ENGINEER - Vol. LVI, No. 02, pp. [01-11], 2023

DOI: https://doi.org/10.4038/engineer.v56i2.7573

Cost Effective Reliability Improvements in 33kV/11kV Electricity Distribution Networks – A Case Study in Western Province South 1, CEB, Sri Lanka

W.R.V.G.D.R. Chameera, W.D.A.S. Wijayapala and Late (Prof.) H.Y.R. Perera

Abstract: Electricity Distribution system in Sri Lanka consists of 33 kV, 11 kV and LV (400V/230 V) networks. Providing reliable supply to the end user is a challenging task to any utility. Therefore, utility is committed to develop its network to provide reliable supply to electricity users by investing in system developments.

In this research, a methodology is introduced for selecting cost-effective solutions to improve the reliability of the 33 kV and 11 kV distribution systems among different proposals. Improvement of conductor, its insulation and protection of short duration faults are focused to develop the system in this research. Part of the method developed includes a software tool (named as DisFeeRIA) to analyse the reliability indices and economic parameters for the relevant proposal. Database of the DisFeeRIA software tool includes failure rate improvement, mean time to repair and costing of each option under consideration. Medium Voltage Underground Cable (MVUGC), Medium Voltage Aerial Bundle Conductor (MVABC), Medium Voltage Covered Conductor (MVCC), Room Temperature Vulcanizing (RTV) Si-R coating on existing bare overhead line ceramic insulators are considered as options for improving conductor and its insulation. One of the latest and innovative technologies used in distribution network, Pulse Closing Technology, is used to reduce short duration faults (momentary interruptions) and enhance the lifetime of the equipment used in distribution networks.
Developed tool and method were tested by a case study done for distribution network in Western Province South – 01 of Ceylon Electricity Board (CEB). Three (03) feeders were selected in different areas from Urban, Coastal and Rural for this purpose.

MVCC and RTV Si-R coating for existing Medium Voltage Bare Overhead lines can be used for improving the reliability of Coastal, Urban and Rural distribution feeders in a cost-effective manner after proper analysis, based on technical and economic aspects. However, depending on the safety concerns, MVUGC or MVABC can be used irrespective of the economical aspect. Intelirrupter pulse closers can be used to replace traditional auto recloses, especially with MVUGC, MVABC and MVCC in rural feeders. It helps to reduce momentary interruption failures and enhance the equipment lifetime by reducing thermal and mechanical stress on all distribution equipment and cables. Furthermore, it improves the power quality of the system.

Keywords: Underground cable, Aerial bundle conductor, Covered conductor, Room temperature vulcanizing Si-R coating, Pulse closing technology, Cost of unserved energy.

1. Introduction

Sri Lanka is one of the countries that have reached close to 100% electrification level by exceeding the total number of electricity connections 7.2 million [1]. In the present context, consumers always expect a highly reliable power supply. Electricity is an essential commodity of people and therefore, utility has the responsibility and prioritized targets to maintain the supply to the end user with high reliability levels. Ensuring the reliability of power supply from generation station to the doorstep of consumer is a challenging target to any utility. In this research, improvement of reliability of the 33 kV and 11 kV Distribution Networks is targeted. Studying the reliability of 33 kV/11 kV medium voltage line and improvement of the reliability at the conductor and its insulation are mainly focused. Moreover, reducing the number of short duration faults (impulses) have been focused. To achieve this, there are many solutions. Out of these, optimum way should be selected based on economic performance.

Eng. W.R.V.G.D.R. Chameera, AMIE(SL), BScEng (Hons) (Moratuwa), MscEng (Moratuwa), Electrical Engineer, Ceylon Electricity Board. Email:randikadamith@gmail.com
http//orcid.org/0000-0002-1545-0851
Eng. (Prof.) W.D.A.S. Wijayapala, Int.PEng(SL), CEng, FIE(SL), BScEng (Hons) (Moratuwa), MEng(Moratuwa), Professor in Electrical Engineering, University of Moratuwa. Email:anuraw@uom.lk
http//orcid.org/0000-0001-8143-6030
Late (Prof.) H.Y.R. Perera, CEng, MIE(SL), BSc Eng(Hons) (Moratuwa), Dip.Ing(Aachen), Dr.Ing(Aachen), Professor, University of Moratuwa

2. Electricity Distribution in Sri Lanka

33 kV and 11 kV are the voltages used in medium voltage level and 400 V/230 V is the low voltage used for distributing electricity in Sri Lanka. At present, there are five (05) licenses issued for distributing electricity by Public Utilities Commission of Sri Lanka (PUCSL), the Regulator. Distribution license holders are listed below.

1. Distribution Division-1 (CEB)
2. Distribution Division-2 (CEB)
3. Distribution Division-3 (CEB)
4. Distribution Division-4 (CEB)
5. Lanka Electricity Company (LECO)

CEB serves 92% and LECO serves balance 8% of total 7.2 million consumer accounts in Sri Lanka [1], [2]. Distribution licensees of CEB purchase power at 33 kV from transmission licensee and operate their systems with both 33 kV and 11 kV voltage levels for medium voltage distribution and 400/230 V for low voltage distribution.

Three phase 3-wire system (Delta Configuration) is used for 33 kV and 11 kV distribution systems and three phase 4-wire system (Star Configuration) is used for low voltage distribution network. LECO operates the network with 11 kV and 400/230 V voltages for distribution.

Structure of the Sri Lankan power sector and its regulator are shown in Figure 1.

