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Rural Electrification using Iliceto Shield Wire Scheme in Developing Countries: Tanzania Case Study

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Abstract

Rural electrification rate in Tanzania is still very low despite the efforts made by the Rural Energy Agency (REA) in Tanzania. Rural electrification using medium voltage (MV) method has two major obstacles. First obstacle is high cost associated with the cost of extending the grid electricity to rural areas. Second obstacle is remoteness of the villages, which leads to high power loss during transmission. In lieu of economic extension of rural electrification areas, this paper proposes a low cost solution of Iliceto Shield Wire Scheme (ISWS). This technique involves insulating shield wires (SW) from high voltage (132-400 kV) transmission line and energizing (11-33 kV) them from nearby substation at one line and use ground as MV phase conductor. The paper undertakes literature review of ISWS technology as installed in other developing countries. After that, a case study is selected in Mpaji village in Tanga region Tanzania. Analysis was made on voltage drop, power flow and cost for rural electrification using ISWS technology. Using ISWS for Mpaji village resulted in 10.89% voltage drop with total investment cost of about 49.4% compared to MV conventional method.

Keywords: Iliceto Shield Wire Scheme (ISWS), Medium Voltage, Rural Electrification.

Introduction

Majority of rural people in Tanzania have no access to modern energy services especially electricity. According to the International Energy Agency (IEA), “Tanzania Energy outlook 2019” statistics show that about 37% of the Tanzania population have access to grid electricity (IEA 2019). Enhancing energy supply in rural areas through private and public sectors participation will contribute significantly in development of the rural Tanzanians lives.

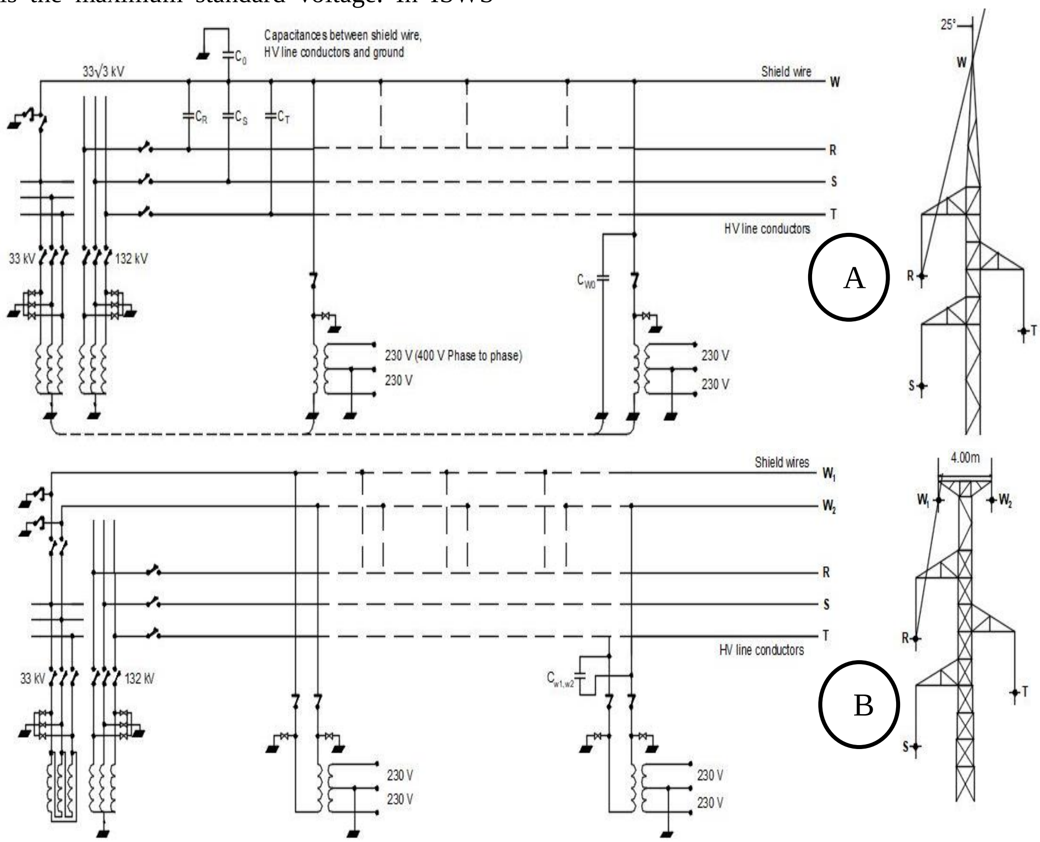
The Iliceto Shield Wire Scheme (ISWS) is a solution for rural electrification with the main purpose of minimizing the cost of power supply from the interconnected grid to villages, communities, farms, factories and water pumping stations located near or at some distance from the route of the high-voltage transmission lines according to Iliceto and Emeritus (2016). ISWS technique is being proposed in order to replace the MV conventional connection to the grid which is not economically feasible for the loads connected far from the MV lines and with small power demands (Iliceto et al. 2004, Iliceto et al. 2005, Chaves and Tavares 2018). ISWS is well implemented in several countries worldwide such as Brazil, Ethiopia, Ghana, Laos, Togo, Burkina Faso and Sierra Leone according to EU Energy Initiative (2015).

