LIGHTNING PERFORMANCE IMPROVEMENT OF THE SWAZILAND ELECTRICITY BOARD TRANSMISSION SYSTEM (66kV & 132kV LINES)

Prepared by:

Luke Mdumiseni Mswane

Submitted to the Department of Electrical Engineering, University of Cape Town, in partial fulfilment of the requirement for the degree of Master of Science in Engineering.

Acknowledgments

I would like to thank the former Managing Director of the Swaziland Electricity Board, Mr. Bruce Farrer, for agreeing to support me in carrying out this project. I appreciate the opportunity he gave me to put in place the tools that enabled me to analyse the causes of power outages within the SEB network.

I am greatly indebted to the Swaziland Electricity Board for giving me both the support and the resources that made this project possible.

I would also like to thank my course supervisor, Professor C.T. Gaunt, for his untiring support and guidance throughout the project. I would like to thank Dr. Laurence Musaba from the Southern African Power Pool Co-ordination Centre for guiding me during the project. I would like to thank Mr. Pat Naidoo of Eskom for his continued encouragement during this entire project.

This project would not been possible without the involvement of the SEB staff, particularly the Transmission Department staff and Mr. Walter Nxumalo, the Transmission Manager, who understood the need for the initial investigation on power outages due to lightning and the subsequent pilot project.

I would also wish to thank my wife, Thembi, and our children for bearing with me at times when I had to work late, sometimes throughout the week.

Above all, this work would have not have been possible without guidance from Almighty God, the Son, and the Holy Sprit.

Declaration

This dissertation could not have been carried out without the guidance and support of Professor C.T. Gaunt of the University of Cape Town, guidance from Dr. Laurence Musaba from the Southern African Power Pool and encouragement from Mr. Pat Naidoo of Eskom. In addition I acknowledge the support from the staff of the Swaziland Electricity Board, in particular Mr. Walter Nxumalo and his Transmission Team, who were involved in the implementation of the 66kV Pilot line Project and the monitoring of the performance of the line. All of these have been mentioned in the acknowledgement section.

I have identified all work done by others in this dissertation and referenced it accordingly.

All photographs in this work are my own.

Signed by candidate

Luke Mdumiseni Mswane
Mbabane
March 2005

Abstract

This thesis describes the investigation of the most common single cause of power outages in the Swaziland Electricity Board (SEB) network as well as the implementation and findings of the pilot project that was undertaken to test the theoretical solution chosen for the improvement of the lightning performance of the SEB transmission network. The implementation of the pilot project commenced in August 2003 and was completed within two weeks.

The SEB has been aware since the late 1990's that most power outages occur during the summer months. This was shown by investigations carried out by one of the Board's major customers and their own customer care survey. These findings indicated the effects of lightning on the reliability and quality of supply in the country. Despite these symptoms, it could not be stated that lightning actually caused the power outages without detailed investigation of specific lines falling within the high lightning intensity area of the country.

A thorough literature search was carried out to understand lightning behaviour and the consequences of direct and indirect strikes to transmission lines. A literature search was also carried out to find out how other organizations have solved this problem in areas where there is high lightning ground flash density. General investigation was carried out to determine the single most common cause of power outages within the Swaziland Electricity Board (SEB) network. This preliminary work was followed by a detailed investigation on lightning outages on three selected 66kV lines situated within the high lightning ground flash density area of Swaziland. The investigation revealed that all three-66kV lines experienced outages due to lightning during the summer months starting in September or October and ending in April or May of the following year. One of these lines was used to implement the suggested solution to this problem as a pilot project. The solution involved the installation of Zinc Oxide Lightning Arresters at selected high-risk areas along the 66kV line.

The results of the pilot project indicate that there were no power outages related to lightning on the selected 66kV line after the implementation of the pilot project.

Because of the positive results of the pilot project, a decision was taken to install Zinc Oxide Lightning Arresters on selected critical 66kV lines of the SEB transmission network over a five-year period.

TABLE OF CONTENTS

Chapter 1

Introduction

1.1 Symptoms of Causes of Frequent Power Outages Within The Swaziland Electricity Board Transmission System

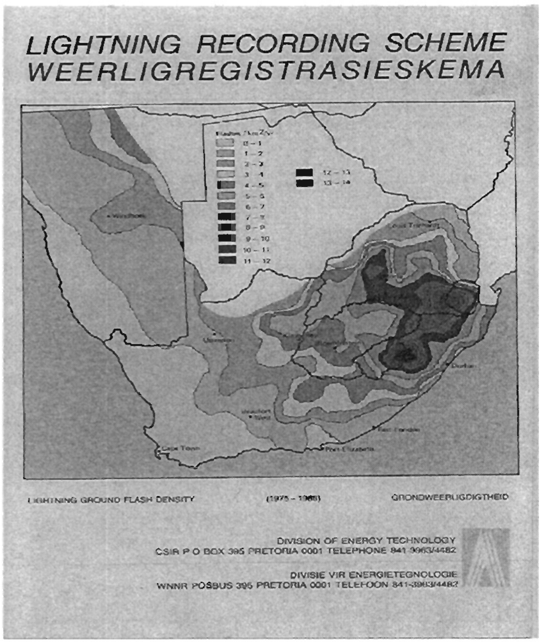
Swaziland is located in the subtropical area of Southern Africa, and has a warm temperate climate of wet summers and dry winters [Swaziland, 2004], [Jumbo Tourist Guide, 2003/4]

The Council for Scientific and Industrial Research (CSIR) carried out a survey of lightning incidence in South Africa, Swaziland, Lesotho and Namibia during the period 1975 – 1986 using ground flash recorders [CSIR, 1986].

Figures 1 and 2 show the lightning activity maps for South Africa, Lesotho, and parts of Namibia and Swaziland respectively [CSIR, 1996], [Capricon, 1996]. From Figure 1 it can be seen that there are high lightning activities in Lesotho and Swaziland. In Swaziland the lightning flash density is as high as 13-14flashes /km^2/year in some areas, particularly in the western parts of the country where a third of the SEB transmission system load is found. Two thirds of the country's load is situated in this area.

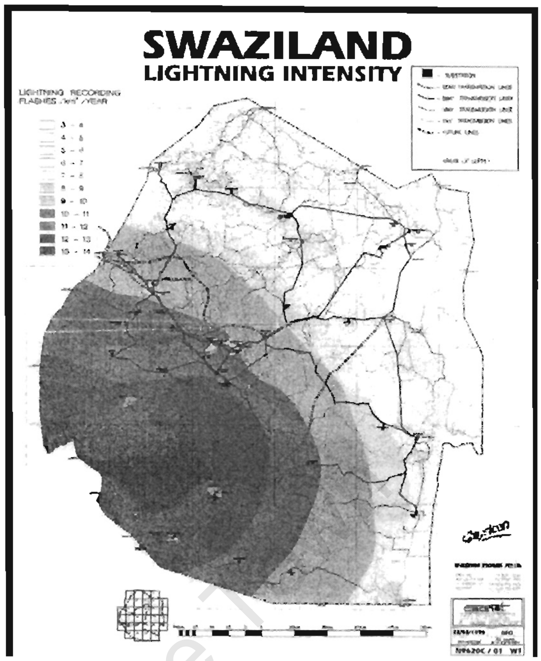
Figure 2 confirms that the western part of Swaziland has the highest rate of lightning strikes. The problems caused by these are aggravated by the nature of the soil found in this part of the country. The soil is characterized by granite rock outcrop and is highly sandy. For this reason the soil resistance there is generally high (>10.0hms) [Dlamini, 1991].

SEB experiences a high number of unscheduled transmission line outages during summer. The summer rains are usually characterized by thunderstorms and lightning. Investigation carried out in the first part of the project indicated that about 40% of power outages in the country are due to lightning [Gaunt, Mswane, 2001]. In South Africa, which has a lower lightning intensity than Swaziland, studies carried out to determine outages in overhead distribution lines showed that approximately one third are due to lightning [Gaunt, 1994]. In his summary, Rosen, remarks that *" Southern Africa has one of the highest lightning flash densities in the world – consequently outages in overhead line feeders are considerable…"*[Rosen, 1990].



Source: [CSIR, 1986]

Figure 1: Keraunic map of RSA, Swaziland, Lesotho, & Namibia



Source: [Capricon, 1996]

Figure 2: Keraunic map of Swaziland

1.2 Complaints of power outages by a major SEB customer

The SEB transmission lines (66kV and 132kV) are evenly spread throughout the country but load distribution is, however, not evenly spread out. A third of the transmission system, particularly the 66kV lines, is in the area with high lightning activity. Unfortunately two thirds of the country's total load is found in this area. Over the years numerous complaints from customers such as SAPPI (Usuthu) have been received about power outages, power dips or brown-outs and descriptions of the consequences of the uneven load quality and reliability of the SEB power supply [Kennedy & Donkin, 1996]. Customers incurred high losses due to frequent production stoppages, low product quality and high operating costs. The poor performance of the power supply resulted in low economic growth particularly in load sensitive industries. Figures 3a and 3b show graphs of power outages duration, and power incidents (dips and outages) recorded by one of the SEB sensitive load/type customers over the summer months in 1999 and 2000 [Usuthu Pulp, 1996].

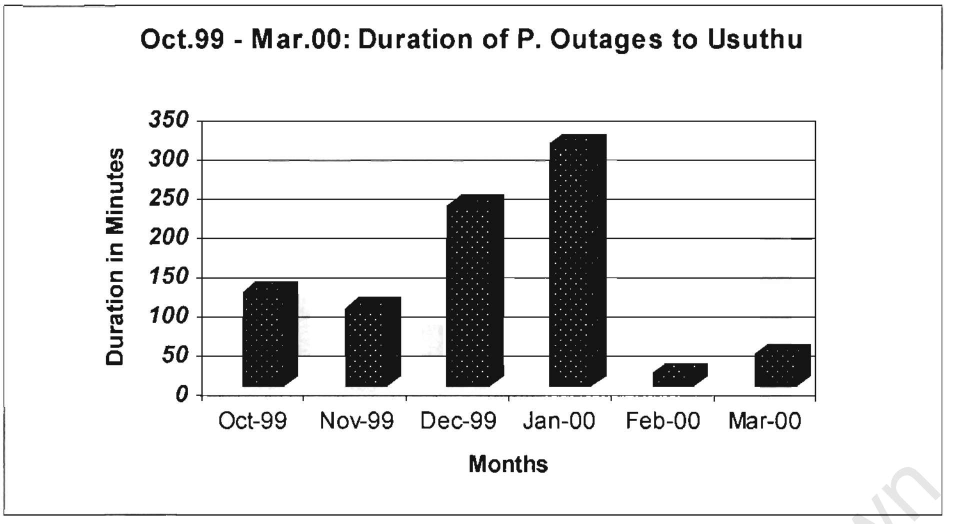


Figure 3a: Duration (total) of power outages experienced by Usuthu Pulp October 1999 to March 2000. [Usuthu, 2000]

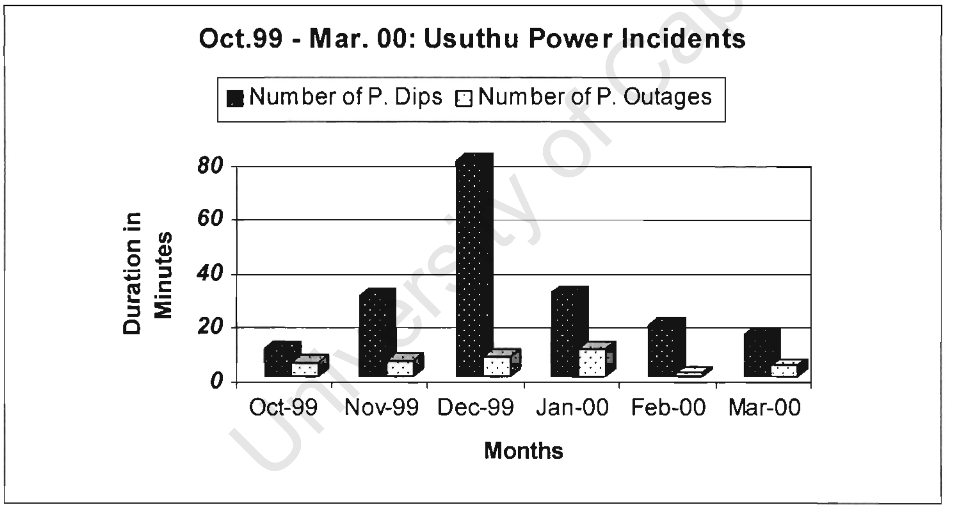


Figure 3b: Power outage/dips experienced by Usuthu Pulp October 1999 to March 2000. [Usuthu, 2000]

1.3 Eskom's Investigation into the Causes of Power outages at Usuthu – 1996

Usuthu Pulp (now Sappi - Usuthu, following acquisitioning by Sappi in the late 1990's) engaged Eskom in 1996 to investigate voltage depressions (dips) experienced at their plant in Swaziland. Usuthu is located in the western part of Swaziland that has high lightning ground flash density. The plant is supplied through two 66kV lines and both of them transverse the high lightning ground flash density area.

The depth and duration of all voltage depressions were monitored at 66kV at the SEB Usuthu substation, 6.6kV bus Usuthu power station bus bar, 6.6kV substation 3 and 6.6kV substation 4 from 11 January1996 to 10 May 1996 [Eskom, 1996].

The investigation pointed out that the number of power dip incidents experienced by Usuthu Pulp is extremely high compared with the average number of power dips experienced by other Eskom customers in Southern Africa [Eskom, 1996]. For the measurement period of four months, 90 voltage power dips were experienced at the 6.6kV substation fed from the SEB line. The report attributed this high number of power dips to the location of the plant in a high lightning area. In a preliminary investigation that was done a year earlier in May/June 1995 it was noted that there were significantly more dips recorded in the summer months than in winter[Eskom, 1996].

Measurements were taken from the following points:

- Prairie 275/132kV substation
- SEB substation at Usuthu Pulp- 66kV Edwaleni feeder
- Usuthu Pulp sub.3, 6.6 kV substation -fed from the SEB 66kV line
- Usuthu Pulp sub 4, 6.6kV -fed from own generation.

Table 1 shows a summary of the results of the full measurement period.

Table 1: Summary Results of the Usuthu Pulp Voltage Dips Investigation-1996

11/01/1996 **10/05/1996**	**Prairie** **132kV**	**SEB** **66kV**	**Power Station(SEB)** **66kV**	**Substation 3** **6.6kV**	**Sub. 4** **6.6kV**
Total Number of Dips	42	78	90	97	0
3 phase	35	34	65	60	0
2 phase	4	22	11	20	0
1 phase	3	22	14	17	0
Plant affected	-	-	-	5	-

Source: [Usuthu, 1996]

1.4 SEB Customer Care Survey -conducted in 1996

In 1996 the Swaziland Electricity Board engaged the services of Kennedy & Donkin to carry out a customer care survey so that a marketing strategy could be reviewed [Kennedy & Donkin, 1996].

The survey was divided into three customer segments as follows:

- Survey 1: a sample of domestic customers,
- Survey 2: a sample of small commercial customers,
- Survey 3: the top 20 industrial customers selected by SEB

The top 20 customers were asked questions such as:

1. What is the nature of your business?
2. What is the nature of your electricity usage?
3. How do you experience the quality of supply of electricity? If problems occur, what type of problems are they and what is the frequency? What are the consequences and the cost of supply failures?
4. How do you experience the quality of service? Etc.

The responses from some of the top 20 customers indicated that they suffer high production losses due to power cuts particularly in summer. Table 2 shows monthly costs suffered by the customers and indications of power cuts. Most of the customer representatives interviewed were engineers.

Table 2: Responses from customer care survey on SEB quality of supply

Name of Organization	Monthly power outages - winter	Monthly power outages - summer	Production losses (Emalangeni)*	Consequential Maintenance cost
Beral	8	90	288000/month	20000/month
Big Bend Sugar Estate	10-15	120	11200/3hr outage/m	-
Conco Swaziland	3	12-20	-	-
Dumisa Sugar	3	Up to 20/day Up to 150/ month	250000/m	100000
Natex	1	15-20	172500/m	-
Ok Bazaars	1	8-16	24400/m	-
Peak Timbers	2	35 trips/ week	850000/pa	100000
Swazi Spa Holdings	2	20	4000/m	-
Swaziland United Bakeries	2	8	-	-
Swaziland Breweries	1	2	-	-
Swaziland Milling	3	90	287000/m	-
Trans world radio	4	8	-	-
Ubombo Ranches	4	2-13	-	-
Ussuthu Pulp	4	12	-	-

Source: [Kennedy & Donkin,1996]

*Emalangeni is the Swaziland Currency. 1 Lilangeni is equivalent to 1 Rand as Swaziland is in the same monetary area as South Africa.

From Table 2 it is clear that most organizations had higher power outages in summer than in winter and that losses were more than E10Million for 1996. This loss only reflected those suffered by twenty major customers. The above figure would be higher if all SEB major customers were interviewed.

These findings are of great concern. Some customers indicated at that time that if the situation continued they would close down their operations in Swaziland and move their plant elsewhere.

It is a fact that:

- Beral who were manufacturing motor vehicle brake pads relocated to South Africa in 1998, resulting in many people losing their jobs and fewer exports from Swaziland, thus decreasing the G.D.P.

- Natex, a textile factory, eventually closed down after initially reducing their operations to only spinning. This too resulted in job loses and a decline in the Swaziland economy.

These companies were amongst those that complained to SEB about dips and power cuts.

The results of the Customer Care Exercise carried out by Kennedy & Donkin was proof that SEB customers, particularly large customers, were not happy and that Swaziland could lose direct foreign investment if the affected organizations decided to close down their operations in the country. The survey showed clearly that what matters most to customers is the level of tariffs [Kennedy & Donkin, 1996] and power supply reliability [ERA technology, 2003]. Since most of the power outages occurred in summer this is a symptom that lightning contributed to these power cuts.

Chapter 2

Background work

2.1 Investigation on general causes of power outages in the country: 1997-1999 records

Ever since the establishment of the SEB in 1963 the traditional method of recording system power-outages has been the use of a hard copy-logbook system. For the purposes of this investigation on the causes of most frequent power outages, log books containing system outages from January 1997 to December 1999 were used as the source of data.

The power outages were logged in chronological order and time tagged. Information captured included the following;

- Weather conditions
- Time of power supply outages and time of restoration
- Circuits/or number of lines affected
- Details of relay indications
- Duration of power outage
- Damage found on the line
- Circuit breakers that operated
- Major customers affected
- Substations affected
- Permit numbers and names of personnel involved in such activity.
- Primary cause of power outage e.g. transformer failure, system overload, broken poles, broken jumper, storm, veldt fire.
- System Control Personnel for that shift.

These hard copy logbooks were filed systematically for ease of reference should the need arise to investigate a system outage.

Day to day details of the power system outages recorded in these log books were accurately fed into the Fault Reporting and Analysis System [FRANS, 1999] that was developed for fault analysis investigation for the SEB Transmission and Distribution systems. Table 3 shows a sample of the record of power supply outages in summer 1997 that affected Usuthu Pulp [Usuthu Pulp Outages, 1997].

Table 3:Faults that affected Usuthu Pulp from 3/31997 to 20/3/1997 (sample)

Date	Time	Affected breaker	Relay indication	Time of restoration	Cause of fault
3/3/97	15:23	3640&232 tripped	3640-o/c b. ATAR 323 –E/F	Re-closed at 15:25	Lightning
3/3/97	15:35	1530& 3640 tripped	1530-E/F 3640-O/C, ATAR	Re-closed at 16:06	Lightning
3/3/97	15:46	3630 tripped	O/C,ATAR	Re-closed at 15:49	Lightning
3/3/97	16:56	3630 tripped	O/C, ATAR	Reclosed at 16:58	Lightning
4/3/97	18:32	1530 tripped	Distance protection R&B	Reclosed at 18:39	Lightning
4/3/97	18:55	323 tripped	E/F	Reclosed at 18:55	Lightning

Source: SEB Fault hard copy log book for March /April 1997

2.2 Description of Fault Reporting and Analysis System (FRANS)

FRANS is a Fault Reporting and Analysis System that helps to identify problematic areas of the SEB Transmission and Distribution system. It helps to identify the causes of system outages. The most commonly occurring failures are readily identified thus enabling SEB to take appropriate corrective measures in a prioritised manner. FRANS consists of three Microsoft Access databases:

- Fault Reporting
- Plant Database
- System Loading

These databases are linked together to provide data to each other and they are also used separately. They are compatible with other software programs used by SEB. Data is entered manually into the fault reporting system. Data entered include:

- Region/ Area
- Circuit number
- Date & time of fault

- Date and time of final restoration
- Date of report
- Weather conditions at the time of the fault
- Fault cause
- Type of Relay Protection Scheme operated
- Damaged components of the system etc.

This system analyses or arranges the faults according to their cause in a manner such that the following can be extracted:

- Number of faults by cause - environmental related i.e. lightning
- Number of faults by cause - equipment related i.e. defective and /or accessories.
- Number of faults per feeder
- Average time to first restoration - countrywide
- Average time to first restoration - by area or region
- Average duration of faults - country wide
- Average duration of faults- by area /or region

In this manner a decision can easily be made as to which fault should be dealt with first and which fault causes can be dealt with last. The output from the Fault Reporting and Analysis System provided interesting results.

There was a distinct pattern in the faults over the twelve month period for all three years (1997,1998&1999). Figure 4 shows a bar chart of the sum of progression faults for the three year sample period. From this bar chart the clear cyclic pattern of faults over the year can be seen.

The bar chart indicates that there is a high occurrence of power outages in summer and fewer power outages in winter. This suggests that the bad summer weather, which is characterized by thunderstorms and lightning, causes many of the faults and subsequent high number of power outages.

The pattern shows that power outages increased towards the end of Spring (October) and peaked around February or March of the following year, i.e. at the end of the bad weather season (summer) in all three years. Also, the analysis of Faults by cause showed lightning was the most frequent cause of power outages for all three years.

Figure 5 shows a bar chart for the progression of power outages for the three-year sample period separated into faults due to lightning and faults due to other causes. This bar chart shows that lightning related power outages occur during the summer season. This results in the cyclic pattern of power outages that occur over the year.

Figure 6 shows a bar chart for the sum of the unknown fault causes for the three-year sample period. There is a pattern, too, with this category of faults. During the summer months there are more unknown causes of faults than in other seasons. This may suggest damage done by thunderstorms and lightning. Some of these outages may have been caused by lightning but due to the auto reclosing system and the transient nature of the fault, the cause could not be found.

Other observations from the output of the fault analysis exercise were as follows:

- Burning pole top faults occurred during some winter months, but not in all the three years,
- Falling tree faults occurred during summer months in all three years,
- Cane fire faults occurred during winter months in all three years,
- Wind related faults occurred during the winter months.
- Transformer fault related power outages occurred in summer, mainly due to overloading.

The above fault patterns generally held no surprises, but surprising fault patterns were as follows:

- In 1998 there were more system overload related power outages than in the other two years.
- Frequency distribution of burning pole top related power outages differed for all three years

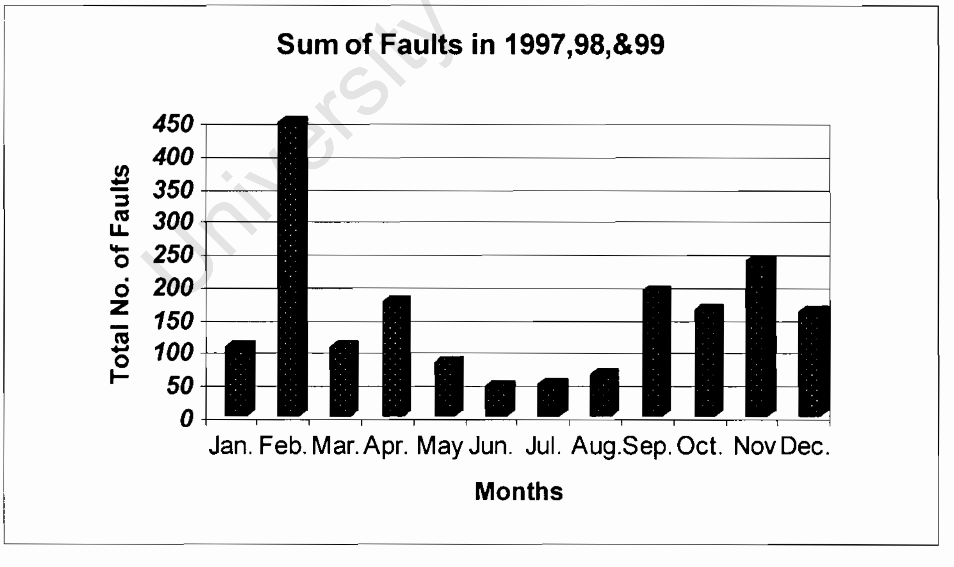


Figure 4: Sum of faults for 1997,98, 99.