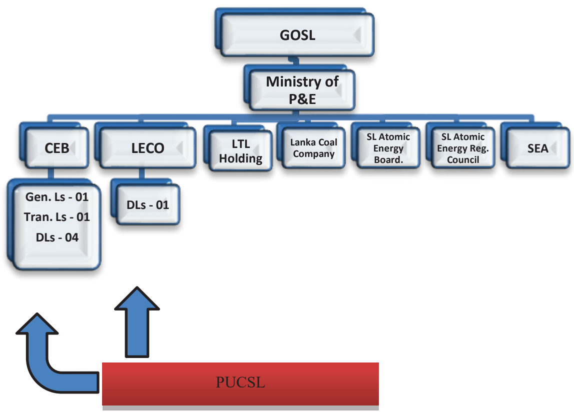

Figure 1 - Structure of the Sri Lankan Power Sector and Regulator

3. Categorization of Interruptions

An interruption is defined as an event where supply voltage drops down to less than 0.1pu. If the voltage is within 0.1 pu to 0.9 pu, it is called as voltage sag (dip) and if the voltage greater than 1.1 pu, it is called as voltage swell. The time frame of the interruption duration is used to define the interruption. Following are the three categories.

- Instantaneous – less than 0.6 s
- Momentary - between 0.6 s to 3 s
- Temporary - 3 s to 1min

In a distribution system, most of the time, entries of the interruption are recorded manually, and it is very difficult to segregate the duration below 1 min. Hence, more than 1-minute interruptions are considered as sustained interruptions and less than 1 min interruptions are considered as momentary (short duration) interruptions.

4. Cost of Unserved Energy

Cost of unserved energy is the measurement used to evaluate the cost of outage. Unreliable supply causes to increase the investment on standby generation by consumers (indirectly increase the fixed asset cost and production cost) and reduce the productivity, increase product wastage, etc. [3]. Hence, cost of outage includes these costs. This value is changed based on the type of interruption (sustained or momentary) and nature of the consumer. Cost of unserved energy is typically categorized as shown in Figure 2.

Recent research has been carried out on determining cost of unserved energy and shown in Table 1 [3].

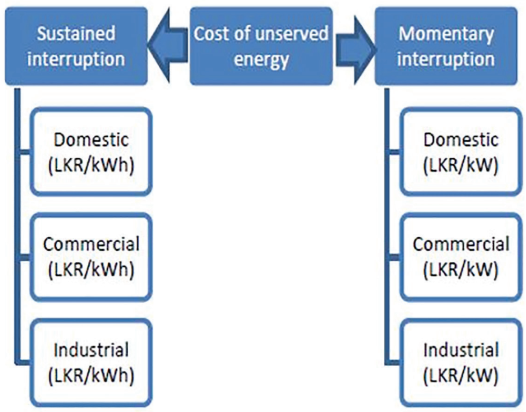

Figure 2 - Classification of Cost of Unserved Energy

Table 1 - Cost of Unserved Energy of Momentary and Non-momentary Interruptions in Both Financial Cost and Economic Cost [3]

Category	Non-momentary interruption Financial Cost in LKR/kWh (Economical Cost in LKR/kWh)			Momentary Interruption (LKR/kW) Financial Cost in LKR/kWh (Economical Cost in LKR/kWh)
	Planned	Unplanned	Combined	
Industrial	191.93 (145.87)	315.88 (240.07)	257.43 (195.65)	78.62 (59.75)
Commercial	453.49 (344.65)	418.19 (317.82)	427.37 (324.80)	191.46 (145.51)
Domestic	232.39 (176.61)	232.39 (176.61)	232.39 (176.61)	0.00 (0.00)
Combined	137.33 (104.37)	152.76 (116.10)	143.92 (109.38)	51.73 (39.26)

5. Reliability Improvement Method in Distribution System

Medium voltage line, which is one of important components of distribution system, consists of conductor, insulation medium, medium to lay conductor/cable and supporting material for laying conductor/cable.

As an example, bare overhead line may consist of the following,

- **Conductor** – Raccoon/Lynx conductor
- **Insulation** – Ceramic Insulators
- **Medium of laying** – Air
- **Supporting equipment** – Concrete pole, insulator, stay, strut, etc.

Apart from above, protection equipment is another important element of the distribution network. In this research, improving the reliability of the conductor, insulation and protection equipment which causes momentary interruption are selected for comparison. Table 2 summarizes the selected options for reliability improvements.

Table 2 - Reliability Improvement Options and Relevant Element of MV System

No	Option	Relevant element of MV system
01	Medium Voltage Aerial Bundle Conductor (MVABC)	Insulation
02	Medium Voltage Under Ground Cable (MVUGC)	Conductor/Medium of laying/Insulation
03	Medium Voltage Under Covered Conductor (MVCC)	Insulation
04	Room Temperature Vulcanizing (RTV) – SiR Coating to insulators	Insulation
05	Pulse closing technology for momentary faults	Protection for momentary interruption

To obtain the comparative improvement percentage of each option, a comparison with the medium voltage bare overhead line, which is in similar environment, was used. Failure rates per km per year of both options have been used to calculate improvement percentage. Mean time to repair in ach option is calculated by considering one year of the studied period of failures and total down time. Under cost calculation, capital cost was calculated per km and maintenance cost (Routine maintenance cost + Breakdown maintenance cost) was calculated per km per year.

5.1 Medium Voltage Underground Cable (MVUGC)

Out of the total distribution network in Sri Lanka, 2.7% (927 km) are underground cables [1]. In early days, paper insulated, copper or aluminum cables were used. However, at present, Cross-Linked Polyethylene (XLPE) insulated MVUGC are widely used, and they show better performance than paper insulation. Conductor screen and insulation screen are made from semi-conductive layers to support for electrical stress control. Cu tape is used for shielding and galvanized steel armor is used as mechanical protection.

Advantages

a. Low breakdown rate.
b. No need of lighting protection.
c. No need of routine maintenance.

Disadvantages

a. More expensive.
b. Mean Time to repair is high.
c. Skilled labor is required for cable joints.