ISWS have been developed from combination of two technologies. First is the use of Insulated SWs in the long high voltage (HV) lines carrying bulky amount of power so as to reduce joule losses (Shu et al. 2020). The second is the single wire earth return technology (Iliceto et al. 2002, Porzi 2021). The ISWS is characterized by direct use of the SWs of the HV transmission line (TL) to transport MV power along the transmission line to a convenient location and then extend the spur line by means of normal MV pole lines to the rural areas (Iliceto et al. 2000, EU Energy Initiative 2015). Distribution transformer is installed near the load to supply electricity to the loads (Bakkabulindi 2012, Bellitto 2021). Transporting electricity using SWs it is necessary to insulate SWs from the towers of HV TL and energize them up to MV level according to Iliceto and Emeritus (2016). This MV level can vary from 11 kV to the upper limit of 33 kV which is the maximum standard voltage. In ISWS the SWLs have the same power distribution capabilities and voltage drops as MV conventional lines of the same rated voltage and length equipped with conductors of the same ohmic resistance as the SWs (Cinieri 1999, Gatta et al. 2005, Huertas and Tavares 2018).

ISWS technology

Different schemes of ISWS (Iliceto et al. 1989, Cinieri et al. 1992, Iliceto and Emeritus 2016) are presented in Figure 1: Scheme A– "Single-phase earth return"; Scheme B– "Single-phase metallic return"; Scheme C– "Three-phase tertiary winding"; Scheme D– "Three-phase with interposing transformer".

In this paper scheme C will be used since the scheme does not need addition of transformer and will provide three-phase four wire electricity.