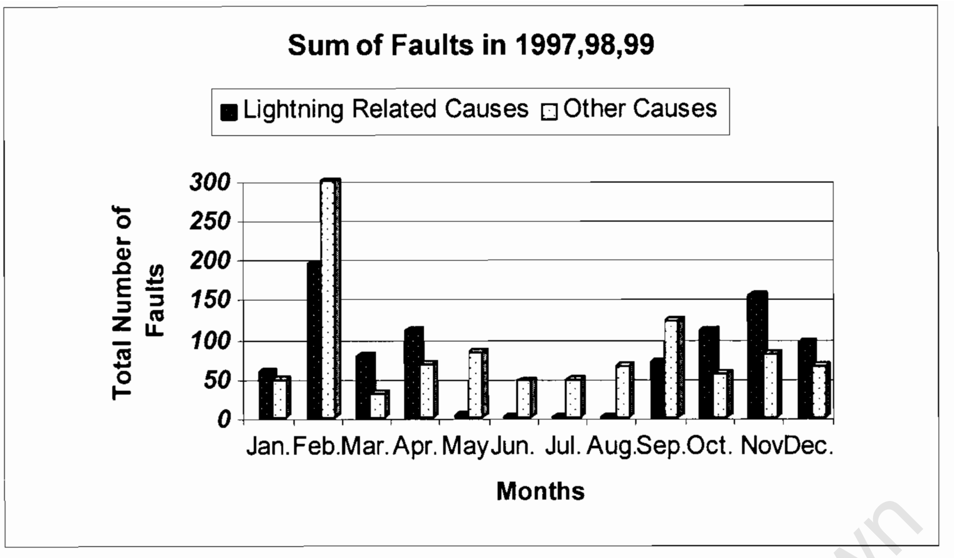


Figure 5: Sum of Faults for 1997,98 & 99 (lightning related and other causes)

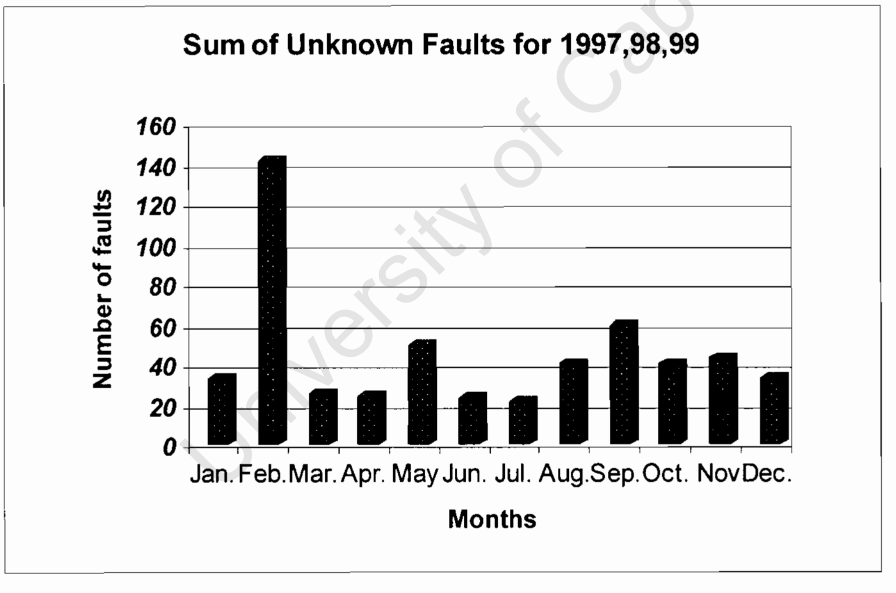


Figure 6: Sum of unknown fault causes

A total of 258 (45%) out of 574 faults were directly due to lightning. It has been observed from this preliminary investigation that generally there is a high percentage of lightning related faults in summer. Table 4 shows a breakdown of percentage number of faults per cause for 1997.

Table 4: 1997 % No. of Faults per Cause

J	F	M	A	M	J	J	A	S	O	N	D	%	
16	6	44	22	-	-	-	-	44	50	45	31	47	LIGHTNING
3	-	2	6	-	-	-	-	2	4	3	2	4	FALLING TREES
5	-	-	-	-	1				5		-	3	RAIN
1	-	-	-	-	-	-	-	-	-	-	-	0.2	CLASHING CONDUCTOR
18	45	13	12	15	5	5	6	11	10	18	13	31	UNKNOWN
2	-	-	-	-	-	-	-	-	-	-	-	1	ERROR BY SEB
1	-	-	-	-	-	-	-	-	2	-	3	1	FAULTY MAINTENANCE
-	8	-	-	1	-	-	3		-		-	2	ESKOM FAULT
-	1	-	-	-	-	-	-	-	-	-	-	0.2	SABOTAGE
-	2	-	-	-	-	-	-	-	-	-	-	0.4	THEFT
-	2	1	1	-	-	-	-	-	2	-	-	3	TRF FAULT
-	-	1	-	-	-	-	-	-	-	-	-	0.2	MECHANICAL SHOCK
-	-	-	3	-	-	-	-	-	-	-	-	1.0	CANE FIRE
-	-	-	-	4	-	-	-	-	-	-	-	1.0	OVERLOAD
-	-	-	-	-	-	-	-	-	-	2	1	1.0	ACCIDENT DAMAGE
-	-	-	-	-	-	4	-	3	-	-	-	1.0	ROTTEN/BROKEN POLE
-	-	-	-	-	-	-	-	1	1	2	-	2	BURNING POLE TOP
-	-	-	-	-	-	-	-	8	-	-	-	0.2	POLLUTION
-	-	-	-	-	-"	-	-	-	1	-	-	0.4	WIND
46	64	61	44	20	6	9	9	69	75	70	50		
Grand Total: 523													

Table 5 shows a breakdown of percentage number of faults per cause for 1998.

Table 5: 1998 % No. of Faults per Cause

J	F	M	A	M	J	J	A	S	O	N	D	%	FAULT CAUSES
26	3	15	-	-	-	-	-	11	52	45	31	42	LIGHTNING
15	3	6	7	23	10	11	10	24	19	18	13	36	UNKNOWN
-	-	-	-	-	-	-	-	-	-	-	1	.2	RAIN
-	-	-	-	-	-	1	-	6	-	3	2	3	FALLING TREE
1	-	-	-	-	-	1	-	-	-	-	2	1	ROTTEN/BROKEN POLE
-	-	1	3	2	2	7	-	4	-	2	1	5	OVERLOAD
-	-	-	-	21	6	5	-	3	-	-	-	8	WIND
-	-	-	-	1	-	-	-	1	-	6	2	2	FAULTY TRFR
-	-	-	-	-	2	4	1	4	-	-	-	3	BURNING POLE TOP
-	-	-	-	-	1	-	-	-	-	-	-	.2	CANE FIRE
-	-	-	-	-	-	-	1	-	-	-	3	1	FAULTY MAINTENANCE
42	6	22	10	47	22	27	12	53	71	71	74	54	
Grand total: 440													

Table 6 shows a breakdown of percentage number of faults per cause for 1999.

TABLE 6: 1999 % No. of Faults per Cause

	F	M	A	M	J	J	A	S	O	N	D	%	FAULT CAUSES
10	101	4	-	2	-	-	-	5	-	48	29	30	LIGHTNING
1	14	-	-	-	-	-	-	-	-	-	-	2	RAIN
-	93	6	5	11	8	5	24	24	11	7	7	29	UNKNOWN
4	66	7	5	1	2	2	9	6	3	3	11	18	FALLING TREES
-	17	-	1	-	-	-	2	-	-	-	-	3	ROTTEN/BROKEN POLES
-	-	-	-	-	-	-	-	-	-	-	-	-	OVERLOAD
1	3	4	-	1	3	1	2	1	2	-	-	3	CANE FIRE
-	10	-	-	-	1	-	1	4	-	-	-	2	BROKEN CONDUCTOR
-	15	-	-	1	1	-	3	1	-	-	-	4	BROKEN DISK INSULATOR
-	10	1	3	-	2	-	-	1	-	-	-	3	BURNING POLE TOP
-	4	-	1	-	2	-	-	-	-	-		1	VELDT FIRE
-	3	-	-	-	1	1	-	-	-	-	-	1	PROTECTION SETTINGS ERROR
-	2	-	-	-	1	-	-	1	-	-	-	1	WIND BORNE MATERIALS
-	21	-	-	-	-	-	-	1	-	-	-	0.3	EHV FAILURE
-	21	-	-	-	-	-	-	1	-	-	-	0.3	UNSUITABLE PARALLEL CONDITIONS
	22	-	-	-	-	-	-	1	-	-	-	.5	THIRD PARTY DAMAGE
-	2	-	-	-	-	-	-	1	-	-	-	0.5	FAULTY TRFR
-	1	-	-	-	-	-	-	-	-	1	-	0.2	FAULT THROWING DEVICE
-	1	-	-	-	-	-	-	-	-	-	-	0.2	FAULTY DESIGN
16	347	22	15	16	21	9	41	47	16	59	41		
TOTAL 666													

Table 7 shows % number of faults caused by lightning per month for 1997.

Table 7: 1997 % No. of Faults due to Lightning

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
% NO. OF FAULTS CAUSED BY LIGTHNING	35	0.1	72	50	-	-	-	-	51	67	61	53

From above, it can be observed that there is a high % faults caused by lightning in January and March.

Table 8 shows % number of faults caused by lightning per month for 1998.

Table 8: 1998 % No. of Faults due to lightning

MONTH	J	F	M	A	M	M	J	J	A	S	O	N	D
% NO. OF FAULTS CAUSED BY LIGHTNING	70	50	68	-	-	-	-	-	-	21	73	61	53

From above it can be observed that there is a high percentage of faults caused by lightning in the months of January, February, March, October, November and December.

Table 9 shows % number of faults caused by lightning per month for 1999.

Table 9: 1999 % No. of Faults due to lightning

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
% NO. OF FAULTS CAUSED BY LIGHTNING	63	21	0.18	-	0.13	-	-	-	-	-	81	71

From above it can be observed that there is a high percentage of faults caused by lightning in the months of January, November and December.

Table 10 shows average percentage of most (top 10) occurring faults per cause.

Table 10: 1997,1998, 1999 Average % of most occurring Fault per Cause (top 10)

1997	1998	1999	%	Fault Cause
47	42	30	39.7	LIGHTNING
31	36	29	32	UNKNOWN
4	3	18	8.33	FALLING TREES
2	3	3	2.67	BURNING POLE TOP
-	8	-	2.67	WIND
1	5	-	2	OVERLOAD
3	0.2	2	1.73	RAIN
3	2	0.2	1.73	TRFR FAULT
1	1	3	1.67	ROTTEN POLES
1	0.2	3	1.4	CANE FIRE

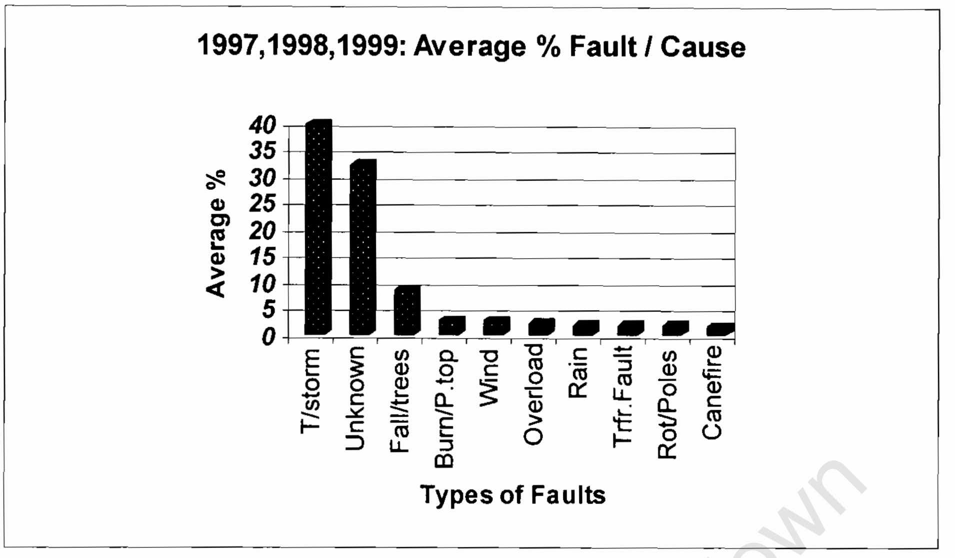


Figure 7:1997/98/99 Average % Fault Per Cause

From table 10 the findings were re-arranged in order to display the most common fault per cause- table 11.

Table 11: Fault per Cause Ranking

FAULT RANKING	AVERAGE %	FAULT PER CAUSE
1	39.1	Thunderstorm
2	32.0	Unknown
3	8.33	Falling trees
4	2.67	Burning pole top
5	2.67	Wind
6	2.00	Overload
7	1.73	Rain
8	1.73	Transformer Fault
9	1.67	Rotten Poles
10	1.40	Cane Fire

Observations from results of the investigation on causes of power outages from 1997 to 1999 are as follows:

1. Lightning is the cause of approximately 40% of all outages that occur in Swaziland- as shown in table 11. With the assumption that faults occurring under the "Unknown Causes" category being mostly suspected to have been due to lightning related flash over, the dominant cause of power outages in the country is lightning. These findings reinforced the hypothesis that lightning is the main cause of power outages in the country.

2. From the progression of faults of 1997,1998 and 1999, we see that the system outages are seasonal.

3. The cause of some 30% of outages in the country is not known. It is suspected, however, that these faults are due to flashovers, brushing trees, etc and that the actual cause of faults is never determined because of the auto re-closing operation of the protection system.

4. Falling trees constitute 8% of the causes of faults due to poor vegetation management.

5. The remaining fault causes contribute about 1 to 2% of fault per cause.

Figure 8 shows a summary of faults per cause for 1997, 1998 and 1999 respectively. This shows the impact of lightning /thunderstorm related fault causes.

2.3 Decision taken from the results of the preliminary investigation

The outcome of the investigation of fault causes for 1997 to 1999 resulted in the decision to conduct a study on three 66kV lines situated in the western part of the country, where there is high lightning flash density. It was decided that a detailed investigation on power outages from 2001 to 2003 would be undertaken.

Chapter 3

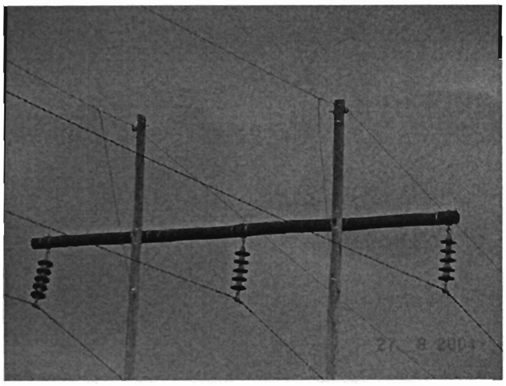
Lightning Related Power Outages - Investigation on three 66kV lines falling within the high ground flash density area

3.1 SEB 66kV Transmission System Configuration brief description

The system is predominantly constructed of wood pole structures. Structure type varies depending on the topography of the route of the line. The structures are mostly of "H" type construction and single pole type construction. The former is predominantly utilized in mountainous terrain and the latter used where the terrain is relatively flat. A shield wire is installed above the overhead-line conductors in all the lines. The shield wire is grounded along the route of the line. Transformation from 66/11kV is through delta-star transformers. The neutral is grounded via a restricted earth fault protection current transformer. The 66kV line and associated equipment is designed for (BIL) 325KV (minimum), and (fault Current) 20KA (Minimum). The system is mainly made up of ring feeders with circuit breakers installed in each end of the line. Because of the size of the country, the majority of line lengths do not exceed 50 kilometres per circuit. Figures 8 and 9 show the single pole structure and the "H" type pole structure construction

Source: Project Investigation photos: by L.M. Mswane

Figure 8: 66kV Single Pole Structure



Source: Project Investigation photos: by L.M. Mswane

Figure 9: 66kV "H" Pole Structure

The three selected lines and the criteria for their selection:

- **Stonehenge- Ezulwini Power Station 66kV line (5.2km)**

This line is the link between Ezulwini Power Station and Stonehenge substation that supplies the capital city of Swaziland, Mbabane. In Mbabane there are several industrial areas, commercial centres and government offices for all Ministries. Mkhinkomo substation. For these reasons it is critical that there is redundancy in the supply of power to Mbabane. Mbabane can be fed through four different sources theoretically but because of the length of two of the four lines, Mbabane is effectively fed from two sources. The other source is the 132kV line link from Mkhinkomo substation

- **Ezulwini-Thompson 66kV line (23.6km)**

This line is part of a critical ring-feed that supplies power to the Matsapha Industrial Area where sensitive manufacturing processes such as paper-tissue, textile industry, plastic extrusion etc are based. Most of their produce is for the export market (Africa outside Swaziland and overseas). In the past, some of these companies have threatened to close down their manufacturing processes owing to the high number of nuisance power outage and poor quality of supply, such low voltage magnitudes. In fact, in 1997 one of the textile manufacturers (Natex) scaled down its operation within the country such that they concentrated on spinning the yarn and exported it to a neighbouring country for finishing into fabric. Some of these power supply concerns have been addressed through the commissioning of the 400kV integration project. Concerns that have been addressed include quality of supply, particularly voltage magnitude, and the number of power outages at 132kV level. Power outages at 66kV and the distribution levels still have to be addressed. As discussed above, the frequency distribution of power outages at 66kV follows a seasonal pattern resulting in more outages in summer months.

- **Stonehenge-Usuthu 66kV line (31.4km)**

Although this line is currently playing a critical role in providing a back-up power supply to Usuthu it will not be fitted with 66kV Transmission Line Arresters (TLA's). In a few years time a 132kV line will be constructed from Edwaleni II bulk supply point to Stonehenge via Usuthu. TLA's will be fitted on this line.

3.2 Investigation process

A similar approach to the 1997 to 1999 investigation of causes of power outages was used. Using results from the previous investigation it was assumed that the single major cause of power outages for the three lines being studied from 2001 to 2003 was lightning. Also, a program of maintenance aimed at significantly reducing the other causes of power outages such as falling trees, rotten poles was initiated immediately after the investigation findings of 1997 to 1999. The findings of the Eskom investigation into the causes of power dips at Usuthu were used to make the above assumptions [Usuthu Pulp, 1996] and therefore no detailed investigation was carried out to determine the single major cause of power outages. Therefore this investigation only focused on the number of lightning related power outages for the years 2000 to 2003 for the three 66kV lines mentioned above. The findings were as follows:

3.2.1 Stonehenge – Ezulwini Power Station 66kV line

This line is located in the high lightning flash density area in the western part of the country where the country is mountainous [Vilakati SS, 2001] and peaks and troughs characterize the line profile [Tourist Guide, 2003/4]. The soil is sandy hence there is high tower footing resistance as shown by the measurements carried out in chapter 6.

Investigation Results.

The results indicated some association between the lightning activity that occurs in summer with the thunderstorms. The summer rain fall season starts in September/October each year and stretches to March/April of the following year [Swazimet, 2004], [Vilakati SS, 2001], [Swazi Telecom, 2004]. The lightning related power outages happened in the summer as shown in table 12. They started during September/October and ended in April/May the following year. The faults peaked around December/January every year except in 2003. In 2003 there were no lightning related power outages starting in September/October as in the previous three years. The implementation of the pilot project was carried out in August 2003. The absence of lightning related power outages during this time is attributed to the transmission line surge arresters fitted along the length of the line in selected positions in August 2003. Lightning related faults were low from January to April 2003 compared to the previous years. This may be because there were fewer thunder and lightning storms during the drought of 2003 [Swazi Bank, 2004], [Central Bank, 2003/4], [Swaziland Electricity Board, 2003/4].

Figure 10 shows the results of the investigation in a bar chart form. The lightning flash density of the area traversed by this line ranges from 9 – 10 to 10 –11 flashes per square kilometer per year [Lightning ground flash density Map, 1996]

Table 12: 2000 – 2003 Stonehenge – Ezulwini 66kV line lighting related power outages

Months												Years
Jan.	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	
5	6	5	3	1	0	0	0	0	4	4	7	2001
4	3	7	2	0	0	0	0	1	3	4	8	2002
3	1	2	1	0	0	0	0	0	0	0	0	2003

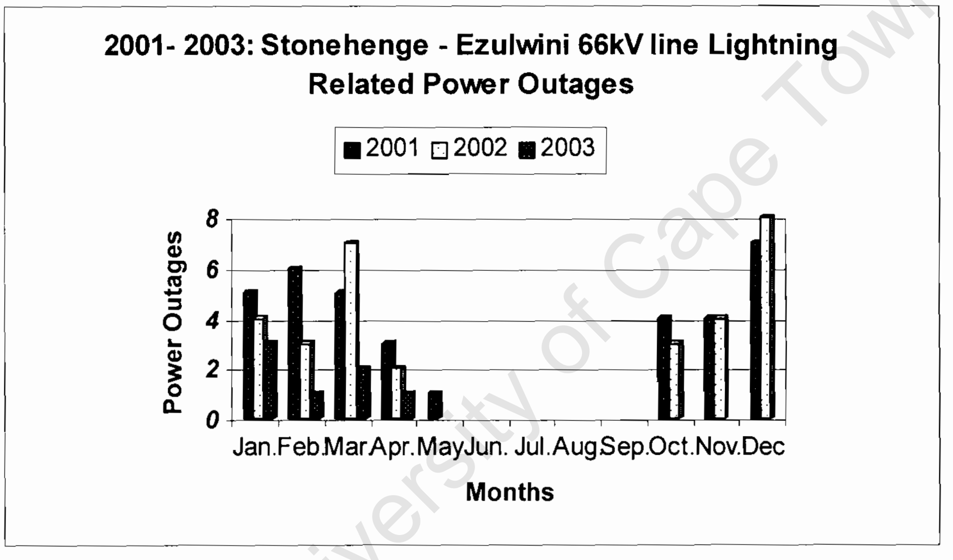


Figure 10: 2001 – 2003 Stonehenge – Ezulwini 66kV line lightning Related Power Outages

3.2.2 Stonehenge-Usuthu 66kV line (31.4km)

This line is located in the mountainous western part of the country [Vilakati SS, 2001].

Investigation Results

The pattern of results for the investigation for this line was similar to the results for the Stonehenge – Ezulwini 66kV line. Lightning related power outages occurred during the summer months from September/October to April / May of the following year. These findings correlated with the findings of the investigation carried out by Eskom on the causes of power dips to Usuthu [Usuthu Pulp, 1996] The pattern of power outages related to lightning were similar for the first three years (2001, 2002) but decreased significantly during 2003. This decrease may be attributed to the drought that took place in 2003 [S E B, 2003/4]. Table 13 shows the results of the investigation. Figure 11 shows the results of this investigation in a bar-chart format.

Table 13: Stonehenge -Usuthu 66kV line Lightning Related Power Outages

Months												Years
Jan.	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	
5	6	4	2	1	0	0	0	0	4	6	6	2001
4	5	6	1	1	0	0	0	0	2	5	7	2002
3	2	-	1	0	0	0	0	0	1	2	2	2003

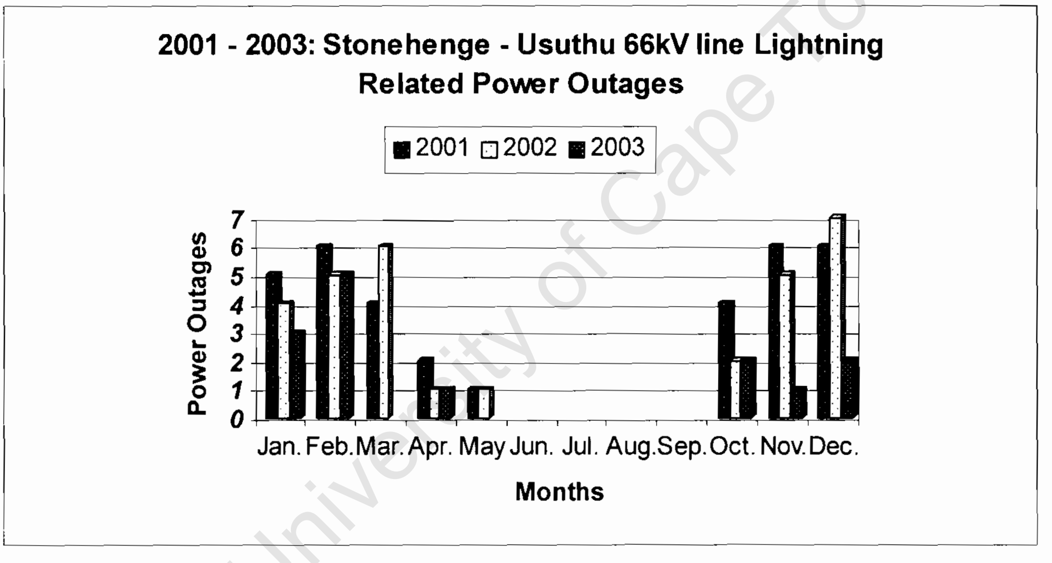


Figure 11: Stonehenge – Usuthu 66kV line Lightning Related Power Outages

3.2.3 Ezulwini-Thompson 66kV line (23.6km)

The terrain along this line is undulating and less mountainous than that of the two 66kv lines investigated above. It is also located on the western part of the country where there is high lightning flash density.