5.2 Medium Voltage Aerial Bundle Conductor (MVABC)

Medium Voltage Aerial Bundle Conductor is generally called as MVABC. Its appearance is same as low voltage ABC, but cable construction is totally different. Furthermore, the cable is suspended to the pole using suspension bracket or wedge type clamp (at tension point) using a separate messenger wire. But in LVABC, the neutral is used as messenger.

Simply, MVABC construction follows MVUGC and the difference between MVABC and MVUGC is that each of the three phases of MVABC have been bundled together after the outer sheath of each core. MVABC is the one and only option that can be laid overhead which is safe to touch.

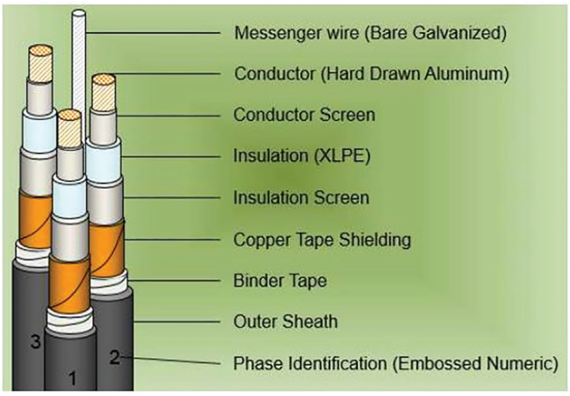

Figure 3 - Construction of MVABC [4]

However, heavy weight of the cable causes to maintain a low span between poles (around 35 m – 40 m). It is very inconvenient to erect poles in short spans in highly congested areas. In addition, loosening of the cores from bundle because of weight causes visual pollution, especially in urban areas. Another drawback of the MVABC is rectifying a cable damage in middle of the span involves a high cost and long time because of the comparably high cost of cable joints and because an additional support tray with an additional new pole is needed to be installed. If it is not possible to erect an additional pole, the relevant full span needs to be laid with two cable joints.

Advantages

a. Safe to touch.
b. No need of lighting protection.

Disadvantages

a. Loosening of cores from bundle causes visual pollution.
b. Mean time to repair is high.
c. Maintaining short spans between poles is difficult.
d. Skilled labor is required for stringing and cable joints.
e. Cost of construction and breakdown maintenance is high.

5.3 Medium Voltage Covered Conductor (MVCC)

This is a partially insulated conductor which is not safe to touch. Medium voltage covered conductor has been introduced in 1980s and it has only an insulation layer and water blocking layer over the bare conductor. Later, it has been improved by adding semi conductive layer to equalize the electric field. Furthermore, HDPE outer layer over the insulation (XLPE) has been added for strengthening the cable [5].

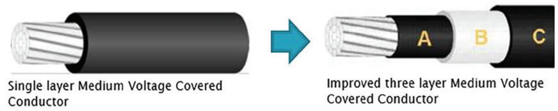

Figure 4 - Change of MVCC from Earlier Construction [5], [6]

By adding a semi-conductor layer, equalized electrical field is produced around the conductor through insulation (XLPE). Uneven electric stress leads to reduced lifetime of the insulation. Figure 5 shows the electrical stress around the conductor with and without conductor screen.

Figure 5 - Comparison of Voltage Stress Distribution with Semi-conductor Layer Around Conductor [5], [6]

Wrong construction practices, such as use Aluminum binding with ceramic insulators, use metallic tension insulator hardware, splice the insulation layer etc. are common reasons to failure of the earlier MVCC line.

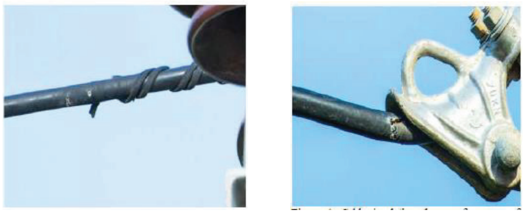

Figure 6 - Pin holing of Cable Insulation from the use of "Floating Potential" Metallic Pre-form Tie and Cable Insulation Damage from use of Metallic Dead-end Clamp [5]

Tracking and eventual pin holing of the cable sheathing are common failures of the earlier experience, because of the metallic components (Aluminium bindings, metallic hardware) have been used. Reason for this is, metallic components are always seen as a "floating earth" and discharged, charged during the voltage cycle.

Normally, insulation of MVCC construction is not designed for continuous voltage. Hence, tracking condition will occur and fail the conductor. Figure 7 describes the two different methods that apply excess voltage to the insulation of the MVCC.

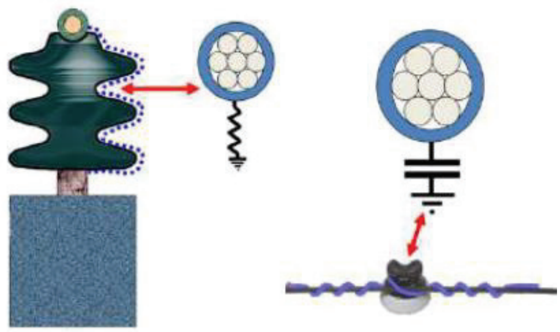

Figure 7 - Two Different Methods that Apply Excess Voltage to the Insulation of the MVCC

Therefore, Cable supports have been modified by introducing new design wedge type clamps for dead ends; UV stabilized helical cable ties, polymer insulators and insulation piercing connectors, for tapping new lines, etc. Furthermore, sufficient surge protection has been added such as arc horn, surge diverters etc.

Changing the construction of the MVCC and the modification of used accessories, have minimized most of the drawbacks of earlier design.

Figure 8 - Modified Accessories of MVCC

5.4 Room Temperature Vulcanizing (RTV) – SiR Coating to Insulators

Hydrophobicity is the most important property of silicone rubber insulators [7]. Porcelain and glass are commonly used as insulators for overhead electricity distribution network. However, both these options do not have high "hydrophobic" property on surface. Hence, polymer insulators (named as composite or non-ceramic) have been introduced to obtain improved performance due to high hydrophobicity.