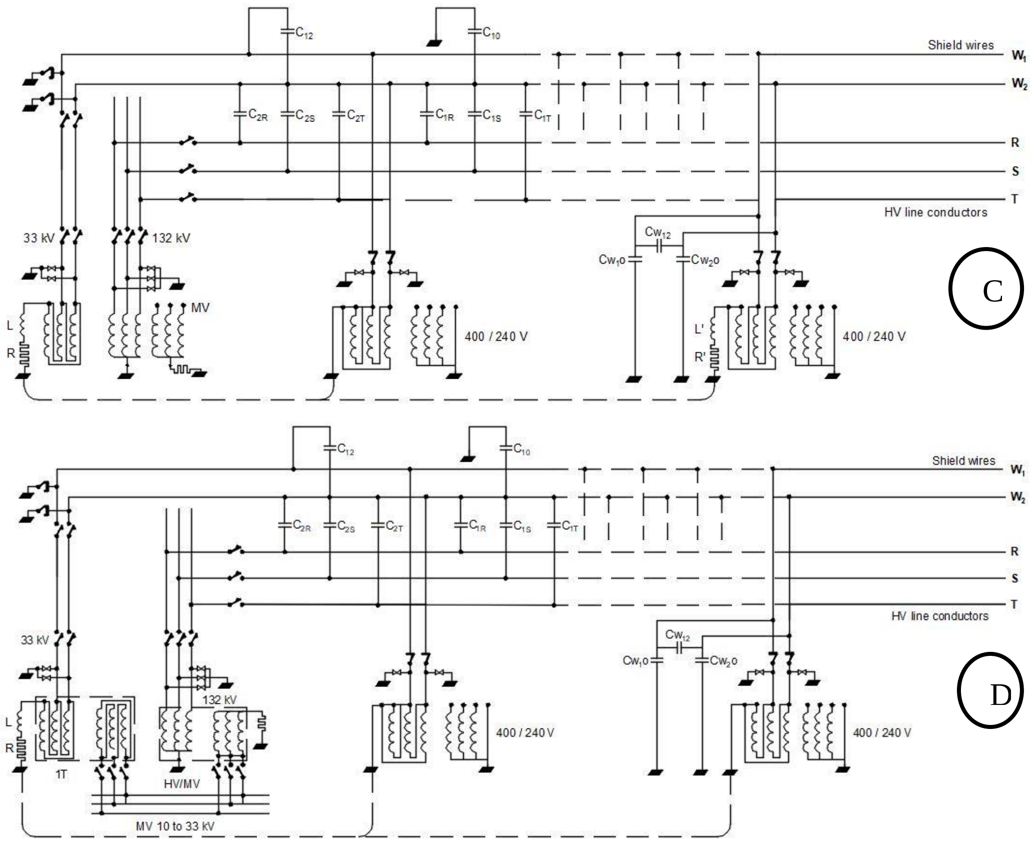


Figure 1: ISWS schemes.

Materials and Methods

Case study description

The Chalinze-Hale-Tanga HV TL was built for power supply to major areas and for connecting remote power plants to the grid as shown in Figure 2. Adjacent to the route and not so far from highways there are several villages, mines and small towns without electricity supply. Examples of these villages include Lunga, Lugoba, Mindutulieni, Mndukene, Mtindi, Mapinduzi, Mpaji, Mchokozi, Kitumbi, Komnara, Komkomba and Zunga villages. Figure 3 shows some of the villages located between Chalinze substation and Hale substation without electricity.

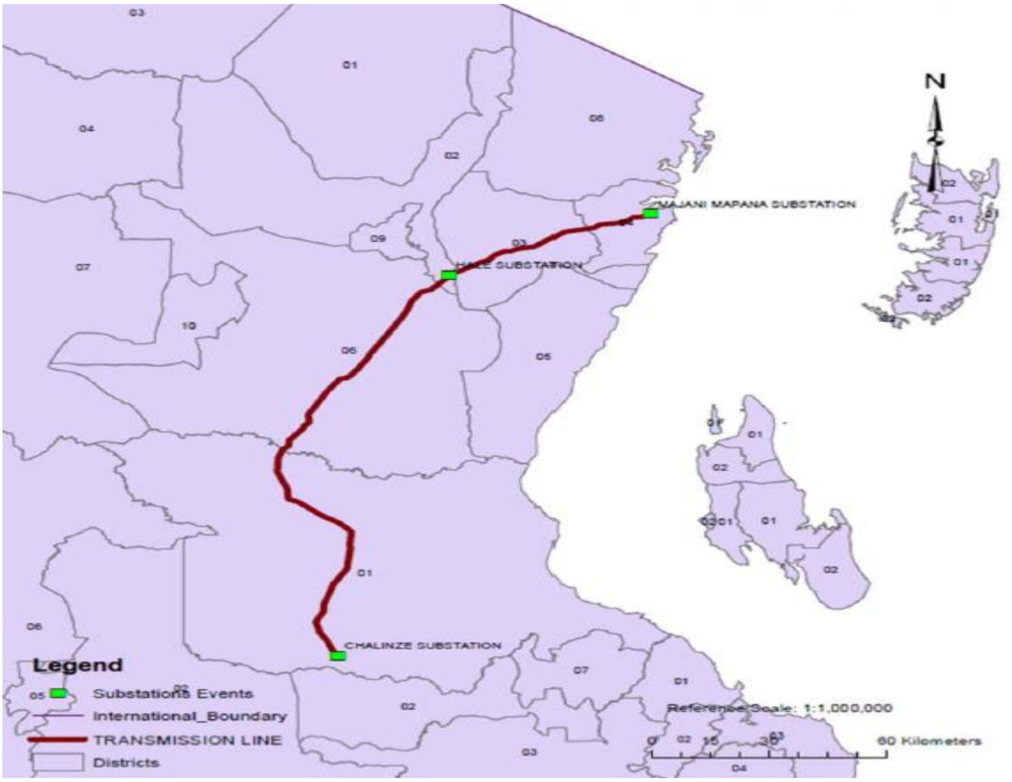


Figure 2: Chalinze-Hale-Tanga high voltage transmission line.