Investigation Results

This line falls within the same zone of lightning flash density traversed by the other two lines that were investigated above. The pattern of lightning related power outages is similar to the Stonehenge – Ezulwini 66kV line and the Stonehenge – Usuthu 66kV line. Power outages started around September/October and finished around April/May of the following year. This pattern matches with the summer season in Swaziland where the lightning activity occurs with the summer rains [Usuthu Pulp, 1996] Table 14 shows the results of the investigation. Figure 12 shows the same results in a bar-chart form.

Table 14: Ezulwini-Thompson 66kV line Lightning Related Power Outages

Months												Years
Jan.	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	
3	4	4	2	1	0	0	0	0	3	6	5	2001
5	6	4	3	1	0	0	0	0	2	3	6	2002
2	3	2	0	0	0	0	0	0	1	1	2	2003

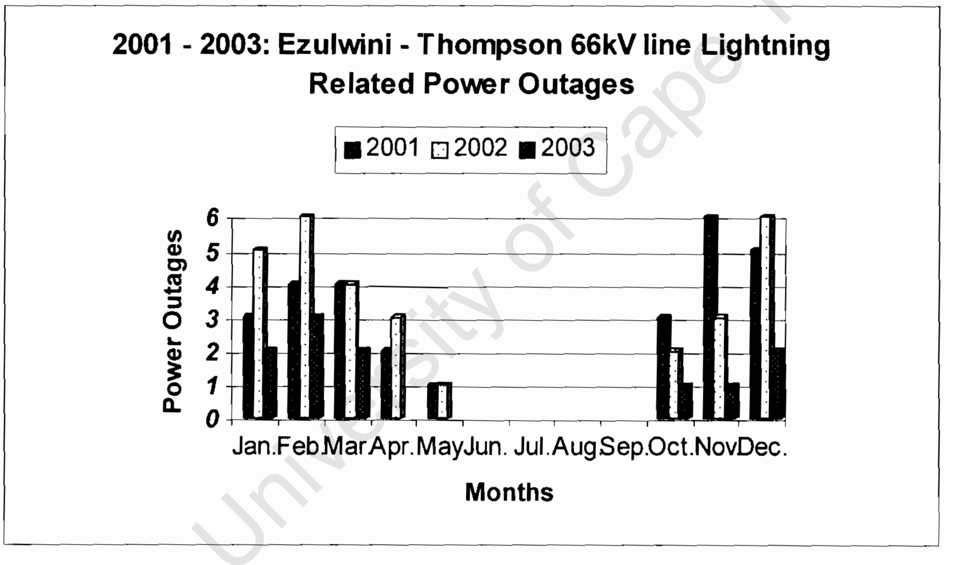


Figure 12: Ezulwini-Thompson 66kV line Lightning Related Power Outages

3.2.4 Summary of findings from the above investigation:

- Lightning is the single most common cause of power outages in the three 66kV lines investigated.
- Lightning related power outages occurred in summer during the years of investigation.

Lightning related power outages on the three 66kv lines occurred during the summer months only. This correlated well with the investigation carried out by Eskom on causes of power dips at Usuthu Pulp in 1996 [Kennedy and Donkin, 1996]

3.3 Conclusion:

As result of the above investigation into the causes of power outages of the above three 66kV lines and the results, a decision was taken to undertake a pilot project. The decision was that the pilot project would involve the installation of Polymer-Housed Zinc Oxide Surge Arresters on selected structures along a 66kV line (Stonehenge – Ezulwini 66kV line) located in a high lightning ground flash density area.

3.4 The Research Question

Would the installation of ZnO surge arresters improve the lightning performance of transmission lines in the SEB transmission network?

- Would the results of the pilot project indicate that installation of TLA's on the pilot line reduce the number of outages caused by lightning compared with the two lines without TLA's?

- Would the cost of installing, and maintaining the TLA's be less than the cost of remedial work and revenue loss?

- Would the installation of TLA's provide better service to customers; would they avoid production losses and less complains to the SEB?

- Would the implementation of this program be of economic benefit to the country due to the reduction of production losses to industrial customers?

The purpose of this pilot study would be to determine if the surge arresters improved the performance of the 66kV line fitted with TLA's, and to test the viability of this project related to revenue loss and other economical gains to SEB customers.

Chapter 4

Effects of Lightning on power systems and Experiences from other countries

4.1 Introduction

According to line fault records, lightning causes as much as 30% outages in most of utilities [Bologna et al, 2004], [Gaunt, Mswane, 2001], [Mobedjina, Strenstrom, 2000], [INMR, 1997], [Electra, 1999].

Reliable power supply is critical for the economic sustainability of any country. Electricity supply service is critical not only for Business-to- Business (B2B) but also for Business-to-Consumers. From a B2B point of view, an unreliable supply will not only affect the power supply provider but also the receiver or the consumer. Electricity is a unique commodity as it cannot be stored and as such if there is an outage there is an instant stoppage of the metering system from the supplier point of view, and to the customer, i.e. there is a production process stoppage. Production process stoppage means the loss of sales revenue to many companies. [Zeithaml, and Bitner, 2003] argues that "... *Service Equals Profit*..." and [Billinton, Allan, 1980] says that..." *reliability consists of both adequacy and security of supply; hence supply interruptions, regardless of the cause, constitute a reduction in reliability*..." Lightning strikes reduce utility profitability by causing service interruptions, as well as damage to power system equipment. The motive behind the Electricity Supply Industry restructuring changes taking place now in many parts of the world is to improve overall service performance. For some industries the tariff plays a decisive factor in business performance, for some industries it is the security and reliability of power supply [Mobedjina, Strenstrom, 2000].

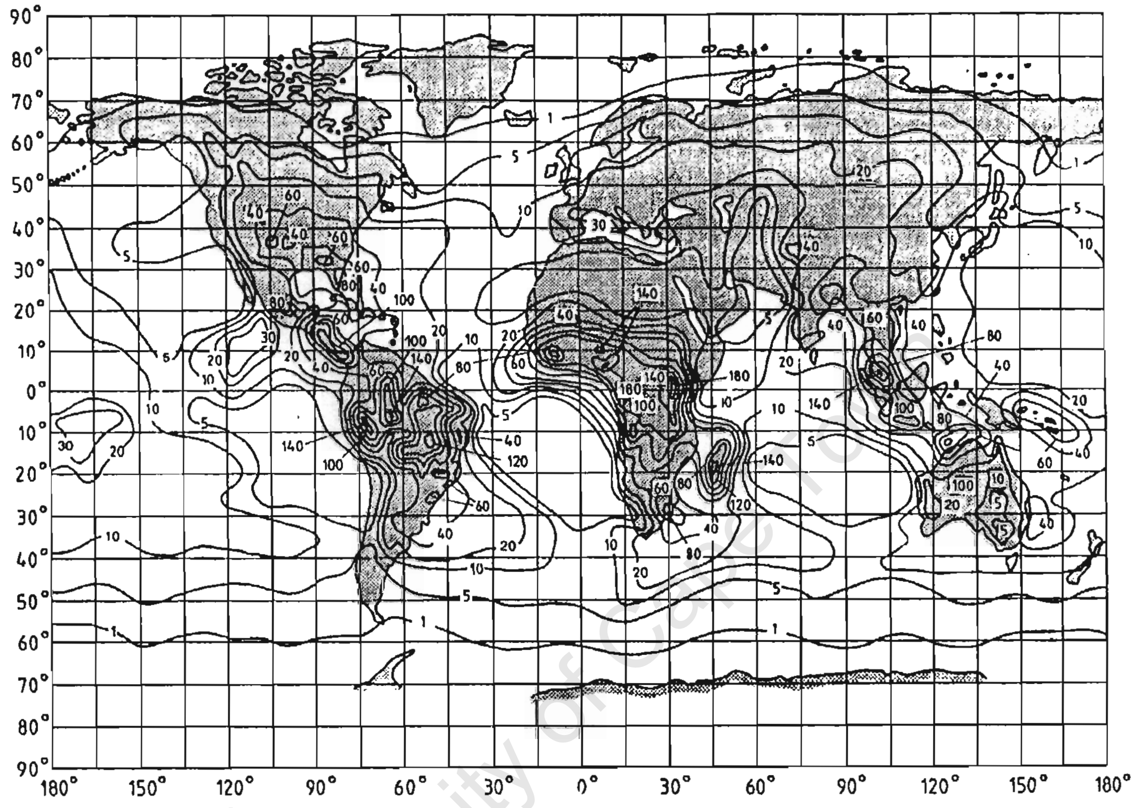
The customer survey conducted by Kenedy & Donkin in 1996, cite costs suffered by the customers as a clear example of the effects of lightning on power outages. (- see table 2.)

Electric Power Research Institute (EPRI) project manager Andrew Phillips argues that:

> "*Lightning is the most frequent cause of transmission outages and service interruptions in the U.S.,*". " *Some 30% of all power outages are lightning – related, with total costs approaching one billion dollars annually*...." [Posada, Restrepo, 1996], [Boutacoff, 2004].

The high number of power outages attributed to lightning clearly does not only affect Swaziland. More than 50% of electrical faults on transmission overhead lines are due to lightning [ELECTRA, 1999], [Bolonga et al, 2004]. A study conducted by Minnkota Power (Grand Forks, North Dakota, U.S.) in 1994 concluded that about 45% of all operations were lightning induced [Johnson, 2002]

As lighting causes electrical faults in all five continents, a number of electrical power utilities have gathered statistics on the number of electrical faults caused by lightning. Figure 13 is a world map showing thunderstorm days/year. This shows clearly the severity of lightning worldwide.



Source: [BS 6651, 1999]

Figure 13: World map showing Thunder Storm Days/year

Statistics from an analysis of outages on overhead distribution lines in South Africa, shown on table 15, show that 30% of power outages are due to lightning [Gaunt , 1994].

Other major causes of power outages in South Africa that are common to those of the Swaziland Electricity Board are:

- Unknown,
- Wind,
- Trees,
- Fire,
- Inadequate rating.

Table 15: Analysis of Causes of power outages in Distribution Lines in South Africa

Reason for outage	Screened Lines	Unscreened Lines	Total	%
Unknown	273	264	537	20,9
Supply system failure	57	72	129	5,0
Operation and Maintenance	94	222	316	12,3
Accidents	32	15	47	1,8
Vandalism	30	28	58	2,3
Poor workmanship	6	4	10	0,4
Known lightning	***121***	***312***	***433***	***16,8***
Presumed lightning	***200***	***224***	***424***	***16,5***
Wind	3	95	168	6,5
Fire	4	4	8	0,3
Population	1	10	11	0,4
Birds	24	29	53	2,1
Animals/reptiles	5	5	10	0,4
Debris	0	3	3	0,1
Corrosion	18	14	32	1,2
Insects/Rot	5	6	11	0,4
Trees	64	46	110	4,3
Equipment failure	95	69	164	6,4
Inadequate rating	1	1	2	0,1
Other	23	24	47	1,8
Total Outages Causes	1 126	1 447	2 573	100

Source: [Gaunt, 1994]

Other countries also have high lightning ground flash density and overhead transmission -lines are negatively affected by lightning. Table16 shows statistical data on power outages on transmission lines that are attributed to lightning during the period from 1980- 1991 in Japan [Electra, 1999].

Table 16:1980-1991 Statistics on power outages on overhead lines in Japan

Transmission line voltage Level rage	Total number of outages	Outages caused by lightning	Outages due to other causes	% No. of power outages caused by lightning
66kV-77kV	4431	2211	2220	49.9
110kV- 154kV	733	411	322	56.1
187kV- 275kV	122	21	81	33.6
500kV -	5	1	4	20

Source: [Electra, 1999]

4.2 Brief description of Lightning Activity

Bolonga et al, 2004 state that "... Lightning is defined as transient, high current electric discharge from a charged cloud to another cloud or earth ..." Thunderclouds are formed when moist air ascends and cools below the dew point, enabling condensation to take place [Guile, Paterson:

1977]. This process is followed by the freezing of water droplets as they are carried by the rising air currents into regions where the ambient temperature is far below the freezing point. In the course of these processes, charge separation and accumulation occur and a positive space charge occurs in the upper sections of the cloud and a negative charge elsewhere, except at the cloud base where a localized positive charge accumulation forms at the point of highest concentration of rising currents. As the charge accumulates, the field within the cloud, between clouds, or between a group of clouds and earth builds up until breakdown processes occur. By this time the potential difference between earth and the thunderclouds lies in the region of millions of volts. The thunderclouds can grow to 12 miles high and up to 15 miles across [Freeman, Bettermann, 1999], [Williams, 2003], [Uman, 1984]

The lightning stroke consists of two components. A leader stroke from the cloud initiates a streamer from the earth. The streamer channel completes a conducting path along which a return stroke passes [Uman, 1984]. The 'stepped leader' is the initial streamer out of a cloud. It progresses very quickly in jerky branches extending down wards. When it is some 10 to 100 metres from the ground, which is at this time charged, the ground emits streamers upwards towards the stepped leader [Cooray, 2003]. These streamers are usually emitted through tall structures such as transmission towers, trees, tall buildings, external lightning protection rods etc. When they make contact with the stepper leaders the return stroke of the lightning occurs. A very bright flash of light takes place due to the lightning return stroke current and very loud thunder sound is heard. All this happens very quickly. Some lightning strikes happen between thunderclouds and the ground, called ground flashes, and a lot of lightning takes place between the thunderclouds.

The damaging part of a lightning strike is the return stroke. This is the part of the strike in which a charged cell in a thundercloud is discharged to earth. Current magnitudes in these strokes range from 2000A to approximately 200,000A and their distribution of values is as listed below [Freeman, Bettermann, 1999], [Cooray, 2003].

- 99% of strokes exceed 3,000A
- 90% of strokes exceed 8,000A
- 50% of strokes exceed 28,000A
- 10% of strokes exceed 80,000A
- 1% of strokes exceed 200,000A

When a lightning strike hits a structure it has a huge energy to discharge. Any equipment that stands between this surge of energy and its intended route to earth could be damaged. This damage is as result of the potential difference generated by the lightning strike between the object that it strikes and the earth. The function of the lightning arrester is to remove this potential difference or reduce it to a level that electrical equipment can handle without damage, i.e. the normal system voltage [Hubell, 2003a], [Mobedjina, Strenstrom, 2000].

For engineering purposes the intensity of lightning is measured in-terms of the ground flash density, Ng, which is expressed in flashes/sq km/annum and is read from a flash density map. The isokeraunic level defines the number of annual thunderstorm days for a given area or region [Ohio Brass, 1995]. Only lightning flashes to ground are significant for power lines as cloud to cloud flashes have a negligible effect. Lightning causes faults in power system by three mechanisms. These are direct strikes to the phase conductor, the inducing of over voltages in the line when lightning strikes the ground close to the line, and back flash after striking shielding earth wires or supports [Gaunt, 1982 and, Bologna et al, 2004] in the following ways:

- Direct strikes

Direct strikes usually inject negative voltages on the phase conductors of the affected line. This consequently leads to phase-to-ground and phase-to-phase faults and subsequently power outages due to protection operation [Britten, 1990].

- Indirect strikes that cause induced over voltages

Indirect strikes result in induced voltages as result of magnetic coupling between nearby flashes to ground and the affected transmission line. On unshielded lines with rated voltages below 50kV and on shielded lines below 20kV, the nearby lightning strike induces voltages in the phase conductors that are comparable to the impulse level of the line insulation and there is a possibility that a flashover may occur. The arresters can protect systems from induced voltages in the same way as for shielding failures and direct strokes [Electra, 1999]. However, if the insulation levels of all lines are 300kv or more for a well grounded system, it is expected that the induced surges may result in flash over of the line insulation, and fitment of arresters may not further improve a line's response to induced voltages. Table 18 shows characteristic stresses caused by lightning on overhead lines [Gaunt, 1982], [Nucci, Rachidi, 2003], [Electra, 1999].

- Back-flashes that cause over voltages

In simplest form the process involves the strikes to the tower or the shield wire and/or a phase. Normally this surge is discharged through the footing resistance of the structure. If the tower footing resistance, or the lightning current, or both are high the voltage potential across the insulator may be high enough to exceed the insulation level of the line and to initiate a back flash to the phase [Electra, 1999], [Bologna et al, 2004]. Under normal circumstances, if the tower footing resistance is within acceptable levels, the surge is successfully discharged to the ground [Bologna et al, 2004], [Electra, 1999], [Ianoz, 2003].

When a lightning strike occurs directly to an overhead transmission line, a high voltage is injected into that line, generating an electric current surge. It is the action of this current surge that causes an over voltage [Meliopoulos, 1988], [Hubbell, 1995].

Following a direct strike on a power line, the lightning current can be distributed in different ways of the transmission line depending on the point at which the line has been hit [Electra, 1999]. For example, a lightning strike penetrating the shielding system and terminating a phase conductor will result in two travelling waves of voltage and current surge of the same magnitude and polarity but propagating in opposite directions from the stroke terminal. The magnitude of the impulse voltage and current is determined by the stroke current magnitude and the surge impedance of the line [Ohio Brass, 1995]. When one of these waves reaches a tower it can flashover the insulation and dissipate to the ground. This is as a result of the transient voltage that develops across the insulator of the phase that has been affected [Meliopoulos, 1988]. However, depending on the tower surge impedance and the tower footing resistance, the some current can continue travelling beyond the tower along the conductor.

If a lighting arrester is connected across the insulator string the flashover at that point is avoided and protection of all the three phases with transmission line arrester against lightning improves considerably [Cherchiglia, 2000], [Mobedjina, Strenstrom, 2000], [Hubell, 2003].

When the stroke strikes a ground wire it is conducted to the ground. This occurrence could also involve several towers. However if the potential reached at the top of the tower as a result of high surge impedance of the tower and the ground exceeds the insulation level of the transmission line a back flash could occur [Ohio Brass, 1995]. This could be avoided by the installation of lightning arresters on the transmission line.

As discussed above, when there is a direct stroke to the line, travelling waves of current propagate in different directions along the line until a flash over occurs through the process of equalizing the potential difference between the line and earth or between phases as result of insulation break down. It is such flashovers that are detected by the protection system that results in either a permanent or temporary power supply interruption. The flashovers sometimes result in insulator string damages as shown in figure 5 above. Figure 14 depicts a typical wave propagation and the eventual flash over that would occur if the surge voltage across the insulator is adequate, i.e. without the presence of a transmission line arrester fitted across the insulator.

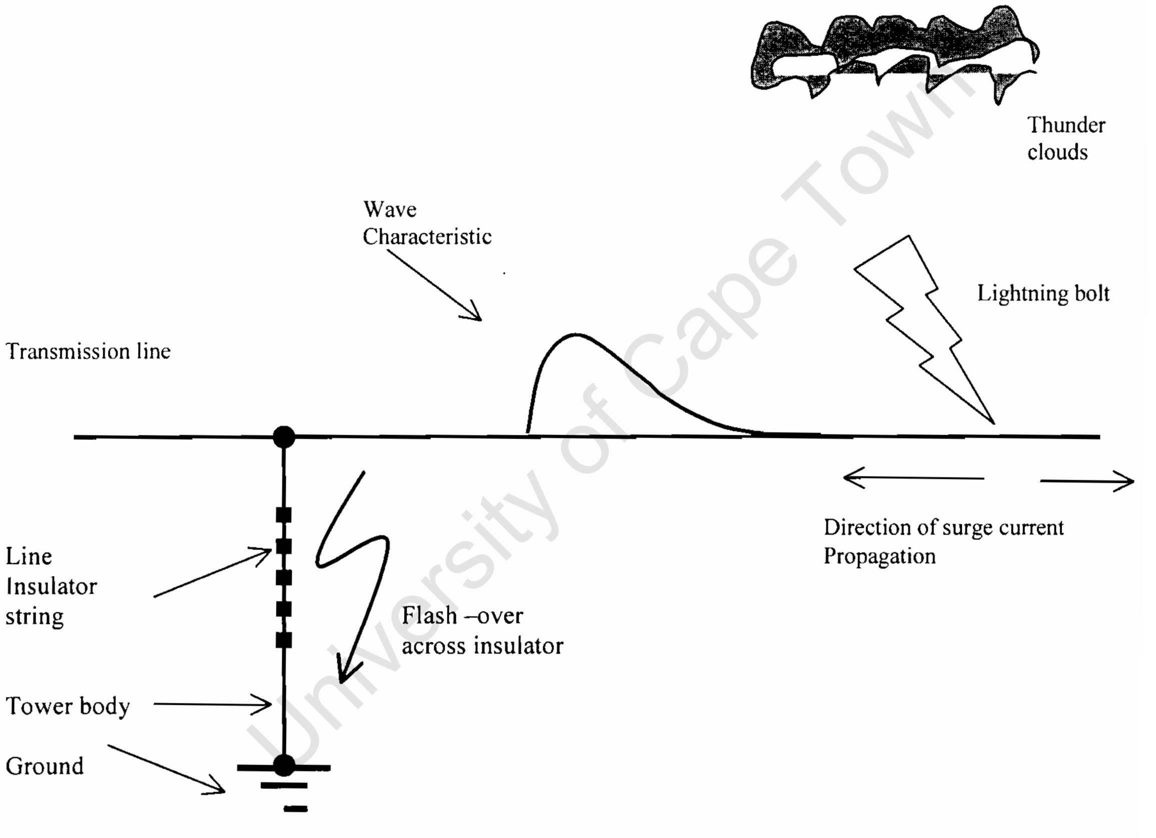


Figure 14: Lightning wave characteristic & flashover across insulators

4.3 Global experiences on application and performance of zinc oxide transmission line surge arresters

Activities in response to lightning are found in many parts of the world. Electric power utilities supplying customers with sensitive industrial processes across the globe have had to implement lightning performance improvement solutions in order to reduce lightning induced power outages to levels acceptable to their customers. From figure 13, the world map showing the mean thunderstorm days, it is clear that many countries across the world have high isokeraunic levels.

Electric power utilities in countries such as Brazil, Japan, USA and South Africa have had to install zinc oxide (ZnO) surge arrestors in order to reduce the high number of unscheduled power outages caused by lightning [Chechinglia LCL, 2000], [Electra, 1999].

4.3.1 Brazil:

The application of ZnO surge diverters in Brazil began in 1996 on lines where other means of improving the system performance had no benefit. ZnO Surge arrestors were installed on a number of transmission and distribution lines. Companhia Energetica de Minas Gerais- CEMIG [Cherchiglia LCL, 2000] had to install Zinc Oxide Surge Arrestors in order to improve performance of their distribution lines in the mid 1990's.

- Diamantina – Gouveia 43.5kV wood pole line;
  Surge arrestors were applied to this line in every pole of three stretches of the line corresponding to 50% of the total line length. The performance of the line was then monitored 1997 to 2000 and the outage rate decreased to 40% of the observed outages in former years and all the outages occurred in stretches without surge arrestors.

- Ouro Preto – Ponte Nova 138kV steel structure line;
  Application of ZnO Surge arrestors started at the beginning of 1998 following an un-satisfactory performance of the line due to lightning induced power outages. Performance of the line improved tremendously.

- Peti – Sabara 69kvV wood pole line;
  This line is located in a high lightning flash density area and hence it was specifically designed to have surge arrestors installed on it. Surge arrestors were installed in 1999. Performance of the line improved significantly.

Summary of results for lines fitted with surge arrestors are shown in table 17.

Table17: Performance Improvement of CEMIG Transmission & Distribution lines after implementation of Metal Oxide Surge Arrestors

Transmission Line	Outages/100km/year	
	Before	After
Diamantina – Gouveia	62	24
Ouro Preto – Mariana	41	0
Ouro Preto – Ponte Nova	31	9
Itutinga – Minduri	19	6
Peti - Sabara	40	13

Source: LCL Cherchiglia: Service Experience with lightning arrestors in CEMIG Brazil

In view of the good results of the line performance improvement obtained after the application of ZnO surge arrestors, CEMIG decided to continue applying such surge arrestors on its lines.

4.3.2 Japan:

Isokeraunic levels are also relatively high in Japan and many customers have highly sensitive industrial processes. The article in INMR Magazine states that

> "*In Japan, well over half of all faults on overhead lines are a direct result of lightning, even though isokeraunic levels in that country are not so unusually high. At the same time, Japanese utilities are faced with ever- greater demands for reliability from their customers. Due to the combination of these factors, transmission line arresters have become an important component in the various measures utilities in this country uses to reduce lightning-induced trip-outs*" [INMR, 1997].

Because of the high number of power outages that are lightning induced, a number of electric power utilities have installed ZnO surge arrestors.

Electric Power Utilities such as Chubu Electric and Kansai Electric Power have installed ZnO on all important transmission and distribution lines [INMR, 1997].