High hydrophobic (Water repellent) property results in minimization of the surface leakage current and dry band formation on the surface. Polymer insulator has a very weak bond with oxygen (chemical degradation) compared with porcelain. Coatings such as grease, Room Temperature Vulcanizing Silicon Rubber (RTV Si-R) and Nano coating are used for the purpose of adding the hydrophobic property to reduce the surface leakage current on ceramic insulators since silicone rubber insulators are not available to directly replace them.

Table 3 - Summary of the Features of Different Coating Methods [7]

Coating Method	Suppressed Leakage Current	Reduced Energy Absorption	Flashover Voltage compared with uncoated insulator	Hydro-phobicity
Grease	Yes	Yes	Higher	Yes
RTV Si-R Coating	Yes	Yes	Higher	Yes
Nano Coatings	Yes	Yes	Lower	Yes

5.5 Pulse Closing Technology for Momentary Faults

Pulse closing technology is the newest technology that is being used to replace the traditional auto reclosers. Traditional auto recloses identify the faults after allowing few attempts of reclosing (normally 3 or 4 times) full fault current to the system. Because of this, uneven stress is applied on the system. This may cause reduction of lifetime of the equipment and causes power quality issues to upstream customers. Therefore, it is very important to minimize the unwanted stress on the equipment of the system [8]. Pulse closing technology uses very low current to determine whether the fault remains in the system or not. Figure 9 shows the Current flow Vs Time through the typical Auto Recloser and Figure 10 shows the current flow Vs Time across Intellirupter pulse closer, during the identification of the sustain fault. It clearly shows that, low current has been used to identify the same fault in intellirupter pulse closer.

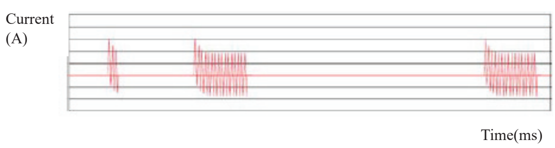

Figure 9 - Current Vs Time of Conventional Recloser [8]

Figure 10 - Current Vs Time of Pulse Closing Technology [8]

This technology is equipped with very short switching time, such that close and open contact before the first current zero crossing. Importance of this technology is that the closing point can be decided. It is decided such as to measure and analyze the fault by minimizing the let through energy as low as possible. After voltage peak, interrupter is closed for creating an asymmetrical current within the first loop as a minor loop. Hence, only this minor loop of current is allowed to flow. Therefore, peak current is only limited to 3-8ms and this minor loop of fault current is used to test the line.

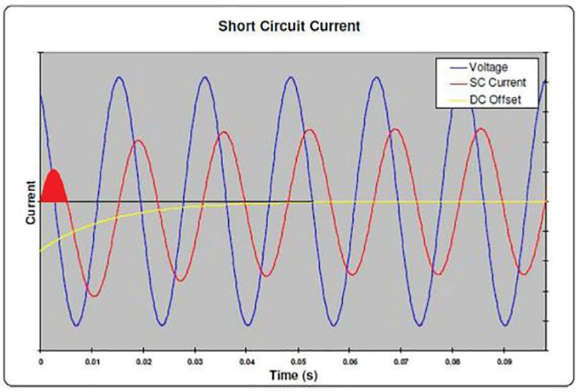

Figure 11 - Minor Loop (Shaded in Red) of Fault Current is Allowed to Flow [8]

6. Reliability Improvement, Mean Time to Repair and Cost of Each Option

To obtain the comparative improvement percentage of each option, a comparison with the medium voltage bare overhead line, which is located in a similar environment, was used. Failure rate per km per year was used to calculate comparative improvement percentage. Mean time to repair of each option is calculated by considering one year of the study period of failures and total downtime.

Under cost calculation, capital cost was calculated per km and maintenance cost (Routine maintenance cost + Breakdown maintenance cost) was calculated per km per year. Each cost calculation has been done for 33 kV and 11 kV distribution systems separately.

As an example, by considering the lifetime of the MVUG cable and load growth, it was decided to select the 240 sq mm size. Annual maintenance cost was calculated based on routine maintenance such as service of RMUs (Ring Main Units) and breakdown maintenance cost. Breakdown maintenance cost consists of abnormal breakdown cost due to faults of the UG cable (1 incident per 10 years). It is assumed and calculated that there are two (02) RMUs in 1 km length of cable. Price List of CEB 2019 [09] used in 2020 was used for material cost.

Cost constructing 1 km of 33 kV 240 mm^2 /Cu/XLPE/SWA Line

- Material Cost = LKR 25,486,520.00
- Labor cost = LKR 3,678,630.00
- Transport cost = LKR 70,000.00
- Authority charges = LKR 5,787,170.00

Total Cost = **LKR 35,022,320.00**

Maintenance Cost of 33 kV 240 mm^2 /Cu/XLPE/SWA Line per year per km.

- Routine Maint. per RMU = LKR 12,050.00 (A)
- Breakdown cost per Breakdown = LKR 696,060.00 (B)
- Total = A*2+ B/10

= **LKR 93,710.00**

Comparison was done between MVUGC and MVBOH based on two feeders which are in the same environment. Tripping data of following feeders have been collected and calculated independently. Improvement of failure rate was calculated as a percentage compared to MVBOH in the same environment.