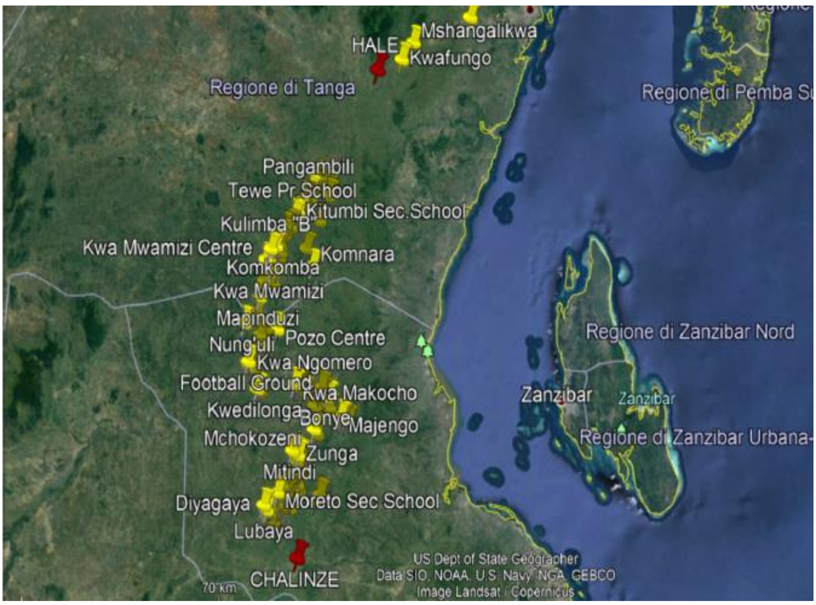


Figure 3: Villages between Chalinze and Hale without electricity.

Mpaji village is located in Pwani region within Mbwewe ward which is 86.5 km from Chalinze substation and 1.8 km from HV TL as shown in Figure 4. The population up to December 2020 in Mpaji village was 3,052 inhabitants with 560 households. Red case shows 86.52 km of MV conventional method for Mpaji village electrification. Yellow case shows ISWS technology route for electrification of Mpaji village.

Data type and source

During data collection, data were obtained through observations, oral interviews, documents and records, and surveying. Additional instrument used was Miller 400D digital resistance meter with model number of 30160000-010 for measuring soil resistivity. Data collected for ISWS analysis from Chalinze-Hale-Tanga HV TL, HV/MV substations and shield wires are shown in Table 1, Table 2 and Table 3 for different parameters.

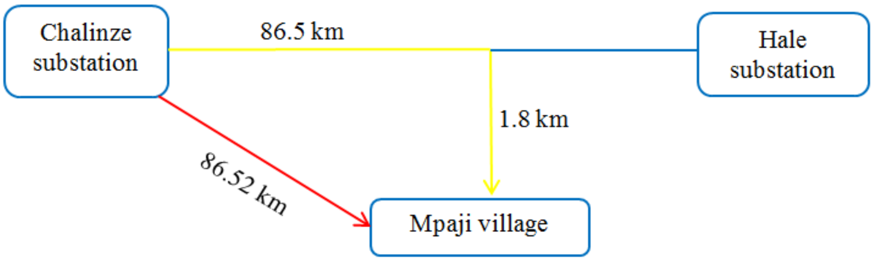


Figure 4: Physical planimetry for Mpaji village electrification.

Table 1: Chalinze-Hale-Tanga HV TL

Parameters	Chalinze to Hale	Hale to Tanga
Type of HV TL	Single circuit	Single circuit
Rated voltage	132 kV	132 kV
Type of conductor	Wolf ACSR 150 mm^2	Wolf ACSR 150 mm^2
Length	175 km	60 km
Shield wire (material type and cross section)	2 Overhead steel wires, 50 mm^2	2 Overhead steel wires, 50 mm^2
Type and presence of isolators to protect TL	Air Breaker Switches (ABS)	Air Breaker Switches (ABS)
Type of transmission towers/poles	High tensile steel structure towers	Wooden poles
Estimated power to be transmitted	102.88 MW at 0.91 p.f.	51.44 MW at 0.91 p.f.
Direction of power flow (mono-directional or bi-directional)	Bi-Directional	Mono-Directional
Number of towers	532	389