- Chubu Electric, the third largest utility in Japan, commenced a program to fit gapped type surge arrestors in selected points along 77kV and 154kV transmission lines as far back as 1986 and within10 years had installed over 20,000 units. At the conclusion of the program 37% of 77kV towers and 10% of 154kV towers in its network were equipped with surge arrestors [INMR, 1997].
- Kansai Electric Power, the second largest power utility in Japan, based in Osaka, has fitted polymeric gapped arrestors on selected points along its transmission system up to 500kV. Reports by engineers suggest that application of surge arrestors on a 77kV line resulted in considerable performance improvement on the line after all towers were equipped with surge arrestors [INMR, 1997]

4.3.3 USA:

Isokeraunic levels are also relatively high in the USA, where there are highly sensitive industrial processes similar to those in Japan. In some parts of the USA mean thunderstorm days/year are as high as 80. Due to a high number of power outages that are lightning induced a number of electric power utilities have installed ZnO surge arrestors.

Nearly 50% of the USA's 30 largest utilities, and over 90 utilities in total, have installed arresters on lines from 69kV to 230kV. A large percentage of applications are found in the southeast region of the USA where lightning ground flash density is very high. In this part of the USA the isokerounic level is in excess of 80 and the ground flash density is excess of 10 flashes/sq. km/year [Electra, 2003]

- A utility in Georgia (Georgia Power) decided to install metal oxide arrestors on a 115kV line that had excessive power outages [Electra, 2003]. This application resulted in the performance improvement of this line.
- XCEL Energy, a transmission company in Minneapolis, which had several hundred miles of unshielded lines with unacceptable service levels because of lightning induced outages introduced ZnO surge arresters in order to improve the performance of their transmission system [LaCasse, 2003], [Hubell, 2003a]. Over a period of three years, from 1994 to

1996, XCEL Energy installed about 6,000 Ohio Brass Protecta* Lite ZnO systems to help protect the troubled 69kV lines. The program was a great success. From a high of 20 to 30 trips per year per 100 line miles, the number of lightning induced trips was reduced to between 8 and 10 per year.

- The Municipal Electrical Authority of Georgia (MEAG) experiencing a high number of power outages due to lightning on some transmission lines that were shielded and those not shielded. The isokeraunic scale of lightning incidence in the state of Georgia ranges from 60 to 80. The installation of metal oxide lightning arresters resulted in the reliability improvement of the MEAG system from 16 outages per 100 miles of line to 9 per 100 [Hubell, 2003b].
- Duke Power Co. experienced an insulation flash over problem with its 100kV Westmininster B&W line in the early 1980's. Following an analysis of the causes of the power outages on the line, some 40 Zinc Oxide arresters were placed directly on selected transmission structures which consequently eliminated the flashover problems and reduced the number of outages [Boutacoff, 2004]

4.3.4 Colombia:

- An electric power utility in Colombia, Empresas Publicas de Medellin (EPM) had a dedicated 115kV (Guatape-Rioclaro) transmission line to a cement plant that had been fitted with a certain type of lightning arresters but experienced a high number of power interruptions. A study was subsequently undertaken and resulted in the replacement of the previous type of lightning arresters. The installation of the ZnO arresters had positive results. Following the good performance of this line EPM decided to install ZnO arresters on other transmission lines that had been experiencing similar problems [Posada, Restrepo, 1996].

4.3.5 South Africa:

- In South Africa, a 275kv transmission line belonging to Eskom running from Bighorn to Pluto substation showed a tremendous improvement of lightning performance of the line after a tower were fitted with surge arrestors in 1994. This line is located in an area with approximately 60 thunderstorm days per year.

4.3.6 Lesotho:

In Lesotho, another country with high isokeraunic activity, the levels are as high as 10 and 13 strikes per sq. km per annum in some parts. In 1995 metal oxide arresters were installed at carefully selected positions along 110 km of the line linking the Katsi Dam and the rest of the network [Schuld, 2003].

General

In recent years the application of overhead transmission line arresters containing ZnO elements has been an effective method to prevent line faults due to lightning.

The conclusion of a paper on the application of metal oxide surge arresters to overhead lines in stated "...The expansion of the application of metal oxide surge arresters to the overhead lines has been remarkable in recent years. The voltage class of the applications ranges from several kV to EHV voltages. The operating experiences have shown their excellent performance...." [Electra, 1999].

4.4 Common aspects of utilities that have applied Metal Oxide Surge Arrester solution

- All utilities are found in countries with high isokeraunic levels.
- All utilities were experiencing a high rate of power failures due to lightning.
- All utilities decided to apply metal oxide surge arrestors on key lines that were performing poorly.
- All utilities reported good performance improvement of the affected lines after the application of metal oxide surge arrestors.

4.5 Comments on Current Usage of Spark Gaps & Gapped Surge Arresters

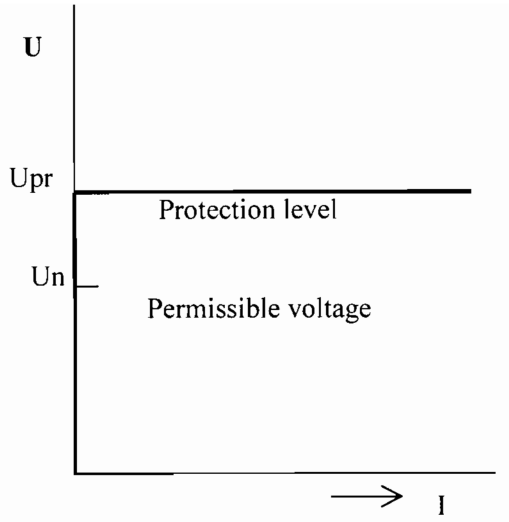
4.5.1 Spark Gaps

A spark gap is a protective device that consists of an open-air gap between an energized and an earthed electrode or rod. These devices are installed in parallel with insulators between the live terminal equipment and the grounded equipment. Arresters have replaced these in recent years. The operation of a spark-over voltage and the time-to-spark over of the gap depend mainly on the gap or distance between the live electrode and the earthed electrode. The spark gap setting is such that it breaks down at voltages well within the breakdown insulation level of the equipment that this device is meant to protect. The shape of the arcing horns influences the operation of this device or electrodes as does the distance to neighbouring live and earthed parts. In order to improve the performance of a spark gap under steep-fronted surges and to provide a flatter impulse spark over voltage time characteristic, the geometrical configuration of a simple rod-rod electrode arrangement can be modified, such as by appropriate shaping of the electrode and an insertion of a central auxiliary electrode [van der Merwe, 1990]

The characteristics of a spark gap is influenced by the following;

- The dispersion of the spark-over voltage of an air gap,
- The increase in the spark-over voltage with increasing amplitude of the applied wave.

When spark over takes place on the front of the wave, the protection obtained by means of spark-gaps is less accurate and the protection level cannot be guaranteed as can the protective level of non linear surge arresters. Figures 15 and 16 show the characteristics of a spark-gap and that of a non linear surge arrester respectively. The performance of a spark gap under impulse, switching or lightning, is characterized by the 50% value and the standard deviation of its discharge voltage under standard laboratory conditions. Also, for the reasons given in the first bullet above, knowledge of the times to- spark-over of the spark gap for values of the applied impulses high above the 50% spark-over value is often required [van der Merwe, 1990].



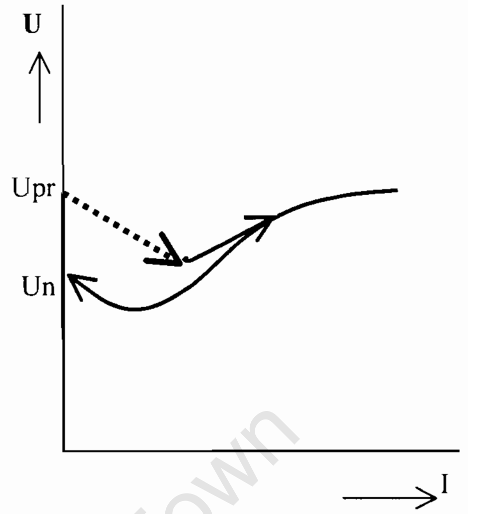


Figure 15: Current- Voltage characteristic of an ideal surge arrester

Figure 16: Current-Voltage characteristic of present day arrester with spark gaps

Source: [van der Merwe, 1990]

Spark-gaps limitations

Although relatively straight-forward and easy to make, spark gaps have several limitations in terms of effectively protecting equipment that they are required to protect [van der Merwe WC, (1990)]. These limitations are discussed below:

- When the spark-gap operates a short circuit power arc fault is created which causes the protection system to operate and isolate the circuit. However this arc frequently persists until a fault protective device disconnects the system, with the effect that a phase-to-earth fault persists in the case of a system with a directly earthed neutral. This causes stresses on various parts of the system where the system is directly earthed and may cause disturbances to users. The positioning of the spark-gap must therefore be considered in relation to its effect on the system protection and operation.

- A spark gap is not preferred in the sense that service continuity in its presence increases the number of circuit outages, provided the flashovers are neither self extinguishing nor interrupted by means of a high-speed tripping circuit breakers followed by high-speed auto re-closing operation.

- Equipment could be damaged by power-arc across the spark gap if this is not installed in a suitable position. If a spark gap is fitted to the bushing of a transformer, its distance from the bushing surface must be sufficiently large to prevent a power-arc being blown towards the transformer bushing.

- The operation of spark gaps causes chopping of the wave and increases the probability of producing chopped waves close to the terminals of the protected equipment. Equipment with high voltage windings, such as transformers and reactors designed to withstand only full-wave tests, is vulnerable to a surge of high amplitude chopped in its vicinity since higher internal stresses than under full-wave conditions can be developed across adjacent turns and coils. All flashovers to earth in a substation result in chopped waves of various degrees of amplitude and steepness. If spark gaps protection policy is adopted then, due to the possibility of flashovers occurring frequently in service, the withstand strength of the windings against surges must be pre-determined by appropriate testing with suitable chopped wave.

- The spark gap on each of the phases must be situated such that the risk of arc spreading across the neighbouring phases is minimized. If this precaution is not taken there is a possibility of transforming a single-phase fault into a three-phase fault.

4.5.2 Gapped Surge Arresters

The main difference between the design of gapped TLA and a gapless TLA is the series gap arrangement between the bottom of the lightning arrester element it self and the spark gap.

There are advantages and disadvantages to using both the gapped and the gapless line surge arresters. Table 21 shows a summary comparison of characteristic of the gapless and the gapped transmission line arresters.

4.6 Gap-less Surge Arresters (ZnO) and their applications to transmission lines

The development and use of different types of arresters has evolved over a long period as indicated by the following schedule [Mobedjina et al, 1998].

1892 – 1908	Air gaps
1908 – 1930	Metal-resistors
1920 – 1930	Oxide-film resistors
1930 – 1954	SiC resistors with passive gaps
1954 – 1976	SiC resistors with active gaps
1976 – to date	ZnO resistors with no gaps

In the middle of the 1970s the most advanced SiC arresters could give some adequate protection against over voltages but the technique had reached its limits [Mobedjina et al, 1998]. It was difficult to design arresters with several parallel columns to cope with the high energy requirements needed for HVDC transmission lines. The statistical scatter of the spark-over voltage was also a limiting factor with regard to the accuracy of the protection levels.

Metal-oxide (ZnO) surge arrestors were introduced in the mid and late 1970s and proved to be a solution to problems that could not be solved with the old technology. The protection level of a surge arrester could be accurately controlled because, without a gap, the protective function was no longer dependent on the installation or vicinity to other apparatus, compared to SiC arresters for which spark over voltages could be affected by the surrounding electric fields. The ZnO arresters could be designed to withstand virtually any energy requirements just by connecting ZnO varistors in parallel even though the technique to ensure a sufficient good current sharing, and thus energy sharing, between the columns was complicated. The possibility of designing protective equipment against very high energy stresses also opened up new application areas such as the protection of series capacitors.

4.6.1 Operating principle of ZnO lightning arrester

Surge arresters play a key role in the protection of all other components in a transmission network against overvoltages that may occur due to lightning activity, other system faults or general switching operations [Electra, 1999], [Mobedjina et al 1998], [Asokan, Kishore , 2000].

Overvoltages caused by lightning are of special significance with regard to the electrical stress at all voltage levels in a network. Lightning is a major cause of power outages, and recently metal oxide arresters have been used successfully to improve coordination due to their excellent electrical characteristics [Electra, 1999], [Bialek, 1999]. Lightning is responsible for approximately 10% for all short circuits in substations and for almost 50% in all short circuits on transmission lines in systems of 300kV and above.

The theory of operation of the metal oxide lightning arrester is simple and effective. A metal oxide lightning arrester connected in parallel with the line insulation limits voltage across the insulation to a value below the insulator flashover voltage during a power surge. The lightning current passes through the arrester due to the increase in voltage between the arrester terminals caused by lightning stroke to the tower or the grounding wire or the phase conductors [Electra, 1999], [Hubell, 2003a], [Bialek , 1999],[Ianoz, 2003]. The arrester contains ZnO elements that have very good non-linear voltage-current (V-I) characteristics. Under normal circumstances the applied voltage is low, i.e. the system voltage, only a very small current will flow through the element due to its high resistance. However when the applied voltage is increased, i.e. the lightning stroke voltage, the arrester element conducts a large current due to its reduced resistance. Consequently the voltage across the arrester does not reach the breakdown voltage of the line arrester and hence no flash over will occur.

The main element of the lightning arrester is the highly non- linear, voltage dependent resistor, called the varistor. The varistor elements are arranged in a series blocks so that they have high impedance at the rated system voltage but a much lower impedance when the voltage is very high. By the action of the arrester block as discussed above surge current is diverted to ground in a controlled manner and power supply is not interrupted.

Previously varistor elements were made of silicone carbide (SiC). The zinc oxide elements called metal oxide varistors (MOV) show more non-linearity than the silicone carbide elements. Consequently these have largely replaced the silicone carbide elements in modern arresters.

Development of ceramics-based zinc oxide in the 1970's resulted in a very strong non-linear current voltage relationship such that it makes it possible to approach the ideal surge arrester characteristic even more accurately [van der Merve WC, 1990]. Due to the extreme non-linear characteristic the surge arrester does not require a spark gap to isolate the circuit under normal power frequency conditions. Figure 17 shows the current-voltage characteristic of a Zinc Oxide varistor. This behaviour or characteristic of the lightning arrester led to the name gapless metal oxide arrester.

Physically the lightning arrester is connected in parallel with the insulator on to which the live conductor is suspended or supported [Electra, 1999], [Mobedjina et al, 1998]. Figure 18 shows how the lightning arrester is connected / installed and the arrow shows the surge current path due to the action of the lightning arrester.

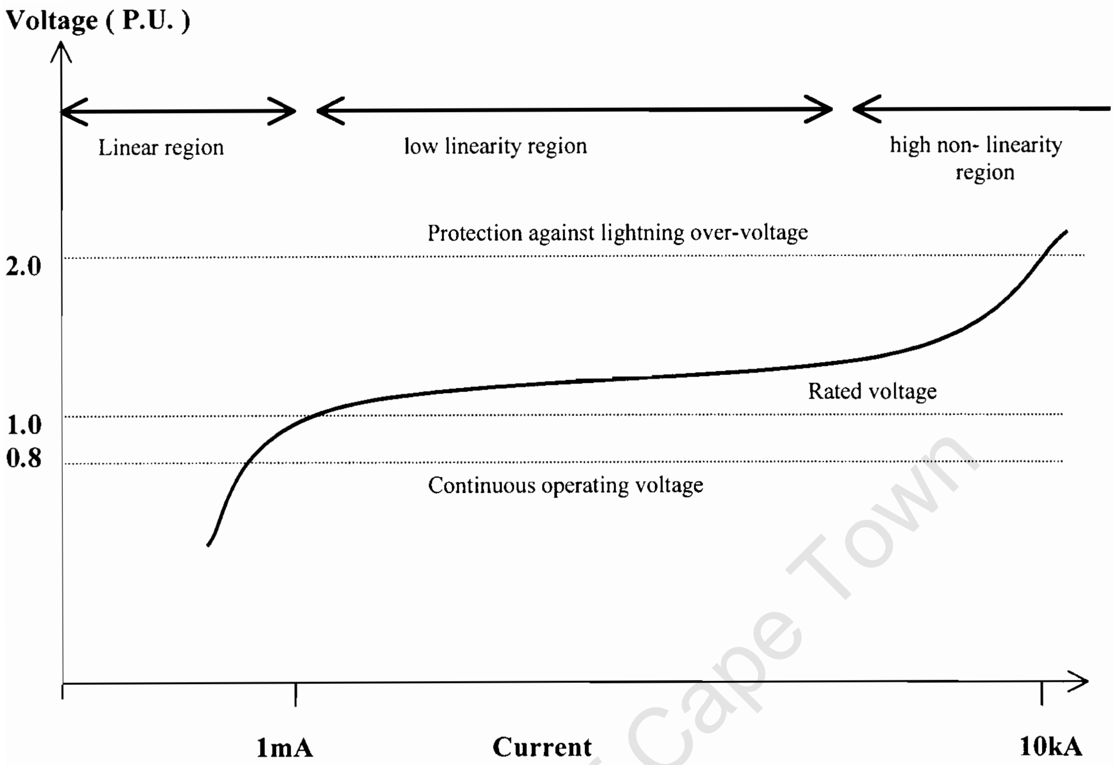


Figure 17: General current-voltage characteristic for a zinc oxide varistor
Source: [Mbedjina et al, 1998]

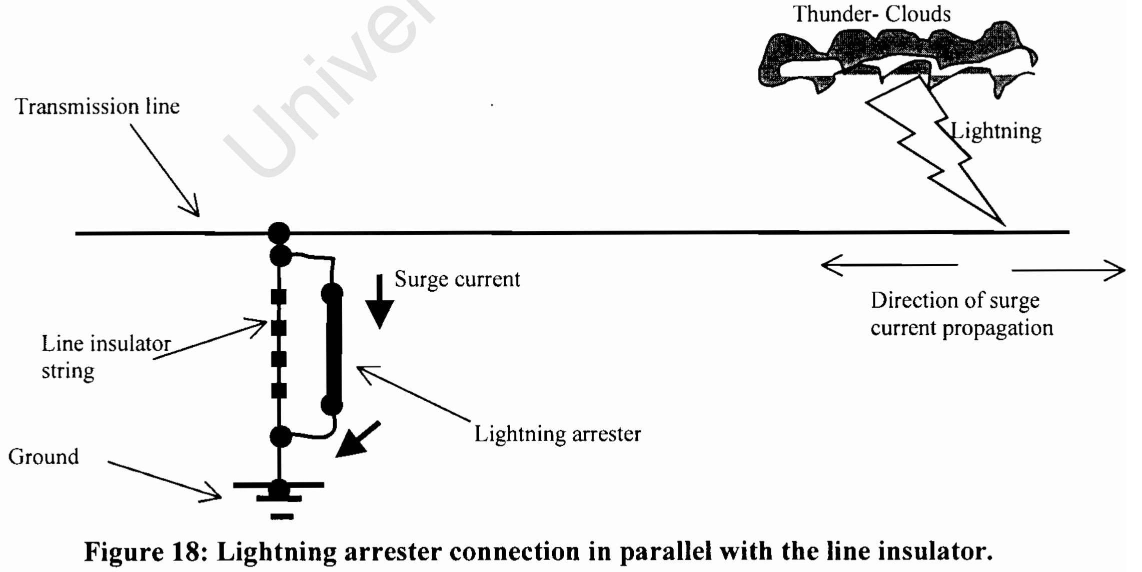


Figure 18: Lightning arrester connection in parallel with the line insulator.

Figure 19 shows how Zinc Oxide lightning arresters limit voltage across the insulation to a value below the insulator flashover voltage during a surge.

- **Urw = Insulation Level of equipment**
- **Up = Protective level of the Surge Arrester**

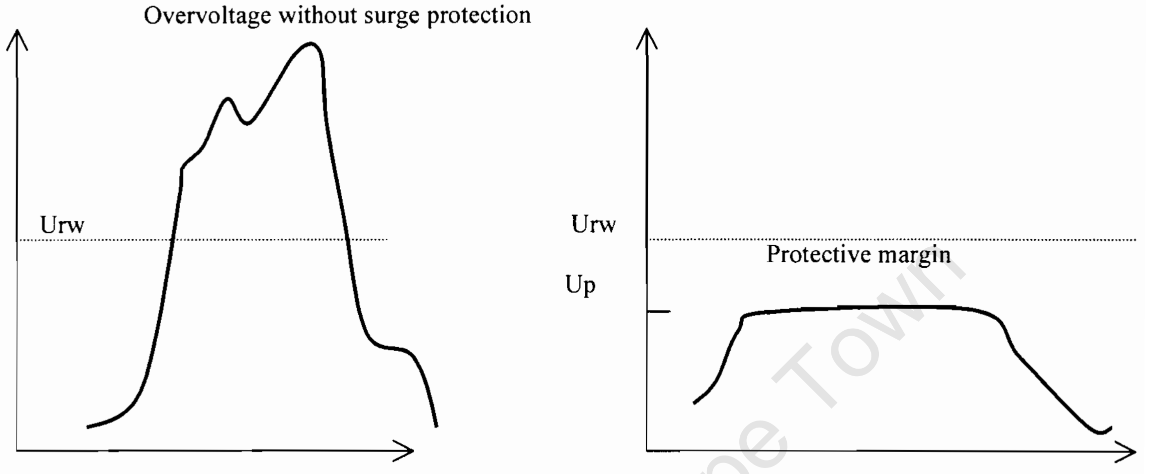


Figure 19: Surge Arrester Protective Parameter
Source: ABB Workshop presentation: Swaziland-1997

The main limits on the application of ZnO surge arresters are as follows [Electra, 1999]:

- The maximum continuous operating voltage of the system to which it is connected,
- The maximum short term over voltage of the system to which it is connected to,
- The protective level that the arrester has to provide for the equipment being protected,
- The discharge current amplitude and the energy absorbed in the arrester resulting in the heating up which can cause disruptive failure, and
- The thermal stability of the arrester element.

4.6.2 Basic Design of Arrester

This description is mainly of polymer-housed Transmission Line Arrestors. A Zinc Oxide Polymer Housed Surge Arrester for high voltage applications is composed of the following main elements:

- Zinc Oxide (Zn O) varistors
- Internal parts
    - Clamping fibre-yokes
    - Securing fibre-glass straps/ or loops
    - Polymer Housing
- Metal end fittings: flanges and/or line terminal
- Grading ring where necessary depending on the voltage magnitude or the application of the arrester.
- Spacers

The most important component of the Transmission Line Arrester is the Zinc Oxide (ZnO) Varistor which gives the characteristic of the lightning arrester. Figure 20 shows a Zinc Oxide cylindrical varistor block. Typical diameter and height of the varistor block are 75mm and 65mm respectively.

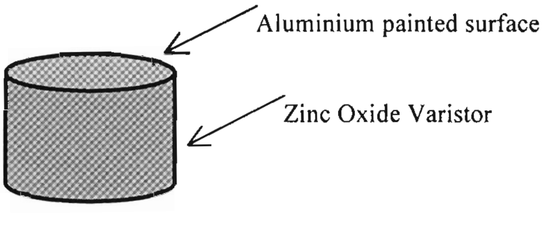
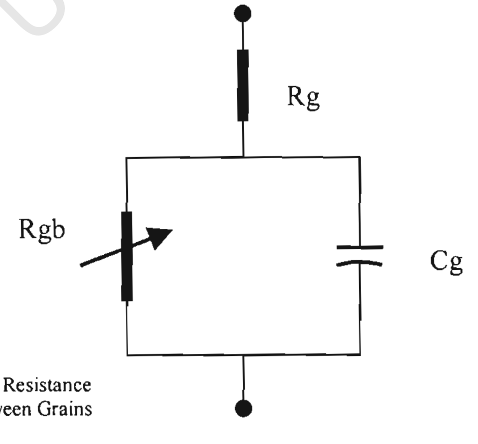


Figure 20: Zinc-Oxide Varistor Block (MOV)
Source: [Mbedjina et al, 1998].

The ZnO Varistors.

The Zinc Oxide Varistor is a densely sintered cylindrical block that is pressed under high temperatures. The sintered block consists of 90% zinc oxide and 10% of other metal oxides, of which bismuth oxide is the most important. During the manufacturing process a powder is pressed into a cylindrical shape under high pressure. These pressed shapes are then sintered in an oven for several hours at high temperatures varying from 1100degrees centigrade to 1200 degrees centigrade. During the curing into the dense cylindrical blocks the oxide powder transforms into a dense ceramic body with varistors properties where the additives will form an inter-granular layer surrounding the zinc oxide grains. These layers are very important and they give the varistor its non-linear characteristics. To improve the current carrying capacity of the cylindrical blocks, aluminium is applied at the end of the finished varistor. This also ensures good contact between series connected varistors. The outside surface of the cylindrical body is then insulated to prevent possible flashover and chemical degradation [Schuld, 2003], [Bialek, 1999], [Mobedjina et al, 1998], [INMR, 2002].

Figure 21 shows a simple electrical model of the ZnO of the disc. There is an internal linear resistance component as a result of the ZnO grains themselves. There is also a non-linear resistance of the ZnO boundary layer, and capacitance between the grain [Bialek, 1999].



