within 6% of rated output voltage over range of 175V ac to 255V ac.The LED indication panel shows input voltage status. Surge and full thermal protection has been provided with automatic disconnection in the case of protection failure. The EVS 1200F has a high performance line filter fitted for the removal of transients and power line noise when used with sensitive electronic equipment.

Specifications

Input voltage range	160 to 290V 50Hz
Output voltage range	220V (+/- 6%)
Max continuous current	2.2A (EVS 500) 5.5A EVS 1200/F
Earth leakage	<2.0mA
Max. discharge current Isn (8/20)	8kA
Temperature range	-10°C to + 40°C
Socket outlet	see table
Indication	Input range, trip, output, low voltage high voltage
Size: EVS 500	320 x 95 x 55mm
EVS 1200,EVS1200F	300 x 95 x 112mm
Weight: EVS 500	1.75kg
EVS 1200	2.9kg
EVS 1200F	3.5kg

ORDER CODES

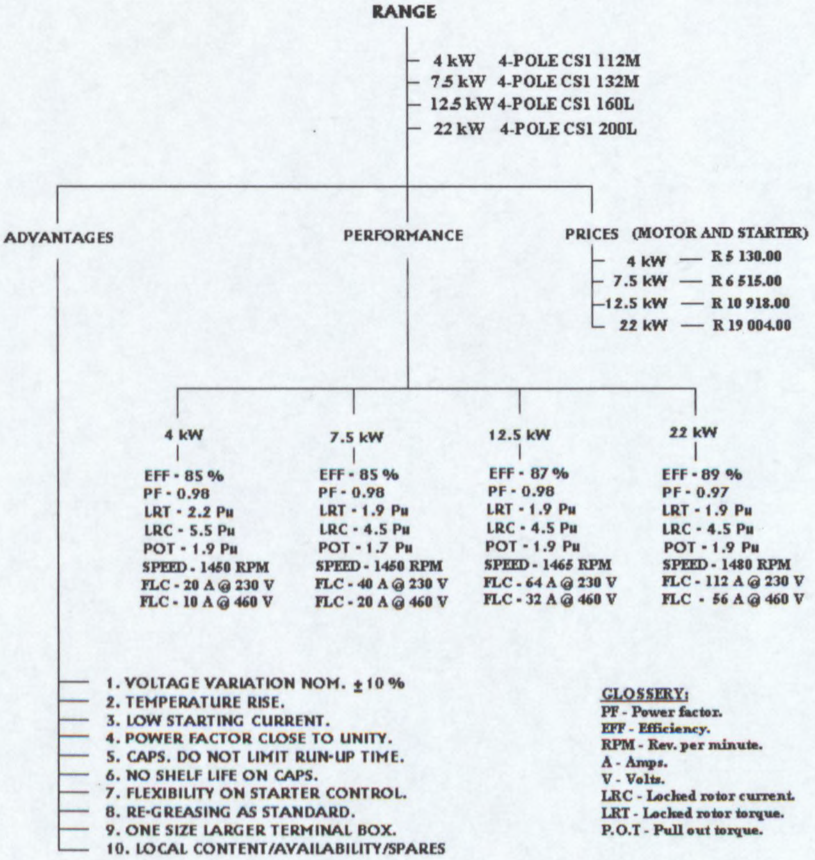
	Australia	U.K.	France	Germany (SCH)	S.A. (15A)
EVS 500	12-00825	12-00824	12-00823	12-00833	12-00810
EVS 1200	12-00829	12-00828	12-00827	12-00826	12-00811
EVS 1200F	12-00921	12-00920	12-00919	12-00918	12-00917

Fig. 81: Technical data sheet of electronic voltage stabiliser from *Clearline*

Appendix E

Available products - *Alstom* large single-phase motor

The technical data sheet of the large size single-phase motors from *Alstom* is shown in Fig. 82. The very high power factor ratings can mostly be contributed to the large installed base of starting capacitors.