Table 2: HV/MV substation data

Parameters	Chalinze	Hale	Tanga
Type of substations	Public HV/MV step down transformer station	Public HV/MV step up and step down transformer station	Public HV/MV step down transformer station
Rated HV/MV in existence	132/33 kV	132/33 kV	132/33 kV
Capacity of the existence transformer	45 MVA	2 x 15 MVA	2 x 10 MVA, 20 MVA, 55 MVA
Soil resistivity	7.7 Ωm	60.8 Ωm	36.3 Ωm

Table 3: Shield wires data

Parameters	Values
Number of shield wire	2
Shield wire resistance	3.22 Ω/km
Shield wire reactance	0.3755 Ω/km
Distance between shield wires	4.00 m
Distance of HV conductors from the ground	11.94 m
Distance of SWs from the ground	15 m

Results and Discussion

Voltage drop results

Voltage drop evaluation consists of analysis of conductor cross section of HV TL such that voltage at the last consumer is not below the acceptable limit. Technical formula has been used adding multiplication factor so as to convert the voltage drop and line loss of receiving end load to that of the distributed load. The per unit voltage drop (ΔV) for ISWS over certain distance is obtained using Equation (1) where V_L is the line voltage, r_{sw} is resistance of SW per km, x_{sw} is reactance of SW per km, d is the length of the line, P is the active power and Q is the reactive power.

$$\Delta V = \frac{d(r_{sw}P + x_{sw}Q)}{V_L^2} \qquad (1)$$

Mpaji village located between Chalinze and Hale substation, thus energizing the SWs can be made from Hale or Chalinze substation. All of the two scenarios were considered in calculating voltage drop taking into account of the loads (villages) along the HV TL. Scenario one, energizing the SWs from Chalinze substation with power flowing from Chalinze to Hale substation. Analysis was made considering the all loads between Chalinze and Hale TL which results to voltage drop of 10.89% as shown in Table 4.

Table 4: Chalinze-Hale voltage drops

Village wards (Loads)	Distance from Chalinze (km)	Active power on the line (kW)	Reactive power on the line (kVAR)	Voltage (kV)
Chalinze	0.0	782.4	378.9	33.0
Msoga	15.7	569.1	275.6	31.7
Lugoba	22.4	424.6	205.7	31.3
Msata	39.9	331.9	160.8	30.5
Mandera	53.8	281.0	136.1	30.0
Kimange	67.3	93.9	45.5	29.6
Mbwewe	80.9	-	-	-
Voltage drop				**10.89%**

Scenario two, consider energizing the SWs from Hale substation with power flowing from Hale to Chalinze substation. Analysis was made which shows the voltage drop of 80% for energizing the SWs from Hale substation as shown in Table 5.

Table 5: Hale-Chalinze voltage drop

Village wards (Loads)	Distance from Chalinze (km)	Power on the line (kW)	Reactive power on the line (kVAR)	Voltage (kV)
Hale	0	2167.07	1049.56	33
Komkonga	42.6	2022.08	979.34	23.49
Kitumbi	53.8	1755.98	850.46	20.21
Mkata	71.5	782.35	378.91	14.96
Mbwewe	106	688.50	333..45	8.83
Kimange	114	501.39	242.83	6.70
Mandera	129	450.44	218.16	2.89
Msata	144	357.72	173.25	-5.07
Lugoba	160	213.23	103.27	-1.23
Msoga	172	-3.06	-	-5.83
Chalinze	175	-	-	-
Voltage drop				**80%**

Considering all of the two scenarios, Chalinze substation will be used for energizing the SWs which will result to low voltage drop.

Power flow results

Knowing the maximum power demands for the whole ISWS project taking into account all the loads located along HV TL it is very important to analyze power flow. Power losses along the line will show how power flows in energizing SWs along HV TL. Power losses along the line at each distance depend on p.f., resistance and reactance of SWs, energizing voltage of the SWs and multiplying factor (MF) as shown in Equation (2).

$$P = \frac{V_L^2 . \Delta V}{MF . d(r_{sw} + x_{sw} \tan\theta)} \qquad (2)$$

Analysis was made using Aluminum Conductor Steel reinforced (ACSR) conductors of different cross sectional area which are highly recommended for ISWS technology. Figure 5 shows how power is transferred using ACSR conductors of different cross sectional areas for three-phase system.