Where: Rg = Grain Resistance
Rgb = Grain Boundary Resistance
Cg = Capacitance Between Grains

Figure 21: ZnO Simple Electrical Model
Source: [Bialek, 1999]

For all different types of housing the ZnO blocks are manufactured in the same manner. The internal parts and the assembly differ significantly for a polymer housed arrester and a porcelain housed arrester. The only common factor is the zinc oxide varistor blocks, which are stacked in series. One major difference between the traditional porcelain housed transmission line arrester and the polymer housed transmission line arrester is that the former has a considerable amount of dry air or inert gas while the later does not have any enclosed gas volume. This means that the short circuit capability requirements and internal corona must be solved quite differently for the two designs. The possibility that porcelain housed arrestors containing gas may explode due to an excessive internal pressure build up means that the condition possibly leading to an explosion must be controlled. For this reason this type of arrester must be fitted with a pressure relief device [Mobedjina et al, 1998].

The cylindrical blocks are stacked together. Figure 22 shows design outlines of a polymer-housed ZnO surge arrestor.

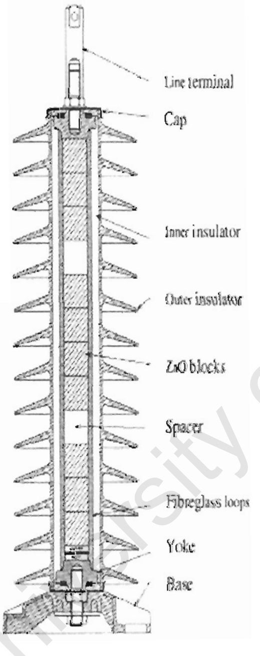


Figure 22: Design of a polymer-housed ZnO surge arrester
Source: [Mbedjina M et al, 1998].

The polymer-housed arresters differ depending on the type of design. Currently these arresters can be found in three groups:

- Open or cage design,
- Closed design, and
- Tubular design with an annular gas-gap between the active parts and the external insulator.

In the first type of design, the mechanical design may consist of loops of glass-fibre, a cage of glass-fibre weave or glass-fibre rods around the block column [INMR, 2002], [INMR, 2004], [Mobedjina, and Strenstrom, 2000]. The ZnO blocks are used to give the design some of its mechanical strength. A body of silicon rubber or EPDM rubber is then moulded on to the internal parts. An outer layer of insulation is then moulded again and is formed into a series of sheds on to the internal parts. The length of the sheds is dependent upon the creepage distance required by the voltage magnitude of that application. This design does not have an enclosed gas for insulation purposes. During a short circuit event, some material will be evaporated due to the arc and this causes pressure increase. This design is deliberately made weak to enable internal over pressure to be controlled through the tearing of the rubber insulator. This rubber tears partly or along the length of the arrester.

For high production efficiency and low operating costs Zinc Oxide cylindrical blocks are manufactured in a highly automated process under strict control with testing at each stage to minimize and detect faulty components as early as possible. By design the ZnO arresters have very low power losses. These cylindrical blocks are housed in a cage formed of fibreglass wrappings placed on brackets at each end. To maintain good contact between the ZnO blocks the assembly is kept under high compression. With terminal caps at each end the assembly a polymer housing is directly moulded on the module under high temperature and in a vacuum to prevent air from being trapped inside [Mobedjina, and Strenstrom, 2000], [INMR, 2004], [Bialek T, 1999].

4.6.3 Dimensioning of ZnO surge arresters

There are several parameters that influence the sizing of an arrester but the demands as required by the applicant can be divided into three main categories:

- High reliability and long service life requirements
- Protection against over voltages requirement
- Low risk to personnel injury in the event of overloading of the arrester

The first two main requirements are somehow contradictory to each other. Aiming to minimize residual voltage normally leads to the reduction in the capability of the arrester to withstand power frequency over voltages. An improved protection level therefore may slightly increase the risk of over loading the arresters. The increase in the risk is dependent on how well the amplitude and time of the temporary over voltage (TOV) can be predicted. This means that the selection of an arrester is always a compromise between protection levels and reliability.

A detailed classification could be based on what stresses a surge arrester is normally subjected to and what continuous stresses is it required to withstand, such as:

- Continuous operating voltages
- Operating ambient temperatures
- Rain, pollution, exposure to sun radiation
- Wind and possible ice loading as well as forces in line connections and additional non frequent abnormal stresses
- Temporary over voltages
- Over voltages due to transients which affect
    - Thermal stability and ageing
    - Energy and current withstand capability
    - External insulation withstand
- Large mechanical forces, say from earthquakes
- Severe external pollution, and
- Internal short–circuit

The primary purpose of an arrester is to protect against transient over voltages but the device must also be dimensioned to withstand both the current through it and the heat generated by the over voltage. Through the design of the sheds of the insulation material the risk of external flash over must also be very low.

4.6.3.1 Surge Arrester Housing

Traditionally, a lightning arrester housing was made of porcelain [Bialek, 1999], [INMR, 2002], [Mobedjina et al, 1998]. These days the traditional material has changed and the housing is made of polymeric insulators. Polymeric insulators have several advantages over porcelain insulators as follows:

- Better performance in polluted arrears due to hydrophobic behaviour. Water-repellent hydrophobic silicone housing provides outstanding performance in contaminated/ polluted environments.
- Light weight, easy installation and safe overload characteristics
- Non brittle, so it can withstand rough transport and handling
- Better short circuit capability with increased safety for other equipment and personnel nearby. Even in overload conditions the housing will not shatter and therefore not destroy other station equipment.
- Long creep age distance prevents flash over
- Wide variety of mounting possibilities (horizontal, vertical, suspended).

Polymeric material generally out performs porcelain material in polluted areas due to the hydrophobic behaviour of the polymeric material, i.e. the ability to prevent wetting of the insulator surface. Not all polymeric insulators have equal hydrophobic behaviour. This is due to the different types of polymeric materials that manufactures use to produce insulators [Mobedjina, and Strenstrom, 2000]

The most commonly used polymeric materials are silicon and EPDM rubber together with a variety of additives to achieve desired material properties and behaviour such as fire-retardant, stability against ultra violent radiation as, degree of hydrophobia etc [Mobedjina, and Strenstrom, 2000]. However polymeric materials, which are organic are inferior in some properties compared with inorganic porcelain in the followings ways:

- Polymeric materials age more quickly through:
    - Partial discharge
    - Leakage currents on the surface
    - UV radiation
    - Chemicals etc

Both silicon and EPDM rubber show common hydrophobic behavior when new. experience shows, however, that the insulator made of EPDM rubber will lose its hydrophobic quality more quickly and is thus regarded as a hydrophilic insulator material. Hydrophobicity results in reduced creep age currents under external pollution, thus minimizing electrical discharge on the surface and thus reducing the aging phenomenon. Polymeric insulators can lose their hydrophobic properties if the insulator has been subjected to high leakage currents for an extended time due to severe pollution such as salt combined with moisture. The silicon rubber will however recover its hydrophobicity through diffusion of low molecular silicones to the surface thus restoring the original hydrophobic behaviour. The EPDM rubber lacks this property completely and so the material is very likely to lose its hydrophobicity completely with time.

The weight difference between polymer and porcelain housed arresters can be significant For example, a lightning arrester with a porcelain insulator for a 550kV system voltage weighs approximately 450kg whilst a polymer housed arrester with the same rated voltage would have a mass of approximately 275kg [Mobedjina, and Strenstrom, 2000]. Further, if suspended mounting is accepted, the weight of the latter can be further reduced to a total mass of approximately 150kg.

Lightning arresters for high voltages and extra high voltages, due to their usually long length, usually achieve the desired strength through the use of stays of polymer materials.

Transmission surge arresters for system voltages of 145kV and above must normally be equipped with several metallic rings hanging from the top of the arrester. These ensure that the electrical field surrounding the arrester is as linear as possible.

4.6.3.2 Specification Parameters for gapless surge arresters

Specifications required for gapless surge arresters require the definition of [Electra, 1999], [Mobedjina et al, 1998]:

- The maximum continuous operating voltage (MCOV)
- Rated voltage (UR)
- Pressure relief current
- Norminal discharge current (In)
- Residual voltage of ZnO elements
- Mechanical specification of insulating housing
- I-t characteristics of arrester disconnector
- Impulse current (switching, lightning) withstand capability
- Withstand voltage of insulating housing (including pollution)

4.6.3.3 Performance of Transmission Line Arrestors

For optimal performance of overhead line surge arresters, considering the stresses on these units, the following types of stress are important [Electra, 1999], [Mobedjina, and Strenstrom, 2000]:

- Back-flash-over to a phase conductor from a ground wire or tower struck by lightning,
- Direct strikes to phase conductors, including shielding failure on lines shielded by ground wires,
- Induced surges caused by lightning strikes to other objects or ground close-by.

Table 18 shows the characteristic stresses caused by lightning on overhead lines with varying nominal voltage magnitudes. Table 19 shows the protection against over voltages or minimization of lightning stresses on transmission overhead lines.

Table 18: Characteristic stresses caused by lightning on overhead lines

Characteristic insulation	Shielded or Un-shielded	Typical Examples	Lightning performance	Stresses
Rated impulse withstand level (BIL)< induced voltages	Shielded; BIL<100kV	10- 12kV line, shielded; BIL=75kV	Induced surges can cause flashover. Most strikes to shield wire cause back-flashover. Direct strikes to shielding failure are similar to back-flashover	Frequent surges sufficient to cause flashover. Flashover probable at more than one structure. Each flashover associated with relatively low energy
	Unshielded; BIL,300kV	20 –24kV line no shield wire. BIL= 125kV	Induce surges can cause flash over. All strikes to line are direct strikes to phase conductor.	High energy associated with direct strikes to the line. Flash over probable at more than one structure
BIL> induced voltages; Switching over voltages not significant.	Shielded; BIL>100kv	20-24kV line, shielded; BIL= 125kV Or 145kV line, shielded; BIL= 650kV	Induced surge not significant. Tower footing resistance(TFR) is a significant factor in back-flash over. Direct strikes by shielding failure depend on shielding angle, but stroke current usually low.	Relatively low energy injected into phase conductors
	Unshielded; BIL>300kV	20-24kVline,unshielded; BIL=300kV Or 69kV line, un-shielded; BIL=450kV	Induced surges not significant. All strikes to line are direct strikes to phase conductors. Flash over to structure from direct strikes to line may be followed by back flashover to other phases if TFR is high, causing multiphase fault	High energy associated with direct strikes to the line.
Insulation level determined by lightning and switching over-voltages	Shielded; BIL>1000kV	400kV line; shielded; BIL=1200kV	Shielding failure usually most significant lightning problem. High TFR at few structures may result in back-flashover	Relatively low energy injected into phase conductors
	Unshielded;	Canadian?	All strikes to line are direct strikes to phase conductors. Flash-over is likely at towers in spite of high insulation level.	High energy associated with direct strikes to the line

Source: [Electra, 1999]

Table 19: Protection against over voltages or lightning stress mitigation on overhead lines

Stress	Mitigation with surge arresters	Critical factors	Alternative mitigation process
High energy direct strikes to lines without shield wires.	Line arrester on most exposed phases at exposed structures. Fit arresters on other phases and adjacent structures if high TFR causes back-flashover from struck phases And structure to another phase.	Arrester must withstand discharge energy and high current amplitude in lightning stroke. High variability of TFRs can stress some arresters.	Install shielding wires to intercept lightning strikes.
Low energy direct strikes arising from shielding failure, also occurring on unshielded lines	Fit arresters to phases for which shielding failure is expected.	Shielding angle.	Reposition shield wire or install additional shield wire to improve shielding effectiveness
Back flashover – low energy injection into the phase conductor from the structure	Fit arrester on exposed structures (high lightning risk at high TFR) on those phases most likely to suffer back flash-over.	Low energy rating adequate because most energy is discharged into the shield-wire earthing.	Reduce TFR by improving grounding. Increase the insulation on the phase conductors.
Induced surges > line insulation	Install arresters on all phases on all structures exposed to high induced surges (e.g. where line passes through forest route and shielded from direct strikes).	Low energy ratings adequate because discharge is shared by many arresters and structures.	Increase the insulation of the phase conductors above the level of the induced surges. Install a shielding wire or an under-running ground wire to reduce the magnitude of the induced surges.
Induced surges < line insulation	Install arresters on associated equipment to protect against damage by incoming surges.	If line insulation>> normal rated insulation of equipment, effects of remote direct strikes may put high a stresses on terminal equipment.	Reduce line insulation to values just above level of induced surges to limit high over voltages caused by direct strikes to the line reaching terminal equipment.

Source: [Electra, 1999].

4.6.3.4 Testing of Transmission Line Arrestors

Transmission line arresters tests must comply with several requirements of IEC 99-4-1991 as shown in table 20 [Electra, 1999]. However transmission line arresters need to have several specific test requirements besides those of the above specification.

Table 20: Arresters classification and test requirements for IEC99-1-1994 and line arresters

No.	Test items	Requirements of IEC99-4-1991		Requirements for line arresters	
		Station type	Intermediate or distribution type	Transmission line type	Distribution line type
1	Rated voltage Ur (kVrms)	3<Ur<756	3<Ur<132	3<Ur<?	3<Ur<?
2	Insulation withstand tests on the arrester housing	AC,(switching) lightning	AC lightning	AC lightning	Ac Lightning
3	Residual voltage test a) lightning impulse b) switching impulse		Not required	Not required	Not required
4	Long duration current impulse withstand test				
5	Operating duty test a) High current impulse b) Switching surge		Not required	Not required	Not required
6	Power frequency voltage versus time curve (TOV withstand)			(not required for gapped type)	(not required for gapped type)
7	Pressure relief (when fitted with relief device)		Not required for distribution type	No fragment is permitted	No fragment is permitted
8	Arrester dis-connector (when fitted)				
9	Polluted housing test (annex F)			(not applicable to gapped type)	(not applicable to gapped type)
10	Ageing test of polymeric housing	Not required	Not required		
11	Mechanical test of polymeric housing	Not required	Not required		Not required
12	External gap test	Not applicable	Not applicable	(not applicable to gapless type)	Not required

Source: [Electra, 1999]

In addition to the test specified above, the following test items must be added.

- Ageing test of the polymeric housing.
- Mechanical Test of Polymeric Housing comprising:
  - Mechanical load-time test
  - Dye penetration test
  - Water diffusion test
- External Gap Test comprising:
  - Lightning impulse flashover voltage test
  - Switching impulse withstand voltage test
  - Follow current interrupting test

4.7 Comparison of gapped and gapless lightning arresters

Table 21: Comparison of characteristic of gapless and gapped transmission line arresters

Arrester Characteristics	
Gapped	Gapless
Line protection only for lightning	Line protection for lightning and switching
ZnO blocks not directly connected to the line, hence fewer ZnO blocks are used for the same voltage level, which implies lower rated voltage, costs and residual voltage	ZnO block directly connected to the line , hence more ZnO blocks are used for the same voltage level which implies higher rated voltage, costs and residual voltage
Additional cost for air-gap hard ware	No air-gap/ no additional cost
Detection of failed units is more difficult and expensive	Failed units are visually identified using line disconnector devices
No influence of contamination on ZnO blocks	Contamination of external housing could overheat the ZnO block.
Air gap flash-over depends on atmospheric conditions	No influence of atmospheric conditions on arrester operation
Live-line maintenance is easier and safe	Arrester must be disconnected during live-line maintenance
Lightning energy sharing among arresters in the same line-section cannot be assured	Energy sharing is assured among the several arresters in the same line-section

Source: [Electra, 1999]

Chapter 5

Lightning experiences in Swaziland

5.1 Damages to Insulators

Swaziland has one of the highest lightning ground flash density areas in the world. Figure 2 shows the spread of intensity across the country. The highest density is located on the western side of the country. Preliminary work described in chapter 2 to determine the single most common cause of power outages and the investigation described in chapter 3 on the causes of power outages on three 66kV transmission lines located on the western part of the country indicated that there is a high number of outages due to lightning. In the SEB Annual Report for 2000, the former managing Director of SEB, Mr. Bruce Farrer, commented on the consequences of bad weather and storms as follows:

> " *Throughout the year we have suffered from severe rain, winds, thunder and lightning storms resulting in numerous system disturbances at all voltages….*" [SEB,2000].

The consequences of the high lightning ground flash density are not only power outages but also equipment damage. In fact the power outages are a result of the operation of power protection systems that trip out the system in order to minimize or prevent damage to equipment. Lightning strikes that hit transmission lines often cause flash-over to conductors in the vicinity through insulation break down [Collinson, Stones, 2001], [Macey, 1990]. Most of these damages are on insulators.

Visual condition assessment inspection along a number of 66kV lines uncovered a number of damaged insulators. The damages ranged from partially shattered disks to completely broken disks. The purpose of the inspection was to determine the extent of damage caused by the effect of flash over and to manage and carry out a remedial course of action to ensure that the lines perform as designed over a full life cycle of the line so that operational targets are achieved. Several transmission lines situated within the high ground flash density area were visually inspected. The lines were photographed and figure 23 shows the damage to insulators found along them.

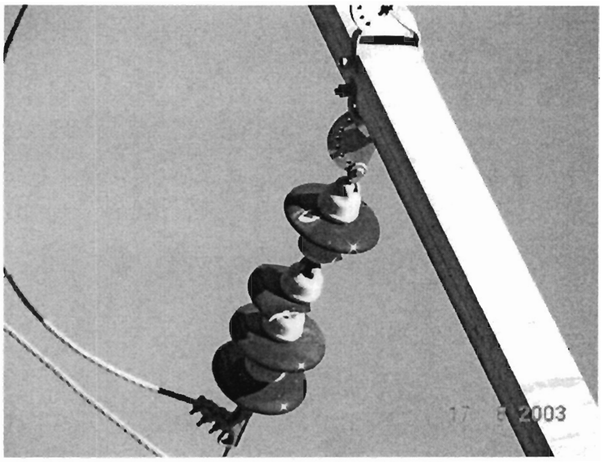


Figure 23a: Porcelain cap partially shattered with burn marks visible on the top disk.

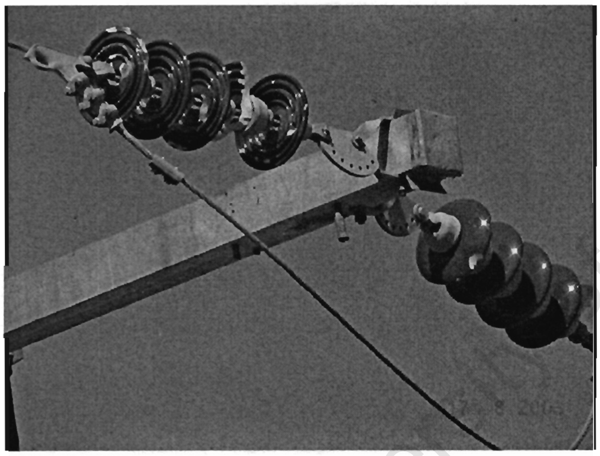


Figure 23b: Damage on the second disk

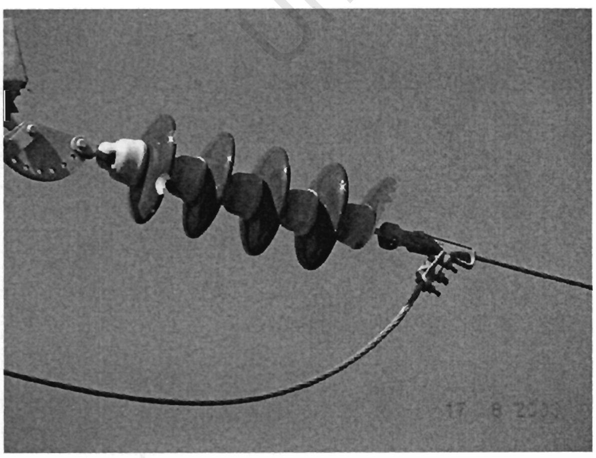


Figure 23c: Damage on the first and the last disk

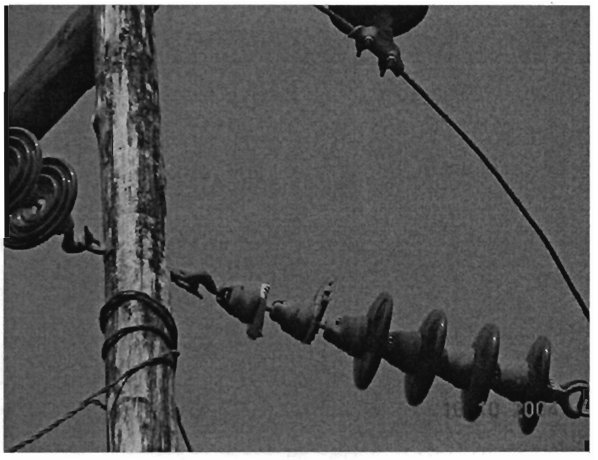


Figure 23d: First two disks broken

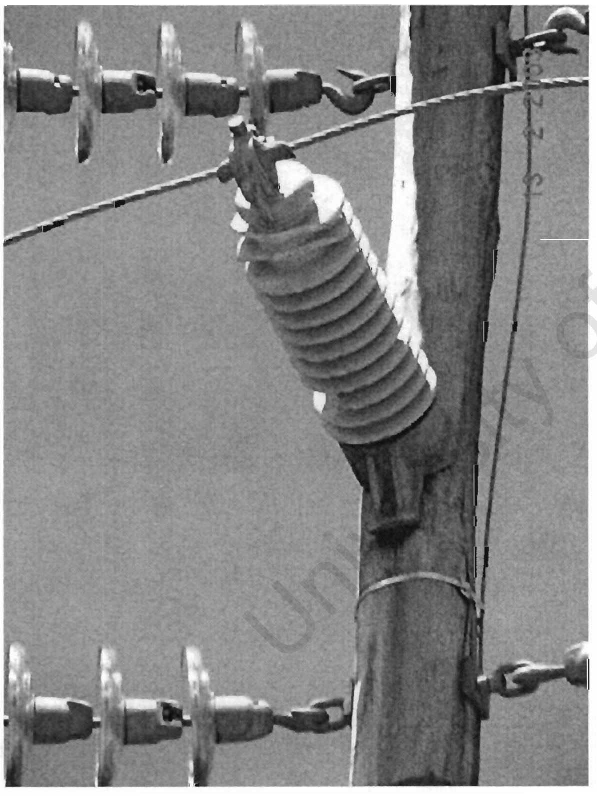


Figure 23e: Broken porcelain sheds on the line post insulator

Figure 23f: Severely burnt porcelain sheds due to flash-over

Figure 23g: Severely burnt porcelain stay insulator

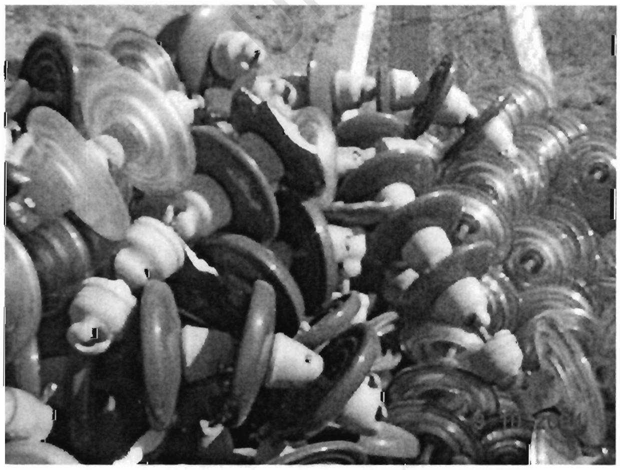


Figure 23h: Defective insulators removed from the system

Most of the damaged insulators were found on transmission lines evenly spread out in the high lightning ground flash density area in the western part of the country. Some however were found on transmission lines located on the eastern part of the country where lightning ground flash density is lower than in the western region. This is attributable to the high footing resistance found in this part of the country. This type of damage is related to flashover activity. The damaged insulators were found mainly on the lines located in the western part of the country evenly spread out. There were no indications that the damage could have been caused by leakage current corrosion. Figure 23f shows a severely damaged porcelain shed indicating the extent of the burn from flash over. This type of damage results in high maintenance and replacement cost.

5.2 Broken jumpers and shield wire

This type of fault is prevalent on the network situated in the western part of the country where there is high lightning ground flash density, especially on the 66kV line from Stonehenge to Usuthu pulp. A thunderstorm passing along this line usually results in broken earth wire and /or broken jumpers. Unfortunately the actual causes of these failures have never been investigated. The nature of the failure, however, shows symptoms of severe currents resulting from lightning. In an effort to manage the high failure rate of the earth wire and jumpers, this line was re-fitted with earth wire and the jumpers were re-made with crimping fittings. The problem of broken jumpers and earth wire seems to have been solved but power interruptions are still high.

The problem of broken jumpers and earth wire is mostly found on the 66kV lines situated in the western area. However at distribution level the problem of broken jumpers is found all over the country and this happens during thunderstorms, again indicating high currents due to lightning.

5.3 Revenue loss incurred by SEB due to high lightning activity

The high lightning activity does not only affect SEB customers, but leads to high business losses to SEB as well. 70% of SEB's annual revenue is generated from the Manzini and Hhohho regions and mainly from industrial customers. Unfortunately these lie in the high lightning density section of the country [SEB, 2004], [Capricon, 1996].