- Failure rate per km per year of MVBOH = FR_{BOH}
- Failure rate per km per year of MVUGC = FR_{UGC}
- Improvement %

$= (FR_{BOH} - FR_{UGC})/FR_{BOH}$ %

Construction	MVUGC	MVBOH
Feeder Name	Dehiwala PSS Feeder 01	Dehiwala PSS Feeder 05
Length	3.2km	2.9km
Line route	Dehiwala Galle road	Dehiwala Galle Road
Failures per year	03 Nos	14 Nos
Failure per year per km	0.94 Nos/year/km	4.83 Nos/year/km
Improvement	3.89 Nos/year/km	
Improvement %	3.89/4.83 * 100 = 80.5 % ~**81%**	

Medium voltage failure report of Colombo city province of CEB was analyzed. Total number of failures and total downtime during the period of November 2018 to October 2019 was used for calculations.

- Total down time = 209,776 min
- Total failure = 632 Nos
- Mean time to repair.

  = 209,776 min/632 Nos

  <u>= 332 min per interruption</u>

Same procedure was used to calculate capital cost and maintenance costs for Pulse Closing Technology except calculating reliability improvement, since there is no experience in Sri Lanka to compare. However, previous research results are used to calculate improvement % of MAIFI.

Results of calculation and gathered data are summarized in Table 4.

Table 4 – Data Used in the Calculations [9-15]

Option	Capital Cost (per km)		Maintenance Cost (per km per year)		Failure rate improvement	Mean time to repair
	33kV (MLKR)	11kV (MLK)	33kV (LKR)	11kV (LKR)		
MVBOH	2.7	2.5	173,000.00	90,000.00	N/A	
MVUGC	35.0	30.9	94,000.00	74,000.00	81%	332 min
MVABC	10.3	8.7	105,000.00	96,000.00	72%	1095 min
MVCC	4.9	4.1	102,000.00	54,000.00	57%	25 min
RTV Coating	0.4	0.3	98,000.00	55,500.00	30%	Same as BOH
IntelliRupter Pulse closer	8.3	7.0	32,000.00	30,000.00	77% MAIFI	N/A

Figures 12 to 15 graphically show the above outcomes of the calculation and can be compared with each option.

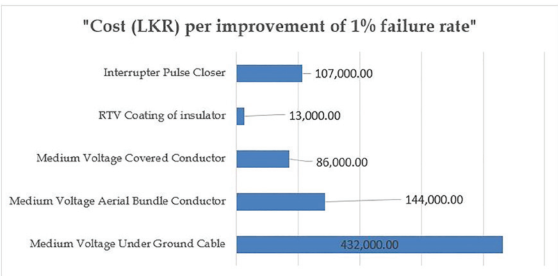

Figure 12 - Comparison of Cost per Improvement of 1% of Failure Rate (LKR)

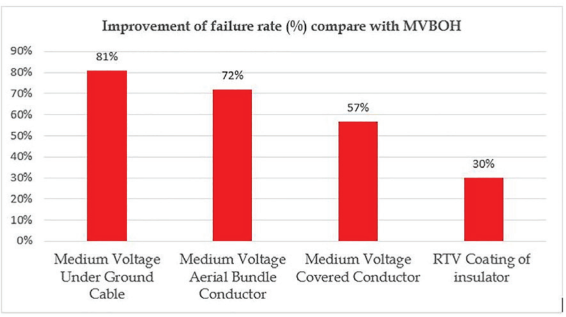

Figure 13 - Comparison of Improvement of Failure Rate of Options Compared with MVBOH

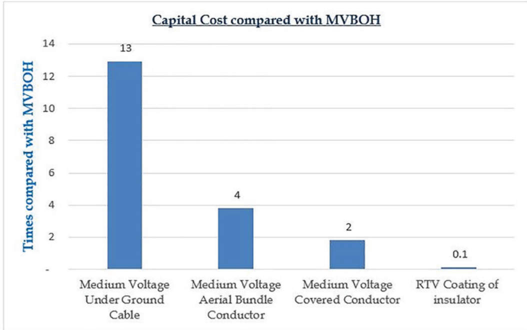

Figure 14 - Comparison of Capital Cost of Options Compared with MVBOH

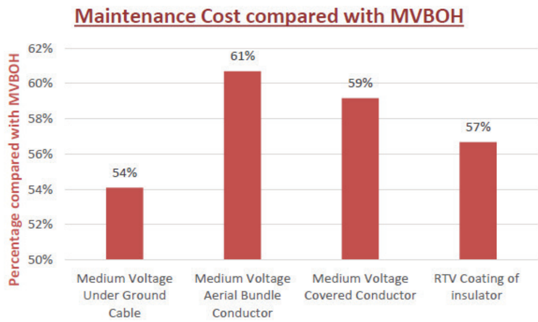

Figure 15 - Comparison of Maintenance Cost of Options Compared with MVBOH

7. Method of Analysis

7.1 Category of Feeders

Distribution feeders of the network can be classified basically under following categories based on the area they are installed.

1. Urban feeders
2. Rural feeders
3. Coastal feeders

Based on above feeder types, different priorities should be considered when there is a proposal to make a change in a distribution network. As an example, for urban feeders, high priority should be given to the space available for the route, visual pollution, etc.

In rural area, there may be forest reserves, archeologically conserved places, etc. Along the coastal areas, salty wind, visual pollution (because of tourism and sight of the beach), deposit of salt, etc. should be considered.

Therefore, available options must be sorted out depending on feeder type. Table 5 has summarized the preliminary filtration based on the priorities.

Table 5 – Preliminary Filtration

Feeder Type	RTV coating for insulators	MVUGC	MVABC	MVCC	Intellirupter Pulse Closer
Urban	Yes	Yes	No	Yes	No
Rural	Yes	No	Yes	Yes	Yes
Coastal	Yes	Yes	No	Yes	No

MVABC option is not considered in urban and coastal feeders, since it causes visual pollution after some duration of installation because of the loosening of the cable from bundle. Furthermore, span between two poles should be maintained around 30-35 m. Generally, MVBOH has 50–60 m span. Therefore, it is required to erect poles at extra locations between typical MVBOH lines if it is changed to MVABC. This is a very difficult task in urban areas. Therefore, MVABC is not considered for urban feeders for reliability improvements.