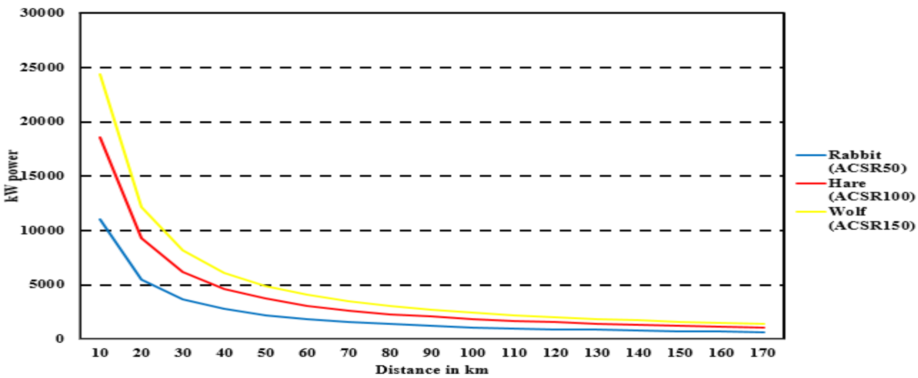


Figure 5: Power transfer capability for three-phase ACSR conductor.

Figure 5 shows that using three-phase wolf ACSR 150 mm^2 conductors for SWs replacement will result into high power flow capability with minimum power loss. Two-phase rabbit ACSR 50 mm^2 conductors have low power transfer capability.

Economic comparison results

For MV conventional method, pole spacing according to REA standards is 80 m for MV line and 50 m for LV lines. MV conventional method route of 86.52 km from Chalinze substation to Mpaji village, 1,081 MV wooden poles are required. For ISWS technology MV poles will be used for the 1.8 km were only 22 poles will be required. The existing galvanized steel SWs are old in age and should be replaced with ACSR wires of 150 mm^2 so as to increase power flow and decrease power losses. Considering 86.5 km from Chalinze substation and 1.8 km from HV TL to Mpaji village, then for ISWS 176.6 km of Wolf ACSR 150 mm^2 will be required. MV conventional method will require 259.56 km of Wolf ACSR 150 mm^2.

Chalinze-Hale TL has a length of 175 km with 532 towers; this is equivalent to a distance of 330 m between towers. Mpaji village located 86.5 km from Chalinze substation is equivalent to 262 towers to Mpaji village. Each tower will carry 2 insulators leading to a total of 524 insulators to Mpaji village. Table 6 and Table 7 show cost analysis for supplying ISWS technology and MV conventional method for Mpaji village electrification.

Table 6: Costs for supplying Mpaji village with ISWS technology

Material	Unit price (Tsh./km)	Quantity	Total price (Tsh.)
Wooden poles (13 m medium)	492,108	22	10,826,376
Distribution transformer (250 kVA, 33/0.4 kV)	17,392,500	1	17,392,500
Increase of tower weight	695,700	86.5	60,178,050
ACSR conductor	3,335,200	176.6	588,996,320
Insulators string and assembly	208,710	524	109,364,040
Capacitor banks	11,595,000	Lumpsum	11,595,000
Resistor reactor compensator	13,914,000	Lumpsum	13,914,000
Labour, design, transportation and supervision	1,500,0000	88.3	132,450,000
Total			**944,716,286**

Table 7: Costs for supplying Mpaji village with MV conventional method

Material	Unit price (Tsh./km)	Quantity	Total price (Tsh.)
Wooden poles (13 m medium)	492,108	1,082	532,460,856
Distribution transformer (250 kVA, 33/0.4 kV)	17,392,500	1	17,392,500
ACSR conductor	3,335,200	259.56	865,684,512
All line insulators	2,233,046	86.52	193,203,140
Labour, transportation, design and supervision	3,000,000	86.52	259,560,000
Total			**1,868,301,008**

These cost values show that the ISWS technology is 49.4% cheaper than MV conventional method for Mpaji village electrification.

Profitability analysis results

Marginal benefit-cost ratio (B_c) will be used to determine if supplying electricity in the village with a certain distribution network would be profitable. Equation (3) shows how B_c ratio can be computed.

$$B_c = \frac{C_i}{C_n} \tag{3}$$

Where C_n is the number of customers connected and C_i is the investment cost.

Figure 6 shows benefit-cost ratio as per Equation (3) for ISWS technology is Tsh. 1,686,993 per household and for MV conventional method is Tsh. 3,336,252 per household.

Designed single line diagram

For Mpaji rural electrification, Scheme C ISWS technology is proposed. The single line diagram is as shown in Figure 7 with the protection system. Protection system will be needed so as to protect the system in case of any failure or to isolate the system during maintenance. Calculation of the short circuit currents is a fundamental requirement to the selection of the protection equipment against the fault and their correct coordination (Bellitto 2021). The protection equipment include devices like circuit breakers, fuse and surge arrester.