Using table 22 the direct revenue losses due to power outages at Usuthu Pulp can be worked out:

Table 22: Duration of power outages for 1999-2000 for Usuthu Pulp

Months	October 1999	November 1999	December. 1999	January 2000	February 2000	March 2000
Duration Minutes	140.0	130.0	250.0	320.0	20.0	50.0

From table 22 above the revenue loss to SEB due to power outages at Usuthu Pulp for the summer period is worked out as follows:

Total outage time = 920 minutes,
=> 15.333 hours

Current Average load for Usuthu Pulp = 7.46MW (load factor +_ 80%)

Direct Revenue Loss on Energy = 7.46MW x 15.333h x 21.30C/kWh [SEB, 2004a], [SEB, 2004b]

= E24364.00 per lightning season

The above amount of revenue loss for the single customer may seem small but taking into account other similar loads located within the high lightning ground flash density area this easily amounts to millions of Emalangeni. SEB major customers that have loads ranging between 1MW and 7MW that fall within this area include:

- Swazi Paper mills, Natex, Spintex, Swaziland Meat industries, Cadbury, Swaziland Breweries, Conco, Hotels (combined), and Coca Cola Swaziland.

Total revenue losses would therefore amount to more than E250000-00 per annum assuming an average load of 5MW for the above customers and typical power outage duration periods.

The above is just an indication of typical revenue loss to SEB. Losses to major customers are ten times higher than the revenue loss to SEB. One SEB major customer reported losses in excess of E10 Million/lightning season [Young, 2000].

Such high annual losses to customers certainly discourage direct foreign investment into Swaziland. Locally produced goods for export would not be competitive as a result of frequent stoppages due to power cuts and certainly goods such as textiles would tend to be of low quality. Overseas markets may be lost consequently.

5.4 High Stoppage and Production Losses to customers:

Two thirds of the SEB network is found in the western part of the country in the high ground flash density area. The make up of this load includes sensitive process industries such as paper industry, textile industry, plastic and cement industry. In this type of industry an auto re-closer operation or a voltage fluctuation can cause an interruption of several hours resulting in high maintenance costs, loss of materials and even cancellation of orders from buyers. Such un-scheduled stoppages can result in losses of millions of Emalangeni per year. The findings of Kennedy and Donkin [1996], although dated some eight years ago, are still valid, since such complaints are still received by SEB. In 2000 Usuthu pulp wrote to SEB about the high stoppage losses that they suffered as a result of power fluctuations and outages. An official notification of the extent of losses by Usuthu pulp's Managing Director was sent to the SEB Managing Director and reads as follows:

"*... following our last meeting I undertook to inform you of the consequential losses with the disruptive loss of SEB power during the high summer rainfall period....., The consequential loss to Usuthu is E17M943,369. Problems associated with mechanical breakdowns, chemical loss and stabilizing that mill after power disruptions have been excluded in order to show you the magnitude of the problem which directly relates to fluctuation and losses. During the period in question the excessive power failures were caused by broken jumpers, faulty insulators and surge arresters...*"[Young, 2000].

Reports obtained from Beral and HVL Asbestos claimed that financial losses due to stoppages were as high as E300,000 per month. Subsequent to the high number of power outages and poor quality of supply, six large companies invested in stand-by generation [Kennedy and Donkin, 1996]. This demonstrates clearly the consequences that poor quality of supply may have on investment decisions by potential or existing investors.

5.5 High maintenance cost to SEB.

Frequent power interruptions result in high operation costs due to several factors. The experience at SEB is that in summer there is a tendency to have more breaker maintenance due to the high number of breaker operations that occurs in summer than in winter. The high breaker maintenance activities result in high transport and labour costs.

There is also more remedial work undertaken in summer because of the high number of system failures. The remedial work mainly entails replacement of damaged insulators with new units. Repairing faults also results in high labour and transport costs.

5.6 High number of customer complaints in summer than in winter.

The study conducted by K&D in 1996 indicated a higher number of complaints in summer than in winter. The complaints included a high frequency of power supply interruptions, power fluctuations, extended duration of power outages, inability to handle the high volume of incoming customer telephone calls by the fault departments.

5.7 Decision Taken

Successes in other parts of the world in reducing lightning related power outages inspired us to implement a similar solution. However conditions in the cases examined are not identical to the conditions found in Swaziland. The lightning ground flash density magnitudes elsewhere, although high, are not identical to those we face. To increase the chances of success in installing ZnO TLA locally, a decision was taken to implement a pilot project first. Implementation of the pilot project would achieve the following:

- To investigate the performance of the line by comparing the power outages of the line caused by lightning before and after the installation of the TLA's.
- To compare the performance of the pilot project with two other 66kV lines before and after the installation of the TLA's.
- Monitoring of line performance before a major investment on the rest of the system can be made,
- To gather accurate data related to the performance of 66kV ZnO TLA's and the associated auxiliary systems such as the X-count,
- To evaluate project cost versus loss of revenue on the selected pilot project line.
- To build up experience and confidence from the pilot project.

The success or failure of the pilot project would determine whether a country wide program would be undertaken.

The pilot project line had to have the following conditions:

- To be situated in a high lightning ground flash density area,
- To be of medium length,
- To be situated in a relatively high soil resistance area.

The precaution of implementing a test case was undertaken by other electric power utilities such as Minnesota Power and Minnkota Power Cooperative [Johnson and Van House, 2002].

Chapter 6

Implementation of the Pilot Project: Installation of Transmission Line Surge Arresters on the Stonehenge-Ezulwini 66kV line (5.2km wood pole structures)

Physical work on the project started in August 2003 after all necessary preparations had been completed. These included selecting the towers, measuring footing resistance at the selected structures, acquiring conductive cement, identifying and briefing the linesmen who would install the arresters etc.

6.1 Tower selection

Specific towers had to be selected in order to optimise the project cost on this line. Two terminal towers and some four other intermediate towers that are highly exposed to lightning due to their elevated heights compared to other towers were selected for the installation of the surge arresters.

Tower selection programs were used in some of the countries that implemented this solution [Stenstrom, Johnnerfelt, 1999]. Line profiles were used to identify and select structures that are at high risk of being struck by lightning. Swaziland has visibly undulating country-side and it was relatively easy to spot the highest towers [Tourist guide, 2003/4]. The first and the last structures chosen to be fitted with TLA were two structures from each end of the line. This is because the ground wire terminates in these structures (No4 and No37). Elevated intermediate towers along the line were numbers16, 21,24,and 32.

6.2 Tower Footing Resistance Improvement

The grounding system is an essential part of any electrical/electronic system. There are several objectives for having a good grounding system for electrical or electronic systems. For electrical systems these objectives include:

- To dissipate lightning strokes,
- To provide means to carry electric currents into earth under normal and fault conditions,
- To stabilize voltage during transient condition and to minimize the probability of flashover during the transients,
- To assure that human and livestock in the vicinity of grounded facilities are not exposed to the danger of critical electric shock etc.

Soil resistivity is generally high in Swaziland particularly on the western side of the country where granite soil type is prevalent.

Tower footing resistance was measured for each of the selected towers. The results of tower footing measurements and subsequent re-dress are shown in table 24-(Stonehenge- Ezulwini 66kV line Footing Resistance Improvements).

Table 24: Stonehenge - Ezulwini 66kV Line Footing Resistance Improvement

Date	Pole No.	Structure type	Initial Resistance	No. of Electrodes	No. of cement bags	Additional electrodes	Final resistance
• 2/6/2003	37	T2HA	107	1	-	-	-
• 16/6/2003	37	T2HA	58	3	10	-	-
• 24/6/2003	37	T2HA	-	-	-	3	31
• 2/6/2003	32	SH	40	2	-	-	-
• 16/6/2003	32	SH	-	2	10	31	-
• 24/6/2003	32	SH	-	-	-	5	29
• 3/6/2003	24	SH	8	-	-	-	8
• 2/6/2003	21	SH	46.5	3	-	-	-
• 17/6/2003	21	SH	-	3	10	-	40
• 17/6/2003	21	SH	-	-	-	1	34
• 3/6/2003	16	T2HA	1.3	-	-	-	1.3
• 3/6/2003	4	T2L	30	3	-	-	-
• 17/6/2003	4	T2L	-	1	10	-	29
• 17/6/2003	4	T2L	-	-	-	1	28

Source: Project Implementation: by L. M. Mswane

6.2.1 Comments on tower footing resistance at the various structures

Most of the footing resistance values were found to be high. Radial counter poise earth improvement was applied to most of the structures. In addition, some conductive cement was used to enhance soil resistance in four of the structures. Figure 24 shows an open trench before back filling with conductive cement.

Figure 24: Connecting the ground wire to the wood-pole structure. Trench at the foot of Structure No. 4:

Source: Project Implementation Photos: Mswane

The ground conditions along this line vary. Some areas have more rocks than others while some have clay soil. The footing resistance measurement was made in June 2003 which, apart from the severe drought experienced that year, is normally a dry season. Because of the uneven moisture content of the soil during the year it is generally expected that the footing resistance also varies during the course of the year. Footing resistance is normally lowest during summer when there are high rains. Improvement of soil resistance was abandoned at around 30 ohms with the hope that during the lightning season, which comes with summer rains, the moisture content of the soil would be at its lowest levels.

6.2.2 Effect of Moisture on Soil Resistivity

Studies at EPRI's Transmission and Distribution Engineering Center in Lenox, Massachusetts, have shown that the dynamic resistance of ground electrodes and concrete tower footings together with the electrical properties of the underlying soils have a profound effect on the lightning performance of transmission lines [Boutacoff, 2004]

Generally Swaziland has wet summers and dry winters. Summer starts in September/October and ends in March/April of the following year [Swazimet,2004]. During this period there is a big variation in the percentage of ground moisture content and this has an effect on the electrical resistance of the soil. The lightning season arrives with the early summer rains.

The moisture content in the ground is very important. A variation of a few percent in moisture content will cause a marked difference in the footing resistance made with electrodes of a given size [Bologna, 2004]. This is especially true for moisture content below 20 percent. Experimental tests made with red clay soil by Practical Grounding (a company) indicated that with only 10 % moisture content, the resistivity was over 30 times that of the same soil having a moisture content of about 20%. For values of over 20% the resistivity is not affected much, but below 20%, the resistivity increases rapidly with a decrease in moisture content. Figure 25 shows a graph of the variation of soil resistivity with moisture content for red clay soil.

Normal moisture content in Swaziland varies for different locations, but generally is about 10% in dry season and improves to about 35% in the wet season with an average of 16 to 18 %. The resistivity measurements carried out by SEB in 1988–1991 along the Stonehenge – Hhelehhele 132kV line, shown on Table 25, indicate periods of minimum rainfall in winter will be followed by a marked decrease in the value of resistance in summer due to the summer rains [Dlamini, 1991].

It is important, therefore, that resistivity remains within acceptable levels even during the dry season and hence resistance enhancement procedure was undertaken to ensure this.

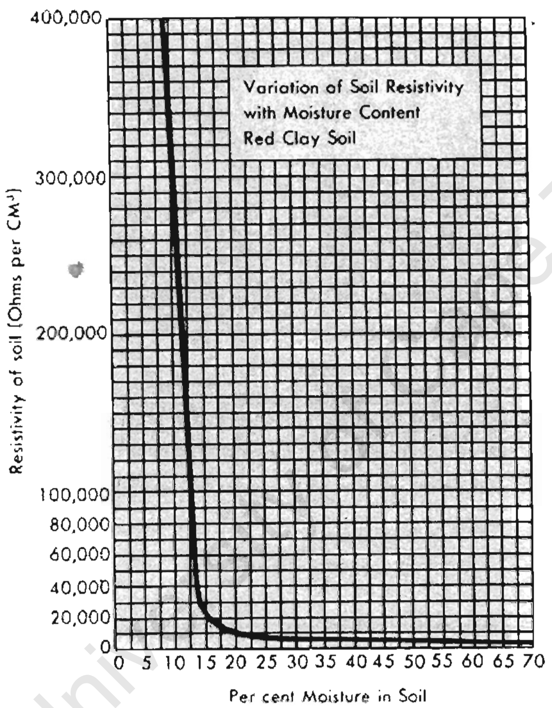


Figure 25: Red Clay Conductivity Graph
Source: [Copperweld, 1973].

6.2.3 Effect of Temperature on Soil Resistivity

Swaziland experiences extreme temperature variations between summer and winter. The summer temperatures are warm to hot and winter temperatures are cold during the night but can rise sharply during the day. In a manner similar to the ground moisture content variation, temperature variation also affects the ground resistivity. Generally ground resistivity tends to increase with the decrease in temperature. Below 0°C the water in the soil freezes and this causes a significant increase in the temperature coefficient for resistivity of the soil. This coefficient is negative, and as the temperature decreases the resistivity rises and the resistance of the ground connection subsequently increases [Copperweld, 1973], [Simonds, 2000].

It is assumed that the effects of this phenomenon in Swaziland, however, are insignificant as it can be seen from fault records above (see tables 9,10, & 11) that the lightning season, which is in summer, occurs during the period of high to moderate temperatures. While there are some seasonal variations which result in temperature decreases these variations do not go below 0°C, i.e. the temperature does not go below freezing point.

The normal moisture content varies for different soil types but generally it is about 10% in dry seasons and around 35% in wet seasons with an average of 16 to 18 percent. Studies prove that resistance values tend to increase during the dry months and decrease during wet months.

The SEB carried out a number of resistance improvements to some of the transmission line footings in the early 1990's. A record of one of these exercises shows clearly the resistance improvement as results of ground moisture content improvement. Table 25 shows part of the Stonehenge – Hhelehhele 132kV line footing resistance.

Table 25: Stonehenge – Hhelehhele 132kV Line Footing Resistance

Pole No.	Structure type	Original Reading Ohms	No. of earth Spikes	June 1988 Reading	October 1989 Reading	Jan 1991 Reading	Additional Earth Spikes May 1991	Final resistance Readings (Ω) May 1991
02	T3SP	72	4	29	44	12	6	6.8
03	T3SP	33	1	20	72	12	6	8.9
04	T3TSP	190	6	30	56	21	6	9.0
05	T3THASP	190	6	20	41	20	5	.7
06	T3SP	70	4	30	36	20	5	9.2
07	SH	20	-	20	27	22	4	8.6
09	SH	21	-	21	17.2	20	5	9.76
10	T2L	30	1	30.9	19	20	5	10
11	T3TSP	21	-	21	14	16	4	9
12	T3TSP	95	4	28.7	49	20	5	9.91
13	T3TSP	53	1	30	48	20	4	8.1
14	T3THSP	200	6	10	28	22	5	7.62
17	T3THSP	50	2	22	59	23	4	2.75
18	T3THSP	35	1	20	30	20	5	9.7

Source: SEB Transmission lines Footing resistance Measurements-1991

Resistance measurements from June 1988, October 1989 and January 1991 in table 25 show a distinct pattern of resistance increase during the dry period and resistance decrease during the wet season when the moisture content had increased. These measurements show that in June 1988 there was more moisture in the soil than in October 1989. The difference between these times signifies the dry season of 1988. In January 1991 resistance measurements show a big decrease. This means that there was a higher moisture content percentage compared to the previous two instances when the measurement was done. It is important to mention that when these measurements were done no additional earth electrodes had been added to improve the earth resistivity. Earth electrodes were only added in May 1991 to bring the footing resistance to below 10 ohms.

For the Stonehenge-Ezulwini 66kV line resistance measurement will be re-done and where necessary more earth electrodes will be added until the resistance is below 10 ohms. Tower footing resistance values will be re-measured to ascertain the correct resistance levels. Normally the acceptable resistance is below 10 ohms.

- **Structure number 37:** This is the first structure from the Stonehenge end of the 66kV line. Initial measured value was the highest in the group of towers that had their footing resistance measured. The initial value was 107 ohms. This figure was reduced to 31ohms after application of 7 electrodes and 10 bags of conductive cement. Soil composition was of dark clay with fine sand.

- **Structure number 32:** This is the second structure from the Stonehenge end that was selected have TLA's installed. 9 electrodes were installed and resistance was reduced from 40 ohms to 29 ohms. The soil composition was of red clay with some gravel.

- **Structure number 21:** 7 electrodes were used to improve resistance from 46.5 to 34 ohms. Visibly this structure had the most rock outcrop compared to the other structures as shown in figure 26.

- **Structure number 4:** This structure is the first from the Ezulwini end of the 66kV line. Footing resistance was improved from 30ohms to 28 and was the most difficult in-terms of step-changes after the addition of electrodes. A total of 5 electrodes were installed.

- **Structures number 16 and 24:** These structures had resistance values below 10 ohms and there was no need to do any improvement.

6.3 Pilot Project Cost Estimate for Stonehenge- Ezulwini Power Station line

- 66kV wood-pole line - Length: 5.2km
- Number of TLA installations on 6 structures =18
    - 2 terminal installations
    - 4 selected high risk points
- ZnO Surge Diverter (each): +- E10,000. i.e. +- E 30,000 per structure
- Labour: (+- 40% of material cost per structure)=E12,000.
- Other costs(ground leads, electrodes, transport)=E5,000
- Total Cost per structure= +- E50,000
- Total Cost for installing TLA on this line is +- E300,000

Figure 26: Earth composition at the base of StrutureNo.21
Source: Project implementation photos by L.M. Mswane

6.4 Installation of Transmission Line Arresters

The installation alternatives are many and varied. They depend on the line and the tower profiles. The Stonehenge- Ezulwini 66kV line is mainly made up of a variation of "H" pole structures. The mounting position best suited for this type of structure was the vertical mounting, or hanging under the line as shown in figure 28. The mounting was made a half metre from the composite line insulator live end such that even if the TLA failed there would be no risk of a flash over to the ground-end of the composite insulator under extreme wind conditions [Mobedjina, and Strenstrom, 2000]. The arrester is suspended from a clamp that attaches this unit to the live conductor. The design of the suspension clamp is such that it enables the TLA some free lateral movement without exerting some bending moment on the TLA. Any bending moment exerted to the TLA is extended to the line and this may result in damage both to the line and the TLA.A flexible jumper is connected between the clamp and the line side of the TLA to provide a good electrical connection between the line and the TLA. Connected in series with the TLA at the dead-end of the TLA a disconnector device is fitted from which a flexible jumper is connected. This jumper is in-turn connected to the surge counter. A ground wire is run from the bottom side of the surge counter to the ground where it is tightly connected to the earth electrode. The jumper leading from the disconnector device to the surge counter, where installed, is such that it is not too short to exert tension to the dis-connector device. The purpose of the dis-connector device is to isolate the TLA if it develops a fault. In the absence of such a device it would be difficult to spot the failed TLA. Surge counters were only fitted to the terminal structures, i.e. at structure no. 4 and structure no. 37. This was done in order to optimise project costs.

This is the type of mounting that was selected by SEB because of the design of the wood pole structures. There are several alternatives for mounting the TLA. These include vertical mounting/suspension from the cross-arm of the towers, angular mounting from the tower or a lower cross-arm, parallel mounting with the insulator etc.

6.4.1 Some Special Care to be taken during installation of TLA's

- The surge arresters are designed such that they have lifting eyes on both ends. These should be used for handling the surge arresters. Mis-handling of the units could cause stress and damage to the ZnO elements.
- The suspension clamp that attaches the TLA to the line should not be over tightened to enable some lateral movement of the suspended TLA to minimize lateral mechanical loading on the line conductor.
- The ground lead from the overhead earth wire should be well isolated from the TLA earth lead to avoid possibility of shielding wire surge false counts by the surge counter.
- Arrester lead length should be kept as short as possible to avoid high lead resistance that would result in high surge impedance.
- Grounding wire clamps should be as tight as possible to ensure low surge impedance.
- The TLA leads to earth should not be tight so that the unit can easily swing about. An over tightened earth lead may cause the disconnector unit to break due to excessive stresses. This could be interpreted as a failure resulting from a failed TLA unit.

6.4.2 Some photos from project implementation process on site:

Figures 27 to 33 illustrate the installation of the transmission line arrestors.

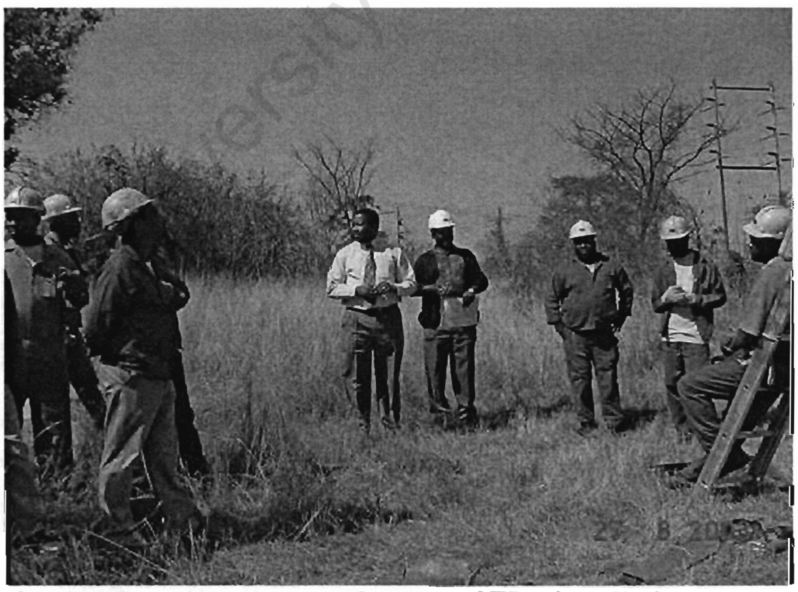


Figure 27: Site briefing of linesman at the start of TLA installation on structure no. 4.
Installation Team being briefed on site during installation of the first set of TLA's on structure number 4 from Ezulwini Power Station. Structure No. 4 is the first pole with overhead earth wire.
Source: Project implementation photos: Mswane

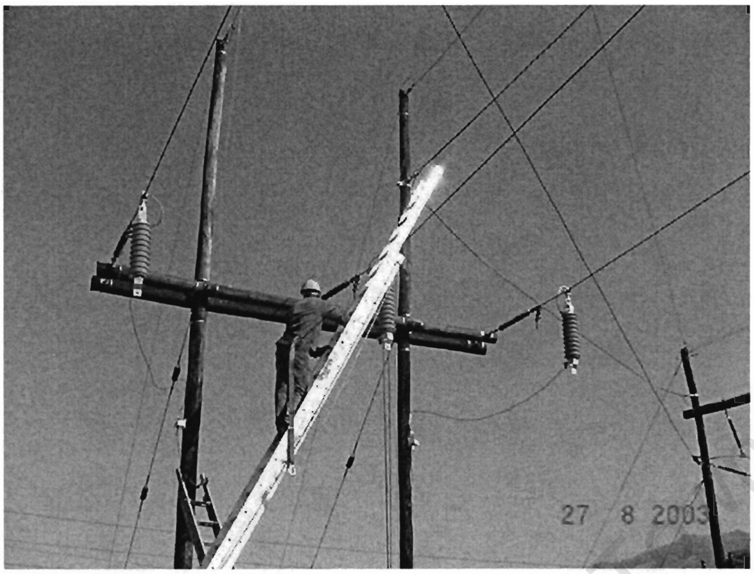


Figure 28: Yellow phase TLA's being installed
Source: Project implementation photos - Mswane

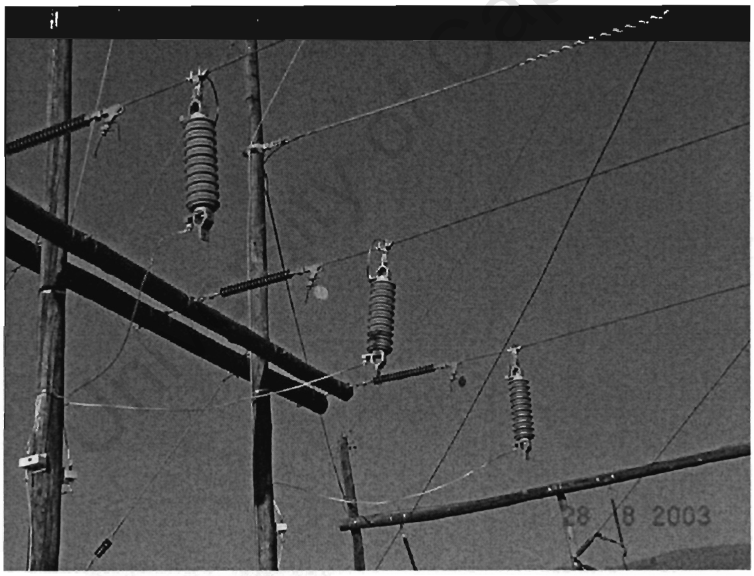


Figure 29: Completed Installation of 66kV Surge Arrester Units
Source: Project implementation photos - Mswane