When MVABCs are considered for coastal feeders, same issue of visual pollution exists. Most of the coastal areas have been now transformed to tourism areas. Therefore, visual amenity and skyline of these areas have become very important to maintain the attraction for tourism. Therefore, MVABC should not be considered when selecting options along the coastal areas.

Laying of MV underground cable involves an excavation at least 1.1 m depth and 0.5 m width. Backfilling is conducted according to the standard material such as sand, poly-ethylene warning tape, cement tile, quarry dust, etc., for laying the MVUG cable. Therefore, excavation along forest areas and backfilling using these materials will disturb the natural activities and there may be objections from relevant authorities and villagers. Besides, rural feeders are long lines and cost of MVUG cables is prohibitively expensive. By considering all these, MVUG cable option is not considered for rural feeders.

7.2 Comparison of Results

After the preliminary filtration, the selected options are combined and checked on a trial-and-error basis in combination of each other in percentage length of the line section considered. Each section involves different figures for reliability [16] and economic parameters. Parameters considered in this study are listed below.

Reliability parameters:

- ***SAIFI*** -System Average Interruption Frequency Index
- ***SAIDI***-System Average Interruption Duration Index
- ***MAIFI*** -Momentary Average Interruption Frequency Index

Economical parameters:

- Investment cost
- Annual maintenance cost
- Simple Payback Period (SPP)
- Internal Rate of Return (IRR%)
- Cost to Benefit Ratio (CBR)

Target values of the reliability indices should be decided according to the vision of the utility or pre-defined target by regulator.

In Sri Lanka, the regulator is in the first stage of implementing distribution performance standards regulations (2016). Distribution licensees are compiling reliability data which will be incorporated into the distribution development plans in future for each distribution utility, which will serve as regulator approved investment plans [17].

Results are calculated based on the percentage length of the options that are selected (according to the feeder type and preliminary filtration) and calculated values of failure rate improvement, mean time to repair, etc. Then it is checked whether the results are within the targets. If it is not satisfied, percentage length of the option should be changed until the target is achieved. Range of the percentage length that satisfies reliability target is then determined. Limit (percentage length of options) of this range will be one of the following points.

a. Point at reliability target.
b. Point at maximum or minimum use of the option.

Pulse closing technology is used in "Intelli Rupter Pulse Closer", to reduce the momentary interruptions [8]. Therefore, it is only used in rural feeders based on the usage of the cable (MVUGC, MVABC, MVCC).

In urban feeders, there are three options that should be considered. Therefore, maximum there are 04 sets of combinations that meet the reliability target. Some of the combinations will not meet the target, therefore, such combinations are not considered further.

Considered options in urban feeders are,

a. MVBOH with RTV Coating
b. MVUGC
c. MVCC

Possible four (04) combinations are,

1) MVBOH with RTV Coating on ceramic insulators, MVUGC and MVCC.
2) MVBOH with RTV Coating on ceramic insulators and MVUGC.
3) MVBOH with RTV Coating on ceramic insulators and MVCC.
4) MVUGC and MVCC.

Economic evaluation and optimization are done by changing the percentage of the options which are within selected range. Out of this selected range, further sorting gives the range that IRR is more than discount rate, then the point which gives maximum IRR of each combination is selected and, finally, the maximum IRR among each combination is selected.

If there is no range that gives IRR>Discount rate, then the range which gives IRR more than zero (IRR>0%) is selected. The same procedure is followed for all options. Entire procedure followed is described in the flow chart in Figure 16.

7.3 Development of Software Tool

Method elaborated in Section 7.2 in this paper involves a trial-and-error method to find the results. Therefore, it is very difficult to calculate them manually.

A Graphical User Interface (GUI) and Microsoft Excel sheet are developed for this purpose. Both tools require a set of user inputs.

Then calculation is done by using user inputs and stored data (Data that was found in this research as discussed in Section 7.1 and Table 5) to calculate the reliability indices and economic indicators for evaluation.