RANGE

4 kW 4-POLE CS1 112M
7.5 kW 4-POLE CS1 132M
12.5 kW 4-POLE CS1 160L
22 kW 4-POLE CS1 200L

ADVANTAGES

PERFORMANCE

PRICES (MOTOR AND STARTER)

4 kW — R 5 130.00
7.5 kW — R 6 515.00
12.5 kW — R 10 918.00
22 kW — R 19 004.00

4 kW	7.5 kW	12.5 kW	22 kW
EFF - 85 %	EFF - 85 %	EFF - 87 %	EFF - 89 %
PF - 0.98	PF - 0.98	PF - 0.98	PF - 0.97
LRT - 2.2 Pu	LRT - 1.9 Pu	LRT - 1.9 Pu	LRT - 1.9 Pu
LRC - 5.5 Pu	LRC - 4.5 Pu	LRC - 4.5 Pu	LRC - 4.5 Pu
POT - 1.9 Pu	POT - 1.7 Pu	POT - 1.9 Pu	POT - 1.9 Pu
SPEED - 1450 RPM	SPEED - 1450 RPM	SPEED - 1465 RPM	SPEED - 1480 RPM
FLC - 20 A @ 230 V	FLC - 40 A @ 230 V	FLC - 64 A @ 230 V	FLC - 112 A @ 230 V
FLC - 10 A @ 460 V	FLC - 20 A @ 460 V	FLC - 32 A @ 460 V	FLC - 56 A @ 460 V

1. VOLTAGE VARIATION NOM. ± 10 %
2. TEMPERATURE RISE.
3. LOW STARTING CURRENT.
4. POWER FACTOR CLOSE TO UNITY.
5. CAPS. DO NOT LIMIT RUN-UP TIME.
6. NO SHELF LIFE ON CAPS.
7. FLEXIBILITY ON STARTER CONTROL.
8. RE-GREASING AS STANDARD.
9. ONE SIZE LARGER TERMINAL BOX.
10. LOCAL CONTENT/AVAILABILITY/SPARES

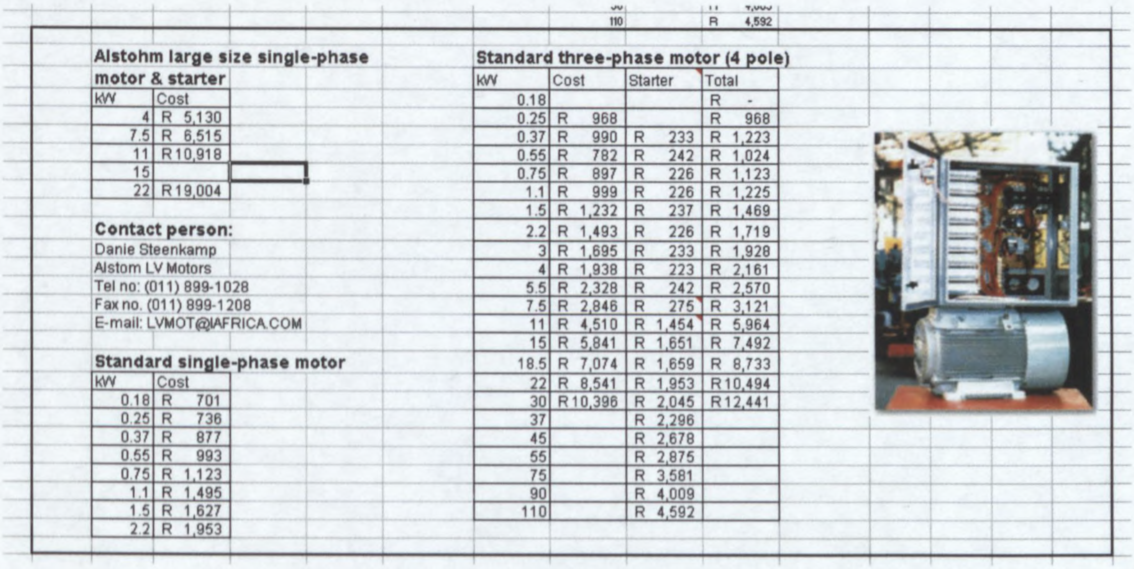
GLOSSERY:
PF - Power factor.
EFF - Efficiency.
RPM - Rev. per minute.
A - Amps.
V - Volts.
LRC - Locked rotor current.
LRT - Locked rotor torque.
P.O.T - Pull out torque.