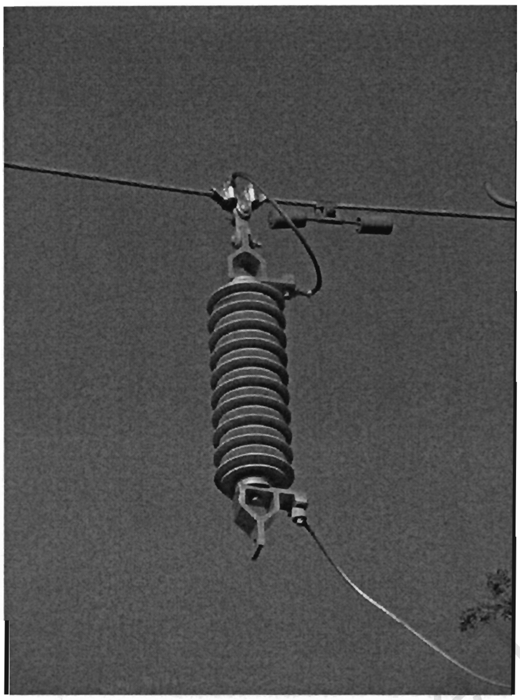


Figure 30: TLA Assembly details
Source: Project implementation photos - Mswane

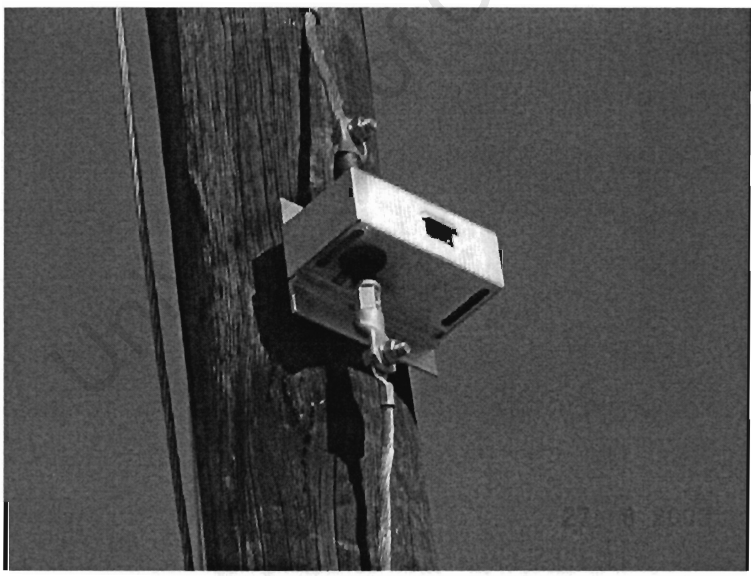


Figure 31: Surge Counter Positioning.
Source: Project implementation photos - Mswane

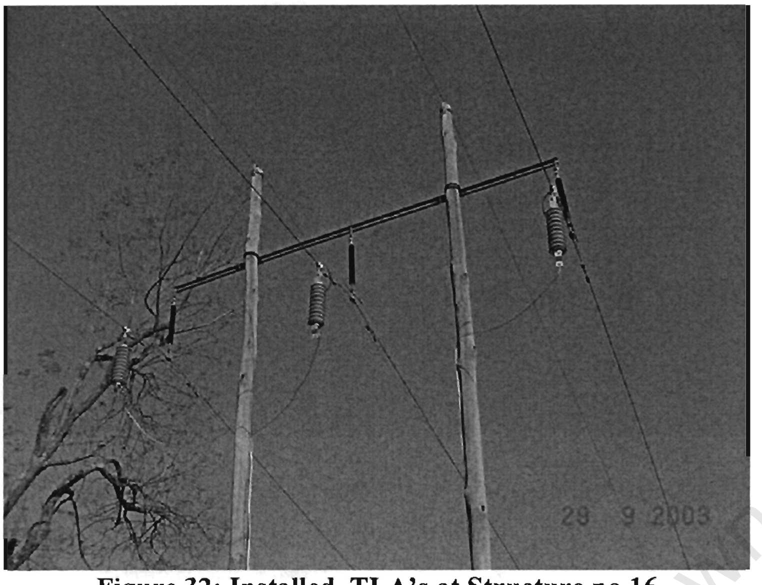


Figure 32: Installed TLA's at Structure no.16
Source: Project implementation photos - Mswane

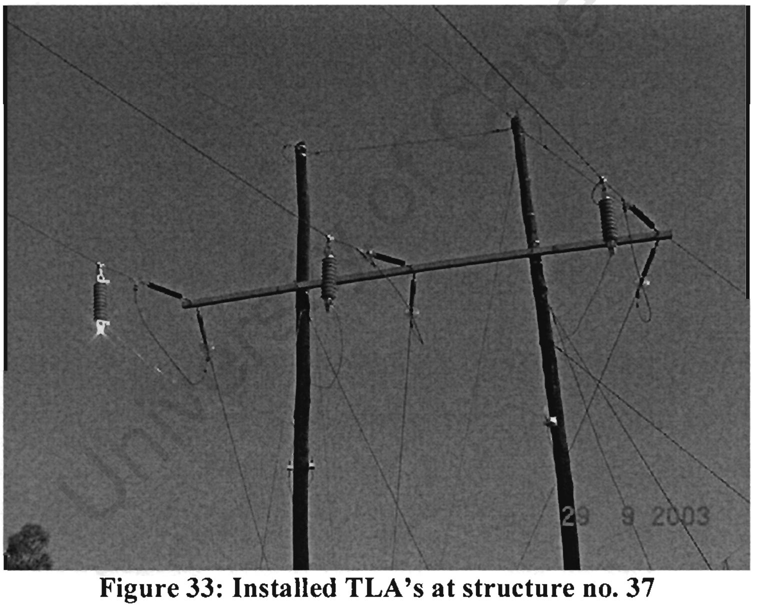


Figure 33: Installed TLA's at structure no. 37
Source: Project implementation photos - Mswane

Chapter 7

Results from the pilot project

The pilot project was implemented in August 2003, just before the start of the summer season and the lightning activity. Performance of this line was closely monitored. Table 26 shows results of the performance of this line for the past 18 months. Also, lightning performance of other two-66kV lines located in the same high lightning ground flash density area has been closely monitored for the past year. Tables 27 and 28 show the results of the performance of these two lines for the past 18 months. Table 29 shows a comparison of performance between the two control lines, i.e. Ezulwini – Thompson 66kV line and Stonehenge – Usuthu 66kV line. Table 29 shows the improved performance of the pilot line project compared to the two test lines. The following has been observed from the results:

- There were no lightning related power outages on the Stonehenge – Ezulwini line (the pilot line project) after the installation of the TLA's. Investigation into the occurrence of lightning related power outages described in chapter 3 showed that power outages caused by lightning usually begin in September/October each year. Following the installation of the surge arresters it was expected that the lightning performance of this line would improve.

- Lightning related power outages continued to occur in 2003 and 2004 during summer on the two- 66kV lines not fitted with TLA's. The lightning related power outages started to occur at the beginning of summer, in October 2003, as in the previous years.

- There was a decrease in the number of lightning related power outages in 2003 and 2004 compared to previous years (2000,2001,2002) on the two other 66kv lines that were used to compare with the pilot line project. This decrease may be attributable to the severe drought that affected Swaziland in 2003/2004 [Swazibank Annual Report, 2004]. It was also observed that there was less rain and the thunder compared to other years.

- There were lightning related power outages on the Ezulwini – Thompson 66kV line and the Stonehenge – Usuthu 66kV line during the months of May and June, and the pattern was usual compared with other years.

- The occurrence of lightning related power outages on the two test lines is cyclic and it occurs during the summer months.

Table 26: Stonehenge – Ezulwini 6kV line Lightning Related Power Outages

Months												Years
Jan.	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	
1	0	0	0	0	0	0	0	0	0	0	0	2003
0	0	0	0	0	0	0	0	0	0	-	-	2004

Table 27: Ezulwini-Thompson 66kV line Lightning Related Power Outages

Months												Years
Jan.	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	
2	1	0	0	0	0	0	0	0	0	2	2	2003
2	0	1	0	0	1	0	0	0	2	-	-	2004

Table 28: Stonehenge – Usuthu 66kV line Lightning Related Power Outages

Months												Years
Jan.	**Feb.**	**Mar.**	**Apr.**	**May.**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	
3	3	0	0	0	0	0	0	0	0	7	4	2003
2	3	2	0	2	1	0	0	3	0	-	-	2004

Table 29: Pilot Line Project Results versus Control Line 1 and Control Line 2 Results

LINE	YEAR	Months											
		J	F	M	A	M	J	J	A	S	O	N	D
Pilot L. Project Stoneheng - Ezulwini	2003	1	0	0	0	0	0	0	0	0	0	0	0
	2004	0	0	0	0	0	0	0	0	0	0	-	-
Control Line 1. Ezulwini - Thomson	2003	2	1	0	0	0	0	0	0	0	0	2	2
	2004	2	0	1	0	0	1	0	0	0	2	-	-
Control Line 2. Stonehenge-Usuthu	2003	3	3	0	0	0	0	0	0	0	0	7	4
	2004	2	3	2	0	2	1	0	0	3	0	-	-

The surge counters were also monitored and showed an increase from initial readings. These were generally monitored monthly, though sometimes the monthly readings were not recorded.. As at the end of August 2004 the readings were 22, 23, and 24. These were on the Red, Yellow, and Blue phases respectively. Accurate recording of the surge counters is important, as it would give accurate data related to the lightning activity per month on the pilot project.

The results of the performance of the pilot line project were as expected. Published literature indicates that all cases where transmission line surge arresters were installed resulted in improved performance of the lines.

The results demonstrate clearly the positive improvement of the lightning performance of the pilot project line compared to the two test lines as can be seen from table 29.

7.1 Benefit of the Pilot Project

Since the installation of the TLA's on the Stonehenge – Ezulwini 66kV line in August 2003 there has been no lightning related power outage on this critical tie line. This has improved the reliability of the line. It can be seen that during the previous years (2001 & 2002) the line had several power outages due to lightning. The cost of this project (E205,816-00) cannot be directly compared to the improved lightning performance of the pilot project line since there are no customers directly supplied from it where revenue loss could be determined. However the improved reliability of this tie line greatly enhances the security of supply in the City of Mbabane, the capital of the country.

Chapter 8

Discussion and future work

The results of the pilot project have been positive. No lightning related power outages were recorded in the first year of the pilot project.

Published literature surveyed on the experiences from other parts of the world indicate that all power utilities that installed the ZnO surge arresters immediately saw improvement on the performance of the transmission lines. As discussed in Chapter 4 under global experiences all utilities had significant improvement of the line performance after installation of TLA's [INMR, 1997], [Hubell, 2003a], [Hubell,2003b], [Cherchiglia , 2000], [Posada, Restrepo, 1996]. The results obtained in the SEB pilot project compares well with experiences of other utilities globally.

One typical success case is the project undertaken by Frankfort Plant Board (FPB), a municipal utility operating in parts of three counties in Kentucky between Louisville and Lexington in the USA. The installation of transmission line surge arresters resulted in the reduction of lightning related power outages to close to zero over a period of three years [Simpson, 2004].

The extent of the current problem on the number of outages caused by lightning is quite high (40%) and this is a cause for concern. With such encouraging results one would tend to recommend that a roll-out program to install lightning arresters in the critical transmission lines should be started as soon as possible in order to reduce the losses to both SEB and to improve the quality of supply to the various customers that are affected by frequent power cuts during summer due to lightning activity.

The approach taken by power utilities in regard to the length of time the pilot projects were allowed to last before other lines were fitted with surge arresters is not clear from the publications, apart from one organization. Minnkota Power (Grand Forks, North Dakota, U.S.) after they had implemented the initial plan, they decided that they would review the program after some two years to determine its effectiveness and to make any required modification or changes [Johnson, 2002]. The study was from 1996 to 2000 and involved more than one 69kV line.

Although it is recommended that a program to install lightning arresters in all critical lines should be started immediately, close monitoring of the performance of the pilot project line would continue for some few years in order to obtain more data and to observe performance of auxiliary equipment such as the surge counters and the lightning arrester units. Footing resistance measurements would be carried out seasonally as the moisture content changes in the ground. This would help to indicate whether there is any need to increase or improve the counter poise electrodes. The dynamic resistance of ground electrodes and the electrical properties of the underlying soils have profound effect on the lightning performance of the transmission lines [Johnson, 2002]. An extended monitoring period would also give time to monitor the surge arresters and the pollution effect on the polymer housing. The location of the pilot project line is across an area where light air-borne particles of precipitate pollution from Usuthu, a craft pulp manufacturing plant, are present.

Selection of structures to be fitted with surge arresters was mainly based on the high exposure of the structure due to the ground elevation across the five kilometres.

8.1 Further Project Cost optimisation for future project:

The cost of implementation of the project can be further improved through the reduction of the number of linesmen during construction. It was found that during the implementation of the pilot project the number of linesmen was more than required per structure. Experience show that four people would be adequate per structure to make the installation. Also, with experience it should take shorter durations to install the units in all three per structure. This would reduce the overall outage time required for installing the arresters in the system. Other utilities took only 30 minutes to fit all three units in the structure [Simpson, 2004].

Transport cost can be optimised through usage of smaller vehicles as the lightning arresters are made of light material and the only heavy equipment to carry to site would be the stepladders. Also, usage of vehicles fitted with buckets would be more efficient, however usage would only be possible on relatively flat ground.

8.2 Answering the Research Questions:

Would the installation of ZnO surge arresters improve the lightning performance of transmission lines in the SEB transmission network?

- The results of the pilot project indicate that installation of ZnO will reduce the number of outages caused by lightning compared with the two lines without TLA's.
- The cost of cost of installing (and maintaining) the TLA's is less than the cost of remedial work and revenue loss.
- The TLA's provide better service to customers; they avoid production losses and less complains to the SEB.
- Better supply quality which has broad economic benefit not taken into account in the cost analysis of the project. Improved quality of supply would enhance direct foreign investment to the country.
- Implementation of this program would be of economic benefit to the country due to the reduction of production losses to industrial customers.

8.3 Improvement measures for other causes of system outages.

Unknown Causes of fault

In this case power outages are caused by certain elements such as flashovers, brushing trees, or even leakage currents on insulators. These are basically transient faults that clear themselves in very short times such that the auto re-closing system re-closes successfully and the power supply is restored instantly. The solution to this type of fault causes is to reduce / or eliminate flashovers in the system. Most probably the flashovers were caused by over voltages due to lightning.

Falling Trees

Definition – faults caused by trees falling on to transmission lines, trees brushing or touching transmission lines. Power outages that are caused by Falling Trees are as a result of lack of proper vegetation management. This is attributed to number of reasons. The growth of trees under the transmission lines is a cyclic process. As Swaziland falls within the sub-tropical areas vegetation growth occurs mostly during the summer period. Tree species like gum, pine, and other indigenous trees grow in summer. The practice within SEB is to carry out vegetation management some few months before the onset of summer. Sometime the bush clearing maintenance process is delayed by some few months and as result trees encroach the transmission lines that causes power outages due to trees touching the transmission lines.

Some times falling trees are as a result of trees growing within way leaves or servitudes. This is a result of private land-owners that refuses to grant SEB the permission to access their farms in order to carry out bush clearing on time.

Wind

Definition - faults caused by strong wind resulting in structural failures.

A number of measures have been taken to stabilize transmission lines to withstand strong wind. In areas known to have strong wind the policy is to utilize "H" type wood pole structures instead of sing pole structures. Wind stays have also been fitted in areas with strong wind.

Overload

Definition - tripping of lines due to system overload.

This problem used to occur before the 400kV integration project was commissioned. The network had run out of spare capacity and flexibility due to the inadequacy of incoming lines at 132kV level.

Transformer maintenance

Definition - power outages that are as result of transformer faults such as bushing failures, tap-change mal-operation, etc.

Proper transformer maintenance schedules are being put in place. SEB has engaged Rotec to introduce proper maintenance procedures to ensure trouble free operation of these expensive assets. The additional scope of work for Rotec is to impart knowledge to SEB technicians.

Rotten poles

Definition - faults due to lines failing as result of rotten poles.

Although currently there is a small number of power outages that are attributable to rotten poles this may increase to significant levels within a few years as the high population of transmission lines poles start to rot. For this reason SEB has introduced a continuous pole testing and replacement process. There is pole-testing team which continuously go around the country testing and marking poles that need replacement. This information is given to a maintenance team that replaces rotten pole structures.

Cane fire

Definition - power potages that are due to faults as result of fire within the sugar cane fields during the harvesting season.

To eliminate this problem a coordinating process has been put in place between SEB and the sugar growing organisations. The procedure that has been agreed between the sugar growing organizations and SEB is that during the harvesting season the following will be done to ensure that power outages are avoided:

- Periodic meetings are held by SEB and the Sugar cane growing organisations to discuss issues of mutual concern,
- A two-meter diameter of sugar cane is cleared around all transmission line poles on circuits that transverse the sugar cane farm to be harvested,
- The affected transmission lines are switched off to the sugar cane field before it is set alight,
- Penalties are imposed to defaulting sugar cane growing by way of payment of line repair costs.
- In future defaulting companies will be required to compensate SEB for loss of revenue.

Burning pole top

This problem occurs as result of insulation failure. Where porcelain/ or glass disk insulators have broken shields, or where there is effectively cement insulation failure between the string of insulators leakage current flow from the live conductor through the defective string of insulators to the ground wire which runs across-arm and connects to the vertical ground lead.

8.4 Proposed program for role-out Implementation of transmission line arresters on the critical transmission lines of the country

It is proposed that the implementation of lightning arrestor project be carried out during the course of the next five years. The approximate budget figure for installing transmission line arrestors on the critical lines of the network is +-E5Million.

Implementation of the project should be on a prioritised manner where the most critical lines falling within the lightning zone shall be fitted with lightning arrestors.

It is proposed that implementation start with the 66kv lines as they are mostly affected compared to 132kV lines.

66kV lines

The order of critical 66kV lines is as follows:

- **Ezulwini Power Station – Stonehenge 66kV line (5.2km):**
  This line is a link between Ezulwini Power Station and Stonehenge substation that supplies the capital city of Swaziland, Mbabane. In Mbabane there are several Industrial Areas and

Commercial shops and Government offices for all Ministries. Mkhinkmo substation. For these reasons it is critical that there is redundancy in so far as the supply of power to Mbabane is concerned.

Mbabane can be fed through four different sources theoretically but because of long distances of two of the four lines effectively we can say Mbabane is fed from two sources. The other source is the 132kVline link from Mkhinkmo substation.

- **Usuthu –Malkerns 66kV line (22.4km):**
- **Malkerns – Edwaleni 66kV line (13.5km):**
  The above two lines are effectively one line supplying power from Edwaleni Power Station to Malkerns then to Usuthu. There are two SEB key customers along this line. Swazi-Can which manufactures jam and fruit juices mainly for overseas market is a sensitive manufacturing process which has suffered high losses in the past due to lightning induced power outages. The other key customer is SAPPI (Usuthu). This customer has been severely affected by lightning induced power outages in the past.

- **Thompson – Ezulwini 66kV line (23.6km):**
  This line is part of a critical ring-feed that supplies power to the Matsapa Industrial Area where sensitive manufacturing processes such as paper-tissue, textile industry, plastic extrusion etc are based. Most of their produce is mainly for export market (out side Swaziland and overseas). In the past, some of these companies have threatened to close down their manufacturing processes due to the high number of nuisance power outages, poor quality of supply where sometimes voltage magnitudes were extremely low. In-fact in 1997 one of the textile manufacturers (Natex) scaled down their operation within the country such that they only concentrated on spinning the yarn and export it to a neibouring country for finishing into fabric. Some of these power supply concerns have been addressed through the commissioning of the 400kV integration project. Concerns that have been addressed include quality of supply, particularly voltage magnitude, and the number of power outages at 132kV level. Power outages at 66kV and the distribution levels still have to be addressed. As already discussed above the frequency distribution of power outages at 66kV follows a seasonal pattern such that there are more outages in summer months.

- **Edwaleni – Lobamba – Ezulwini Power Station 66kV line (28km)**
  This is a critical line that link Edwaleni Power Station to Ezulwini Power Station. Along this line there are key customers such as the Parliament of Swaziland, Pick& Pay shopping complex, Ezulwini Group of Hotels where most of tourist that visit the country stay. These key customers had to install stand-by generators because of frequent power cuts.

- **Thompson – Manzini 66kV line (7km)**
- **Manzini – Magwabayi 66kV line (1.8km)**
- **Magwabayi – Hhelehhele 66kV line (11.2km)**
  These lines supply power to Manzini which is manly a commercial center. Through these lines redundancy is achieved for the supply of power to the Matsapha Industrial Area from Hhelehhele 132/66kV substation.

- **Edwaleni – Maguduza 66kv line (4.6km)**
  This line is mainly a link between Edwaleni and Maguduza Power Stations. Edwaleni Power Station has a black start facility while the other power stations do not have this facility.

- **Stonehenge – Ngwenya 66kV line (17km)**
- **Stonehenge – Kentrock 66kV line (4km)**
  These two 66kV lines also fall within the area with high isokeraunic levels but have less sensitive Industrial processes / or key customers and surge arresters will not be installed in these lines.

- **Stonehenge – Usuthu 66kV line (31.4km) ****
  Although this line is currently playing a critical role in providing a back-up power supply to Usuthu it will not be fitted with Transmission line Arresters (TLA's). In a few years time a 132kV line shall be constructed from EdwaleniII bulk supply point to Stonehenge via Usuthu. TLA's will be fitted on this line. However for the pilot project this line was used as a "control" line. Should a decision be made in future not to upgrade this line to 132kV, the existing 66kV line should be fitted with TLA's.

132kV lines:

The order of critical 132kV lines is as follows:

- **Edwaleni II – Mkhinkomo 132kV line (14km)**
- **Mkhinkomo II – Stonehenge132kV line (27km)**
  These lines are the main in-feeds from the newly commissioned 400/132kV – 2by 250 MVA transformers bulk supply substation at Edwaleni II. They feed the part of the Matsapha Industrial Site through a 132/11kV substation (Mkhinkomo II) and Mbabane through Stonehenge 132/66kV substation.
  Stonehenge substation has three incoming 132kV lines. However the two old incoming lines from Oshoek are mainly used for stand-by purposes because of their relatively low quality of supply and capacity constrains.

- **Mkhinkomo II – Hhelehhele 132kV line (27km)**
- **EdwaleniII – Hhelehhele 132kV line (1)(24.1km)**
- **EdwaleniII – Hhelehhele 132kV line (2)(27.2km)**
  These lines primarily supply Hhelehhele 132/66kV substation that supplies Manzini and the North East through Kalanga 132/66kV substation.

- **NhlanganoII – Kalanga 132kV line (108.5km) (implementation to be on two thirds of the line length from the Nhlangano II end only)**
  This line feeds the Eastern part of Swaziland and has a relatively good quality of supply and capacity. It is also a back-up for the Edwaaleni II lines source that feed Kalanga 132/66kV substation through Hhelehhele 132/66kV substation.

- **Edwaleni II – Usuthu – Stonehenge 132kv line (67. 3km) – to be built in 2004/2005.**
  This line is yet to be built. It will be built in 2004/2005 financial year.
  The primary purpose of this line would be to back-up the Mkhinkomo – Stonehenge 132kV line, i.e. to provide firm power supply to Mbabane and the surrounding areas.
  This line will further enhance the quality of supply to key customers like SAPPI –Usuthu through a local 132/66/6.6kV new substation that will be built with the new 132kV line.
  The Usuthu – Stonehenge section of the route of this line is mountainous and will have the highest concentration of surge arresters compared to the rest of the other lines(both 66 and 132kV lines).

8.5 Summary of total project cost for the installation of Transmission Line Arrestors on critical lines

Tables 30 and 31 show a Summary of total project cost for the installation of Transmission Line Arrestors (TLA's) on critical lines.
Tower Selection for the recommended 66kV and 132kV lines to be fitted with TLA's would be carried out in a similar approach to tower selection of the pilot project. Swaziland is generally mountainous and has visibly undulating terrains [Tourist guide, 2003/4]. Most exposed towers or most elevated structures should be selected from transmission line profiles for fitment with TLA's. Also, the terminal structures on either end of the line should be fitted with TLA's as the ground wire terminates on these structures. Installations of TLA's on selected structures would minimise the cost of this major project.

8.5.1 66kV lines

Table 30: Summary of 66kV lines to be fitted with TLA's

Circuit/ Line	Line Length Km	Terrain type	No of Structures with LA's	Approximate Cost
Stonehge-Ezulwini	5.2	Mountainous	6	300,000
Usuthu- Malkerns	22.4	Mountainous	9	450,000
Malk- Edwaleni	13.5	Hilly	5	250,000
Thomps-Ezulwini	23.6	Hilly	7	350,000
Edwa-Loba-Ezul	28	Hilly	7	350,000
Thomps-Manzini	7	Relatively flat	4	200,000
Manzini-Magwab	1.8	Hilly	4	200,000
Magwab-Hhelehh	11.2	Hilly	6	300,000
Edwa-Maguduza	4.6	Relatively flat	4	200,000
TOTAL	117. 3		52	2,600,000

Total length of 66kV lines = 922km
Total length of 66kV lines to be fitted with TLA's = 117.3km
Percentage of total = 12.86%

About a two-thirds of the total load of the country is situated within the high lightning ground flash density area where only a third of the total 66kV line length is found. Less than a third of the total 66kV line length is classified as extremely important and critical hence only about 10% of the total length of 66kV lines shall be fitted with surge arrestors in the entire country.