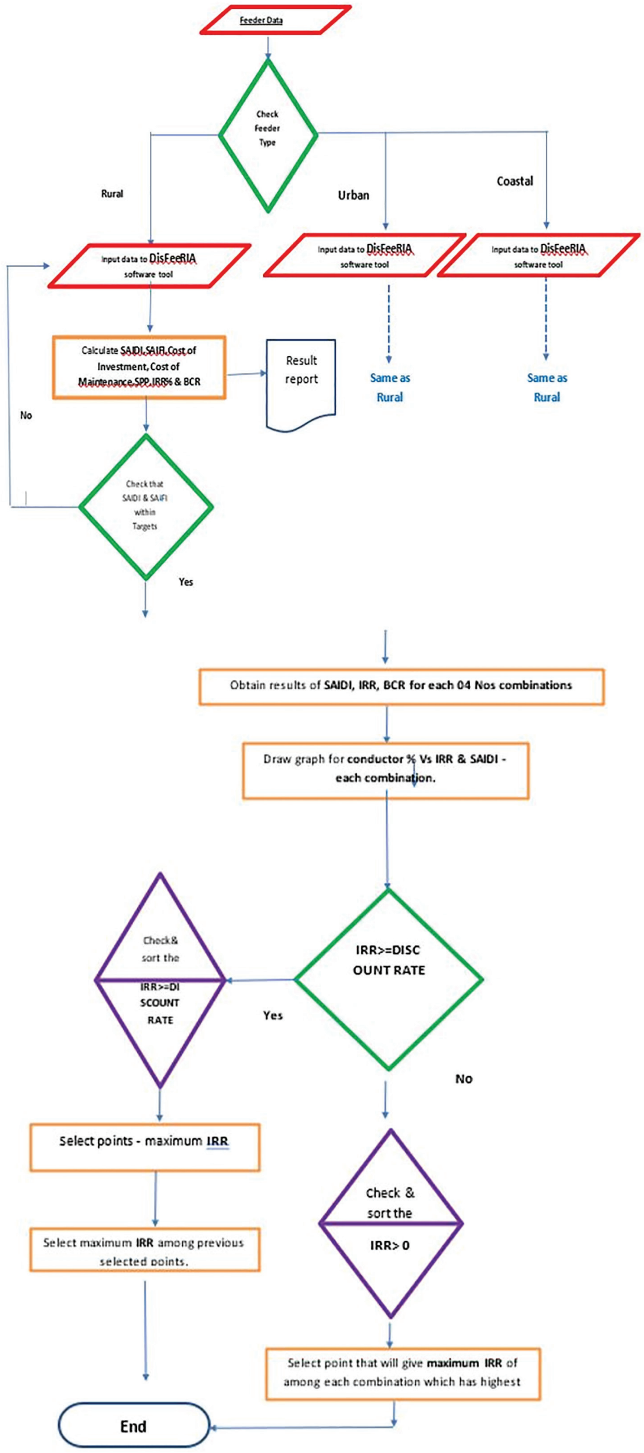

Figure 16 - Flow Chart

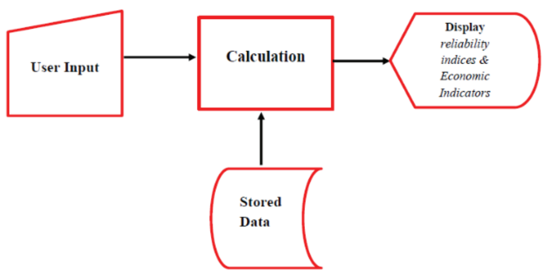

Figure 17 - GUI Tool (DisFeeRIA)

Table 6 - Input, Stored and Output Data of GUI

User Input	Feeder Name
	Feeder Length
	Load of Domestic, Commercial & Industrial sector. [kW]
	Feeder type (Urban, Coastal, Rural)
	Voltage level (33kV/ 11kV)
	Present values of Reliability indices (SAIFI – #int/year/consumer, SAIDI - min/year/consumer, MAIIFI - # int/year/consumer)
	Target of Reliability indices [%]
	Discount rate use for economic analysis [%]
	Proposed feeder length as % to be consider among selected options (MVBOH with RTV coating, MVUGC, MVABC, MVCC
Stored data	% of improvement of failure rate compared with MVBOH in each option.
	Mean Time to repair of each option which analyze.
	Cost of unserved energy in Domestic, Commercial & Industrial sector.
	Capital cost (Investment) of each option which analyze.
	Maintenance cost of each option which analyze.
Display Results	Expected SAIFI, SAIDI, MAIFI
	Target is achieved or not
	Total Investment
	Annual maintenance cost`
	Annual maintenance cost
	Simple payback period
	IRR %
	Cost to Benefit ratio
	Saving
	Proposed line sections length and Number of IPC to be used

GUI tool developed is named as DisFeeRIA (Distribution Feeder Reliability Improvement Analyzer). It has facility to store the results as an MS Excel file.

8. Case Study

A case study was carried out in one of the provinces where Ceylon Electricity Board operates. Data of one feeder in each type (Urban, Coastal and Rural) were collected. The following data are included.

- Failure analysis
  SAIFI, SAIDI, MAIFI
- Analysis of consumer loads
  Loads of Domestic, Commercial &v and Industrial categories.

Feeders listed in Table 7 below were selected for the case study.

Table 7 - Details of Selected Feeders for the Case Study

Feeder Type	Feeder Name	Voltage	Line length	Line route
Urban	Kalubowila PSS F6	11kV	6 km	Kalubiwila PSS to Kohuwala gantry, Dutugemunu street Mudali mawatha LBS, Peters lane to Nugegoda high level rd, Sunethra Devi road to Woodland roadd and LBS at Cemetry Anderson rd
Coastal	Dehiwala PSS F5	11kV	2.9 km	Galle road from Mihindu Mawatha to Dehiwala junction, Senanayaka rd, fair line road and end at LBS DM003S1N near Dehiwala AGA office.
Rural	Matugama GSS F2	33kV	145 km	(i) Mathugama GSS to Kithulgoda Gantry (ii)(a)Kithulgoda gantry to Kalawana rd Athwelthota (Auto recloser KA083R3) (ii)(b) Lathpandura KA021R3 to Kukule (iii)Kithulgoda to Horana rd Kalumale(Auto Reclosers - KA082)

Failure data of each feeder selected under three categories for three years were analyzed. Furthermore, load data of domestic, commercial, and industrial consumers in each feeder were calculated. All the data pertaining to the case study is summarized in Table 8.

Table 8 – Data Pertaining to Feeders used for the Case Study

Feeder Name	Feeder Type	Present reliability indices (per year per customer)			Load data (kW)		
		SAIFI	*SAIDI*	*MAIFI*	*Domestic*	*Commercial*	*Industrial*
Kalubowila PSS F6	Urban	24.7	531.7 min	13.8	578.3	1555.5	Nil
Dehiwala PSS F5	Coastal	20.3	730.3 min	12.5	751.5	926.0	56.3
Mathugama GSS F2	Rural	70.7	1872.8 min	464.0	3355.3	86.3	559.2

Using load data in Table 8 and reference paper data [3] in Table 1, cost of unserved energy of each feeder could be found. Cost of unserved energy of selected three (03) feeders were calculated and summarized in Table 9.