Fig. 82: Technical data sheet of *Alstom* large single-phase motors

Appendix F

Costing structures of the *Alstom* motors and EPC

The costing structures of both the *Alstom* motor / starter and the EPC / motor combination are shown in Fig. 83 and Fig. 84. As can be seen, the EPC / motor combination is mostly cost-effective for higher load ratings and multiple connected motor loads.



110 R 4,592

Alstohm large size single-phase motor & starter

kW	Cost
4	R 5,130
7.5	R 6,515
11	R10,918
15	
22	R19,004

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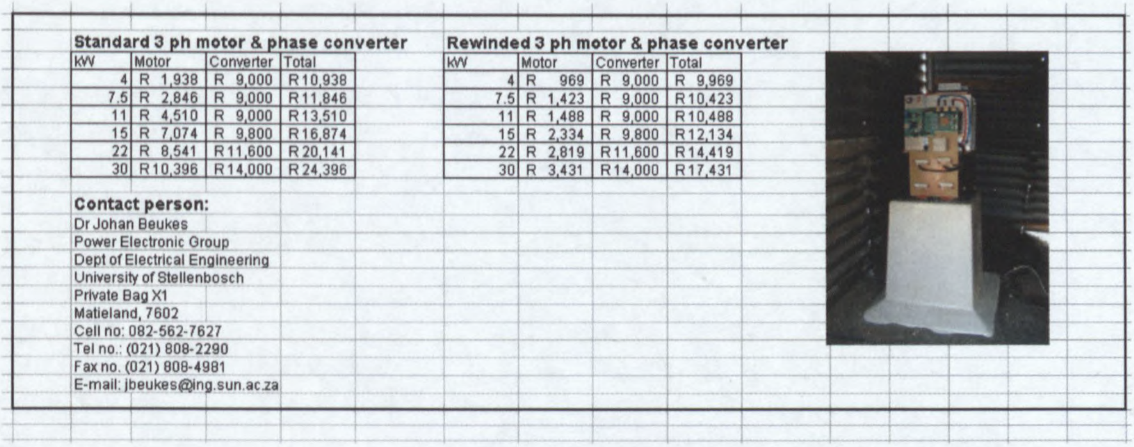
Standard single-phase motor

kW	Cost
0.18	R 701
0.25	R 736
0.37	R 877
0.55	R 993
0.75	R 1,123
1.1	R 1,495
1.5	R 1,627
2.2	R 1,953

Standard three-phase motor (4 pole)

kW	Cost	Starter	Total
0.18			R -
0.25	R 968		R 968
0.37	R 990	R 233	R 1,223
0.55	R 782	R 242	R 1,024
0.75	R 897	R 226	R 1,123
1.1	R 999	R 226	R 1,225
1.5	R 1,232	R 237	R 1,469
2.2	R 1,493	R 226	R 1,719
3	R 1,695	R 233	R 1,928
4	R 1,938	R 223	R 2,161
5.5	R 2,328	R 242	R 2,570
7.5	R 2,846	R 275	R 3,121
11	R 4,510	R 1,454	R 5,964
15	R 5,841	R 1,651	R 7,492
18.5	R 7,074	R 1,659	R 8,733
22	R 8,541	R 1,953	R10,494
30	R10,396	R 2,045	R12,441
37		R 2,296	
45		R 2,678	
55		R 2,875	
75		R 3,581	
90		R 4,009	
110		R 4,592	

Fig. 83: Costing structure of Alstom large single-phase motors



Standard 3 ph motor & phase converter

kW	Motor	Converter	Total
4	R 1,938	R 9,000	R10,938
7.5	R 2,846	R 9,000	R11,846
11	R 4,510	R 9,000	R13,510
15	R 7,074	R 9,800	R16,874
22	R 8,541	R11,600	R20,141
30	R10,396	R14,000	R24,396

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Rewinded 3 ph motor & phase converter

kW	Motor	Converter	Total
4	R 969	R 9,000	R 9,969
7.5	R 1,423	R 9,000	R10,423
11	R 1,488	R 9,000	R10,488
15	R 2,334	R 9,800	R12,134
22	R 2,819	R11,600	R14,419
30	R 3,431	R14,000	R17,431

Fig. 84: Costing structure of EPC