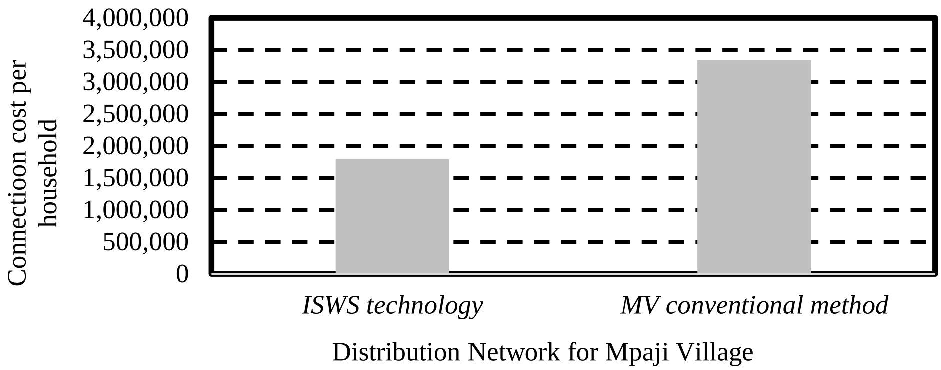


Figure 6: Benefit cost ratio analysis

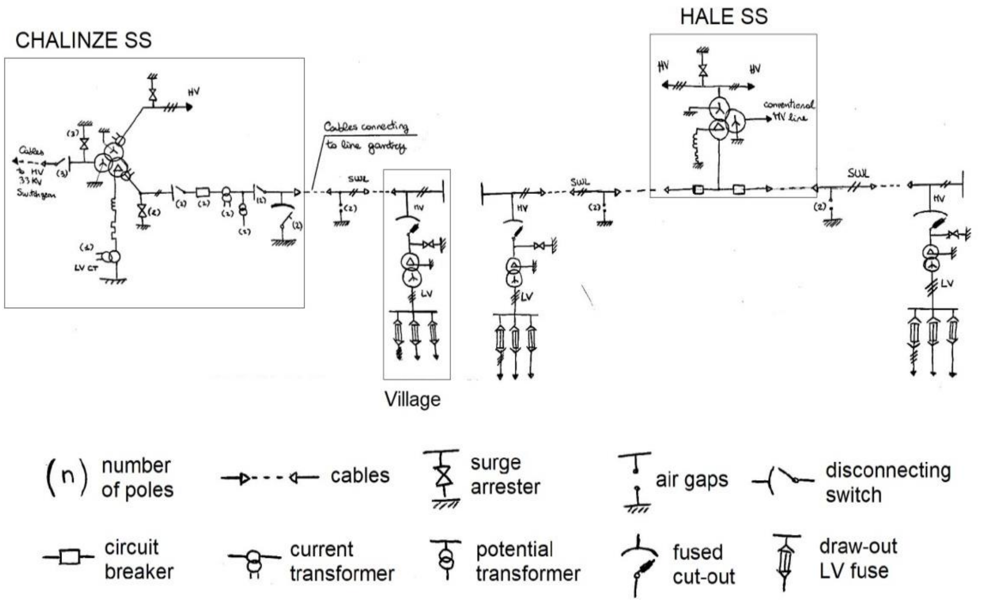


Figure 7: Single line diagram for Mpaji village electrification.

Conclusion

This paper has discussed the advantages of ISWS technology over MV conventional method for Mpaji village electrification. ISWS system showed a voltage drop of 10.8% for energizing the SWs from Chalinze substation going to Hale substation, 80% voltage drop is observed energizing the SWs from Hale substation going to Chalinze substation. ISWS technology for Mpaji village electrification is more economic than using MV conventional method (extending the grid to Mpaji village). Using ISWS technology will have investment cost of Tsh. 944,716,286.00 while for MV conventional method Tsh. 1,868,301,008.00 investment cost will be used. Using ISWS technology for Mpaji village electrification will have more saving in investment cost of about 49.4%. Connection cost per household for ISWS technology electrification is Tsh. 1,686,993, while for MV conventional method is Tsh. 3,336,252. Therefore, ISWS technology is highly recommended for Mpaji village electrification.

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