Table 9 - Cost of Unserved Energy of Selected Three Feeders

Feeder	Non – momentary interruption (LKR/min)	Momentary interruption (LKR/interruption)
Kalubowila PSS F6	10,120.00	226,300.00
Dehiwala PSS F5	7410.00	138,100.00
Mathugama GSS F 03	12,170.00	46,000.00

Collected and calculated data of above are used to find the cost-effective solution as per input data. 40% improvement from present value of reliability indices [18] was selected as the reliability target. 7.5% is chosen as discount rate, as 7.25% is the maximum fixed deposit interest rate given by government banks to the corporate sector (2019 prices).

DisFeeRIA software and method elaborated in section V were used to find the cost-effective solution for above feeders and results of each feeder are shown in Table 10.

Table 10 - Data of the Cost-effective Solutions of Case Study Done for Each Feeder Type

Feeder	Selected option	SAIDI (min/year/customer)	SAIFI (# int/year/customer)	Capital Cost (MLKR)	Maintenance Cost (MLKR/year)	MLKR/1% of SAIFI improvement [MLKR/1%]	IRR%	BCR
Dehiwala Feeder 05 (Coastal)	MVBOH (RTV) 63%, MVCC 37%	403	12.2	4.9	0.16	0.12	41.1	6.10
Kalubowila Feeder 02 (Urban)	MVBOH (RTV) 50%, MVCC 50%	319	14.0	13.2	0.33	0.3	9.6%	2.12
Mathugama Feeder 02 (Rural)	MVBOH (RTV) 62% MVCC 38%	1102	42.2	321.6	14.5	7.98	3%	1.33

9. Conclusion

Most of the time, existing approaches to maintain a reliable supply by utilities are not economically oriented. However, most of these network improvements require comparably high investment. Therefore, utilities should carefully invest on reliability improvement proposals in distribution networks.

Methodology developed in this research can be used by utilities to reach reliability targets by improving the 33/11 kV Distribution network conductors and their insulation.

The Developed software tool (DisFeeRIA – Distribution Feeder Reliability Improvement Analyzer) can be used for analyzing reliability improvement of any distribution feeder while taking economic considerations into account.

Medium Voltage Covered Conductor and RTV Si-R coating for existing Medium Voltage Bare Overhead lines can be used for improving the reliability of Coastal, Urban and Rural distribution feeders in a cost-effective manner after proper analysis done based on technical and economic aspects.

However, depending on the safety concerns, Medium Voltage Underground Cable or Medium Voltage Aerial Bundle Conductor can be used irrespective of the economical aspect.

Intelirrupter pulse closers can be used to replace traditional auto reclosers, especially with MVUGC, MVABC and MVCC in rural feeders. They help to reduce the momentary interruption failures and enhance the equipment lifetime by reducing thermal and mechanical stresses on all distribution equipment and cables. Furthermore, they improve the power quality of the system.

References

1. Ceylon Electricity Board, "Statistical Digest 2020", Colombo, Sri Lanka, 2021.
2. Lanka Electricity Company, "Statistical Digest 2019", Colombo, Sri Lanka, 2020.
3. Colambage D Punsara, Perera H.Y.R." Assessment of Cost of Unserved Energy for Sri Lanka", Dept. Elect. Engineering, University of Moratuwa, Moratuwa. -3.
4. Dissanayake, D.M.A.K., "Techno Economic Analysis on the Use of Fully Insulated Cable for 33kV Overhead Power Distribution System in Sri Lanka", MSc Research Report, Cardiff University, Cardiff, 2017. – 4.
5. Robert Battle, Rajesh Khanna, Blaise Beauger," Aerial MV Covered Networks: Worth A New Look?", 25th International Conference on Electricity Distribution Madrid, 3-6 June 2019,2016, Paper No 2316.
6. Wareing, J. B., "Covered Conductor Systems for Distribution", Report No: 5925, Project No: 70580, December 2005.
7. Shuaib Mohamed Braini, "Coatings for Outdoor High Voltage Insulators", PhD Research Report, Cardiff University, Cardiff, 2013.
8. Ashok Sundaram, Mark McGranaghan, Georges Simard, "APPLICATIONS ASSESSMENT OF PULSE CLOSING TECHNOLOGY", Electric Power Research Institute.
9. Ceylon Electricity Board, "Catalogue & Price List of Materials", Colombo, Sri Lanka, 2019.
10. Ceylon Electricity Board, "Approved rates in Colombo City Branch 2019/2020", Colombo, Sri Lanka, 2019.
11. Ministry of Power and Renewable Energy, "Electricity (Distribution) performance Standards", Colombo, Sri Lanka, 2016.
12. https://www.ensto.com/electricity-distributionnetworks/products/overhead-line-networks/medium-voltage-overhead-line-solutions/ensto-covered-conductors/
13. Martin Bishop, Donna G. Oikarinen, Stephen Williams, and Mike Meisinger," Fault Detection Strategy for Distribution Feeders with OH and UG Main Line Sections", S&C Electric Company, USA, February 4, 2019.
14. Ceylon Electricity Board, "Construction standards for MV Power Distribution Lines", Colombo, Sri Lanka, 1997.
15. Martin Bishop, Donna G. Oikarinen, Stephen Williams, and Mike Meisinger, "Fault Detection Strategy for Distribution Feeders with OH and UG Main Line Sections", Franklin, USA, February 4, 2019.
16. Richard E. Brown, "Electrical Power Distribution Reliability", 13: 978-0-8493-7567-5.
17. Minister of Power and Renewable Energy, "Electricity (Distribution) Performance Standards Regulations 2016–Gazzete Extraordinary of Democratic Socialist Republic of Sri Lanka on 13.07.2016", Sri Lanka, 2016.
18. Western Province South 1 (CEB), "Performance Management Meeting of Western Province South 1 (Review of Performance of the year 2018)", 12th February 2019.