8.5.2 132kV lines

Table 31: Summary of 132kV lines to be fitted with TLA's

Circuit/ line	**Line Length Km**	**Terrain type**	**No of Structures With TLA's**	**Approximate Cost**
Edwa.II-Mkhnk	14	Relatively flat	4	200,000
Mkhnk-Stoneh	27	Mountainous	9	450,000
Mkhnk-Hheleh	27	Hilly	7	350,000
EdwaII-Hheleh	24	Hilly	8	400,000
EdwaII-Hheleh	27.2	Hilly	8	400,000
NhlangII-Kalan	108.5	Hilly	11	550,000
TOTAL	227.7		47	2,350,000

Total length of 132kV lines = 309.7
Total length of line to be fitted with TLA's= 227.7
Percentage of total = 73.5%

Most of 132kV lines are situated in the western part of the country where there is high lightning intensity. In-fact the above percentage does not include the two old 132kV lines coming through Oshoek as these lines are now used for stand-by purposes only.

Total cost for installation of Transmission Line Arresters in 66and 132kV lines = E4, 950,000

Note: It was assumed that the cost for 132kV TLA's is marginally different from the cost of 66kV TLA's. Also, labour cost will decrease as more experience is gained through the installation of 66kV TLA's.

Implementation period

Implementation period is expected to be less than 5 years. Actual execution of the programme should be during winter months when there are less system outages.

About 2 to 3 Million Emalangeni (Swaziland currency and E1=1Rand) shall be set aside per year for this project.

Prioritization

From the statistics it has been seen that the 66kV lines suffer more lightning induced power outages compared to the 132kV lines possibly due to the higher lightning performance of 132kV insulators and hence the priority shall be such that the 66kV lines are fitted with surge arresters first. Also, there is relatively higher redundancy on the 132kV lines compared to the 66kV lines.

66kV lines such as the Ezulwini to Thompson line should be amongst the first group of lines to be fitted with surge arresters as they supply power to SEB key customers in Matsapha Industrial Area.

8.6 Expectation from successful implementation of the project.

1. Transmission lines Lightning Performance improvement:

Successful implementation of this project will greatly improve the performance of the SEB Transmission System, particularly the 66kV network that is highly affected by lightning due to the lower level of insulation performance compared to the 132kV network. Currently about 40% of un-planned power outages are due to Lightning activity -owing to the high isokeraunic levels found on the western part of Swaziland.

The Swaziland Electricity Board shall shortly sign a performance contract with the Swaziland Government where by SEB has to achieve set performance levels during each year. These performance indicators shall include:

- Number of outages on 66kV lines
- Number of outages on 132kV lines
- Duration of outages on 66kV lines
- Duration of outages on 132kV lines

For these reasons SEB is compelled to look closely at the operations and performance of the transmission network and to introduce strategies and measures to improve the system performance technically and otherwise.

The SEB is currently operating under the Electricity Act of 1963 that gives her the mandate to generate, transmit, and distribute electricity in the whole of Swaziland. As it is the only entity that has been given such a mandate, SEB has a monopoly, and unfortunately the service being provided is not as efficient as it would be if SEB were operating under a competitive environment. The Swaziland Government is working on introducing some new bills that would take away the monopoly that is currently being enjoyed by SEB. Competition and a Regulator will be introduced in the near future. This means that SEB has to prepare for the change right now and have to introduce some drastic changes in its policies if she wants to maintain its market share. These changes include drastic improvement in the SEB business efficiency both financially and technically. The introduction of the TLA's for the improvement of the lightning performance of the SEB transmission system would go a long way in improving the reliability of power supply in the country.

2. Revenue Loss Improvement:

When an un-planned power outage occur on radial transmission lines revenue to SEB is affected adversely as during a power failure meters do not advance hence no revenue increase. With less number of power outages power shall be available to customers and hence no reduction to revenue due to power outages.

3. Operating cost reduction:

Frequent power outages result in premature maintenance of equipment such as circuit breakers. Such premature maintenance results in high cost of maintenance of circuit breakers due to:

- Increased transport operating expenditure
- Increased material/ or consumables such as circuit breaker oil

- Increased labour cost due to overtime work etc

The high operating costs that result out of circuit breaker premature maintenance will be eliminated or reduced.

4. **Will reduce losses due to frequent stoppages to sensitive industrial processes as a result of power outages:**

Sensitive industrial processes such as paper industry, plastic extrusion industry,

Textile industry will benefit immensely due to reduction of power outages as there would be no wastages and less frequent start up times. The quality of the finished product will also be improved and thus their customers would be satisfied.

5. **Will encourage Direct Foreign Investment**

Due to the highly un reliable power supply investors are currently discouraged by the poor performance of the SEB system to invest in Swaziland due to the high production losses that they would be exposed to. During idle time employees still have to be paid, rent for buildings and other overhead costs have to be paid. With a reliable power supply there would be no idle time and hence less losses to business owners and hence foreign would be encouraged.

For long-term sustainability of local and foreign investment, for sustainable economic growth and industrial development in Swaziland, one of the key ingredients that a country need to have is a reliable power system with a good quality of supply and good quality of service. If Swaziland has to prosper and have a sustainable economic growth then she has to have a reliable electricity network that has a comparatively good quality of supply to the world and the region. SEB, being the only electric power utility in the country has a mandate through the electricity act of 1963 to generate, transmit, and to distribute electricity in the country [Electricity Act, 1963]. For Swaziland to have sustainable development and economical growth SEB has to provide a reliable power supply free from nuisance power outages that are caused by lightning. Through the implementation of the lightning performance improvement of the transmission network Swaziland will have a reliable electricity network that will help encourage long-term investment. Current and future key customers will have no losses caused by lightning induced power outages.

The implementation of the TLA solution to the SEB transmission system would have significant positive impact on the economical growth of Swaziland. Currently a number SEB customers are suffering a high number of power outages and hence loss of production and other costs. The application of TLA's would improve this situation.

8.7 Additional Future work

Through the work done during this project, through the investigation into the causes of transmission line faults, there are a number of recommendations for other future work that could also improve the performance of the transmission and distribution network for the Swaziland Electricity Board. These include the following:

- That a similar investigation must be done to determine the causes of distribution line faults and that corrective solution be implemented in a prioritised manner.

- That the Fault Reporting and Analysis System be populated with power outage fault activities to enable SEB to be kept aware of the major causes of power outages. This should be done for both the Transmission system and the Distributions system. In so doing SEB can devise a systematic short and a long-term program for improving system reliability.

- That tower footing resistivity in the entire transmission network evaluated and improved where necessary. This exercise could be implemented initially on the western side of the country where there is high ground lightning flash density. This would help to reduce tower footing impedance and hence the reduction of possible back-flashes and hence improve the performance of the lines.

- That auto re-closing schemes for both transmission and distribution systems be reviewed. The investigation carried out using FRANS indicated that about 30% of transmission line faults are caused by UNKOWN elements. These faults are cleared through the re-closure of the line circuit breaker operated by the NCC. This usually takes some few minutes to execute compared to an auto re-closing scheme that operate in seconds rather than minutes.

Figures 23 a b, c, and d show the effect of the high lightning intensity in the country on the string of insulation used on the transmission system. The performance of these damaged string of insulation is down graded through the missing insulator sheds that have been shattered during the flash over activity. The photos used in figure 4 were taken from various parts of the country, particularly on the high lightning intensity region. This represents a small proportion of the of the entire transmission network. One can deduce that a number of such failure exist countrywide. This means that some of the poor performance of the system is attributable to the faulty string of insulators. To improve performance of transmission lines composite insulators should be used. Composite insulators have an advantage over porcelain insulators in that they are shatterproof. Line patrol records could be used to provide locations of broken string of insulators along the transmission lines.

That usage of the Fault Reporting and Analysis System be maintained and the results from these reports be analysed continuously and maintenance carried out where necessary.

Performance of Transmission Lines fitted with TLA's must be monitored continuously together with the associated auxiliary systems such as the surge counters.

That consistency be observed when applying insulator strings on transmission lines. Through this project it was observed that there was no consistency in the replacement of broken insulator strings as shown in figure 34. This inconsistency could lead to insulation coordination problems that could undermine the line performance. Such practices should be avoided and where such an error has been done corrective measures should be done.

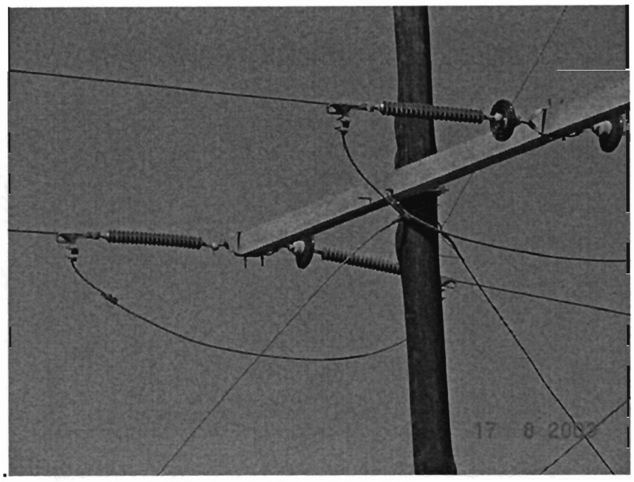


Figure 34: Inconsistency in replacement of broken insulator strings.
Source: Project investigation photos: by L.M. Mswane

Ground wire was found missing on some sections of certain transmission lines. This should be replaced as soon as possible as the ground wire also serve to mitigate the effect of lightning on transmission lines where tower footing impedance is sufficiently low.

Chapter 9

Conclusion

Table 32 shows a comparison of environmental conditions between Swaziland and other countries that have applied Zinc Oxide Surge arrestors on Transmission and Distribution lines in order to improve their performance.

Table 32: Comparison of Environmental Conditions between Swaziland and other countries that have applied Zinc Oxide Surge Arrestors

Country	Isokeraunic Levels	Presence of Lightning Induced faults	Country Terrain	Tower footing Resistance	Zinc Oxide Surge Arrestor Application On lines/ and year of application	
					T.L.	D.L.
Brazil	Up to 140	Yes	Mountainous	Very high	Yes -1996	Yes- 1996
Japan	25 - 35	Yes	Mountainous	Very high	Yes – 1980s	Yes – 1980s
USA	Up- to 80	Yes	Mountainous	Very high	Yes- 1986	Yes
RSA	Up-to 80	Yes	Flat country	Very high	Yes - 1999	Yes
Swaziland	Up – to 80	Yes	Mountainous	Very high	Applied in Aug. 2003	Not yet

For the objective of improving lightning performance of overhead transmission lines and decreasing the outages attributed to lightning some counter measures for improving line performance have included decreasing tower footing resistance sometimes using multiple earthing / grounding wires and increasing the insulation withstand levels etc. However these methods have not constituted the final solution especially in area of isokeraunic levels and high soil resistivity.

From the mid 1980's, as the case in Japan, overhead line arresters containing Zinc Oxide (ZnO) elements have been as an effective method to prevent line outages due to lightning. The transmission line arrester mainly consist of an arrester element that is connected in parallel with the insulator string. The lightning arrester can act to improve the lightning performance of the overhead transmission line by preventing the flash over of the insulator string. There are two types of transmission line arresters. The older type consisted of the gapped type while lately the gapless type housed in polymer housing is more prevalent.

Transmission line arresters basically must have the following capacity.

- The main requirement is that the arrester should prevent the flash over due to direct stroke to the transmission overhead line,
- With an acceptable low failure rate the arrester must be able to withstand possible currents and energy stresses resulting from direct strikes to the overhead transmission line,
- The transmission line arrester meet the capacity as an integral part of the transmission equipment with respect to lightning energy discharge capability, environmental conditions and mechanical strength against natural atmosphere, and
- Special consideration to possible damage to other equipment in the vicinity should be considered as the lightning arrester is installed at high positions along the transmission line.

Through the investigation and the subsequent pilot programme that was implemented, and the results obtained after one year of observation and data collection on the performance of the 66kV line fitted with Transmission line surge arresters it is recommended that:

1. That light-weight polymeric Zinc Oxide Surge Arrestors should be applied to all critical 66kV transmission lines falling within the high lightning activity area in Swaziland. Application of metal oxide surge arrestors on transmission lines, as demonstrated in other parts of the world, will certainly significantly improve the lightning performance of the transmission lines. Lightning induced power outages that are currently affecting sensitive High Technology Industries will be reduced tremendously.

   The decision to use polymeric housed transmission lightning arresters is because of its light mass and explosion proof construction because of installation on the towers.

2. That lightweight polymeric Zinc Oxide Surge Arrestors should be applied to all critical 132kV transmission lines falling within the high lightning activity area in the country.

3. That application of the Surge Arrestors must be implemented immediately on all critical 66kv transmission lines, starting with the most critical circuits first. Utilities around the world have helped to maintain investors in the country through the supply of reliable and high quality of power supply. In Swaziland some of key SEB customers that have sensitive industrial processes include Sappi (Usuthu) who have already sensitised SEB of the high magnitude of losses they suffer due to frequent power cuts which are prevalent during summer months. Currently there is a big drive to encourage investors to come and establish industry in the country in order to decrease the high level of unemployment. As result of this big drive there has been a significant increase in the textile industry coming onto the country. However in order to keep such industry in the long term the performance of the SEB power supply must comparable to regional and international industry norm.

4. That application of the surge arrestors shall be applied selectively on high- risk points along the transmission lines in order to optimise cost. The terrain of the country is mountainous particularly on the western side where there is high lightning intensity.

5. That wining tenders shall be based on quality of surge arrestors rather than low purchase price,

6. That this implementation be done over a reasonable period of time (not more than five years) in order to minimize the losses that are currently suffered by key customers due to lightning related power outages.

7. That in the long term a similar investigation be done, i.e. determine what the most single cause of outages at distribution level is, and that a corrective solution be implemented if found to be economical.

Electric power utilities from other parts of the world, where countries have high isokeraunic levels, have successfully implemented lightning performance improvement solutions on a number of transmission and distribution lines. The results from such implementation is that lightning interruptions costing customers and utilities millions in stoppage losses per year have been greatly reduced.

It is also my belief here in Swaziland that through the application of ZnO surge arresters on the critical transmission lines breaker operations as a result lightning induced outages will be greatly reduced. As already indicated above, about 40% of all outages are due to lightning. Mr. WC van der Merwe comments in his paper presented at one of the Cigre Southern African Regional Conference that:

" *Nobody will deny the necessity for providing power transmission and distribution networks with protection against lightning overvoltages in a region such as Southern Africa which experiences an above average ground flash density. The search for increasingly more effective means of protecting expensive power system equipment and improving system reliability have thus resulted in an evolution surge protection technology from the simple spark gap of 50 years ago the gapless metal oxide arresters of today.* " [van der Merwe, 1990],

and Toshio Fujita of Chubu Electric Power in Japan says

" *If there is a growing demand for higher quality power from customers, then line arresters is definitely one of the measures we will continue to use in order to reduce lightning problems*" [INMR, 1997].

References

Asokan T, Kishore BN, (2000): *Clamping Characteristics of ZnO Arrester Element Under Steep Front Impulses,* 2000 Cigre Group 33, Power System Insulation Co-ordination, Cigre Session Papers, Paris, August.

Bialek T, (1999): Insulation Systems Protection with Zinc Oxide Surge Arresters, IEEE Electrical Insulation Magazine, Vol. 15, No.1, January / February.

Billinton and Allan (1980): *Reliability Assessment Of Large Electric Power Systems*, Kluwer Accademic Publishers, Boston, USA.

Bolonga F, Britten AC, Auditore FA, (2004): *Earthing and Surge Protection of Overhead Line Towers for Power Frequency and Lightning*, the Fundamentals and Practices of Overhead Line Maintenance, 2004, Eskom.

Britten AC, (1990): *Lightning As A Factor In The Design Of Rural Distribution And Reticulation Lines,* Cigre Southern African Regional Conference, Mbabane, 12-13 March.

BS 6651, (1999): Code of Practice for Protection of Structures Against Lightning, British Standards, London.

Boutacoff D, (2004): *Striking Back at Lightning- Caused Transmission Outages*, Epri Journal – Online, www.epri.com/journal/detail/details.asp?doctype=discovery&id=462, 26/08/2004

Capricon, (1996): *Swaziland lightning Intensity*, Capricon Development Specialist, Neilspruit, August.

Central Bank, (2003/4): *Central Bank Annual Report*, 2003/4, Mbabane.

Cherchiglia LCL, (2000): *Service Experience with Transmission Line Lightning Arresters in CEMIG – Brazil*, Cigre Study Group 33/PSI/Question 5.2.

Colloson A, Stones J (2001): *Power Quality*, Power Engineering Journal, April.

Cooray V, (2003): *The Mechanism Of the Lightning Flash*, The Lightning Flash, The Institute of Electrical Engineers, London, p 128, 208-211.
Copperweld, (1973): *Principles and practices for securing safe, dependable grounds by means of driven electrodes,* Practical Grounding – Copper weld Bi-metallics, publication no. 143-5-73..

CSIR, (1986): *Lightning Recoding Scheme-Lightning Ground-Flash Density Map for RSA, Lesotho, Namibia & Swaziland*, Council for Scientific and Industrial Research, Pretoria.

Dlamini S, (1991): *SEB 1998 – 1991 Stonehenge – Hhelehhele 132kV lines Tower Footing Resistance Measurement* SEB Report, May.

Electra, (1999): *Application Of Metal Oxide Surge Arresters to Overhead Lines*, Electra No. 186, Cigre Working Group 33.11 Task Force 03, p 83, 85, 91, 101-103, October.

Electricity Act, (1963): Swaziland Electricity Board Electricty Act no. 10/1963, April

ERA technology, (2003): *ERA technology Integrated Solution* : ref. no AMS 66 24.03.03. March.

ERCHE M, (1999): *Switching Surges,* Insulation Coordination short course, University Of Stellenbosch, Cape Town, November, p D-1, November.

FRANS (1999): *Fault Reporting and Analysis System,* SEB internal document, Regal Consulting, Mick Weller, October.

Freeman M, Bettermann O, (1999): *Lightning and Over-voltage Protection for Electrical Supplies and Data Lines,* ERA Technology, Quality and Security of Supply in Electrical Networks Conference Proceedings, No. 99-0009, London, February.

Gaunt CT, (1982): *Lightning And Woodpole Design*, SAIEE SYMPOSIUM Lightning Performance of Overhead Lines, RSA.

Gaunt CT, (1994): *Analysis of Overhead Distribution Line Outages.* Department of Minerals and Energy Affairs, Report no EL9001, Pretoria, August.

Gaunt CT, Mswane LM, (2001): *Lightning Performance Improvement of the Swaziland Electricity board Transmission System (132 kV and 66 kV).* Cigre 4th Southern Africa Regional Conference, Cape Town, October.

Hubbell, (1995): *Protecta* Lite: A Complete Insulation And Protection System*, Hubbell / The Ohio Brass Company, No. EU1416-H, November, p 4.

Hubell, (2003a): *Lightning Protection for Transmission Lines Virtually Eliminates lightning Related Breaker Outages,* Hubell Tips & News, Vol. 8 No. 1, April.

Hubell, (2003b): *MEAG Drastically Cuts Lightning Surge Outages*, Hubell Tips & News, Vol. 8 No. 8, November.

Ianoz M, (2003): *Lightning and EMC*, The Lightning Flash, The Institute of Electrical Engineers, London, p 479.

INMR, (1997): *Transmission Line Arresters In Japan*. Insulation News and Market Report Vol. 5, No. 3, May/ June, p 6 - 16.

INMR, (2002): Distribution Arresters: *Market Forces, Current Technologies & Future* Directions, Insulation News and Market Report, Quarterly Review, Vol. 10, No. 6 – November/December, p16, 19, 26 & 41.

INMR, (2004): *Designs and Applications for Polymeric Station – Class Surge Arresters*, Insulation News and Market Report, Quarterly Review, Quarter One – 2004, Vol. 12 – No. 1 p 51.

Johnson J, (2002): *Northern Utilities Optimize Lightning Arrester Placement*, www.google.com/search?q=cache:vg_8YbeEapMJ: tdworld.com/mag/power_northern_utilities_optimize/+lightning+arresters+&hl=en,

20/08/2004.

Kennedy & Donkin (1996): *Kennedy & Donkin Customer Care Survey*, SEB internal document Ref. No. 60289

La Casse S, (2003): *XCEL Energy Dramatically Cuts Lightning Induced Trips,* Hubbell Tips & News Magazine – Vol. 8: No. 1, p 7, April.

Macy R, (1990): *Why High Voltage Overhead Line Insulation Fail In Service*, Cigre Southern African Conference, Mbabane, 12-3 March.

Mobedjina M, and Strenstrom L, (2000): *Improved Transmission line Performance using Polymer – Housed Surge Arresters*, CEPSI Seminar Manila, Philippines, October, p 4, 5.

Mobedjina M, Johnnertfelt B, Strenstrom L, (1998): *Design and Testing of Polymer – Housed Surge Arresters,* GCC CIGRE 9th Symposium, Abu Dhabi, 28-29 October.

Nucci CA, Rachidi F, (2003): *Interaction Of Electromagnetic Fields Generated By Lightning With Overhead Electric Networks,* The Lightning Flash, The Institute of Electrical Engineers, London, p 425.

Ohio Brass(1995): *A Complete Insulation And Protection System*, Protecta Lite, Hubbell/ The Ohio Brass Company, Publication No. EU1416-H, November.

Posada JCN, Restrepo JHC, (1996): *Metal Oxide Arresters End Lightning – Caused Outages* Colombian utility uses arresters to mitigate effects of lightning, www.google.com/search?q=cache:rheVA1Uo9YJ: tdworld.com/mag/power_metal_oxide_arresters/+transmission+and+distribution+world+ - metal+oxide+arresters&hl=en,20/08/2004.

Rosen PR, (1990): *Improving Continuity of Supply for Rural Electrification in High Lightning Areas,* Cigre Southern African Regional Conference, Mbabane, 12-13 March.

SEB (2000): *Managing Directors Report*, SEB Annual Report, 2000, Mbabane.

SEB (2004): *Swaziland Electricity Board Annual Report*, 2003/4, Mbabane.

SEB (2004a): *Maximum Demand Accounts KVA/KHW Consumption History*, SEB, Ref. MAHKVA, October.

SEB (2004b): *SEB Summary of Tariffs as from 1st April 2004*, SEB Tariff Pamphlet.

Schuld HL, (2003): *Short report on Implementation of Special Lightning Protection on High Voltage lines in Lesotho,* Plantech Associates, Ref. A-0955-01-001, May.

Simonds P, (2000): *Designing and Testing Low- Resistance Grounding Systems*, IEEE Power Engineering Review, Publication No. 0272-1724/00/S10.00©20001EEE, October.

Simpson R, (2004): Protecta* Lite Arresters reduce lightning outages to near zero on municipal 69-kV system, Hubbbell Tips & News, Vol. 9 no. 2, August.

Stenstrom L, Johnnerfelt B, (1999): Transmission Line Arresters for 275kV line Bighorn – Pluto in South Africa. Energy Requirements and Protection Performance, ABB Switchgear, Report No. SWG/AKB, November.

Swazi Bank, (2004): *Swazi Bank Annual Report*: 2004, Swazi Bank, Mbabane.

Swaziland (2004): *Swaziland Business year- book.* A Commercial Guide, Christina Forsyth Thompson, Mbabane, p 7.

Swazimet (2004): *The Climate of Swaziland*, www.swazinet.gov.sz /climatology/climatology.htm, 29/09/2004.

Swazi Telecom, (2004): *Swaziland's History, Traditions and Geography*, Swaziland Telephone Directory, General Information, p A12.

(Tourist Guide, 2003/4): *Jumbo Tourist Guide to Swaziland*; 10th edition; 2003/4. Jumbo publishers, Johannesburg. P 7.

Uman MA, (1984): *Lightning*, Dover Publications Inc. New York.

Usuthu Pulp, (1996): *Usuthu Pulp Power Dips Investigation Report*, July, p 2

Usuthu Pulp, (1997): *Record of Usuthu Pulp Power Outages*, SEB System Control Log Book, April.

van der Merwe WC, (1990): *Over voltage Protection in a High Lightning Region*, Cigre Southern African Region Conference – Electrical Power for Developing Communities, Mbabane, 12-13/March.

Vilakati SS (2001): *Macmillan Junior Secondary Geography,* Macmillan, p 112.

Williams E, (2003): *Charge structure and geographical variation of thunderclouds*, The Lightning Flash, The Institute of Electrical Engineers, London, p 4.

Young AG, (2000): *Usuthu Consequential Losses due to Disruptive SEB Power During high Rain Fall Period,* Usuthu letter addressed to SEB, April.

Zeithaml V A, Bitner M J (2003): *Services Marketing*, McGraw Hill, New York. p. 31.