Assessment of Feasible DC Microgrid Network Topologies for Rural Electrification in Rwanda: Studying the Kagoma Village

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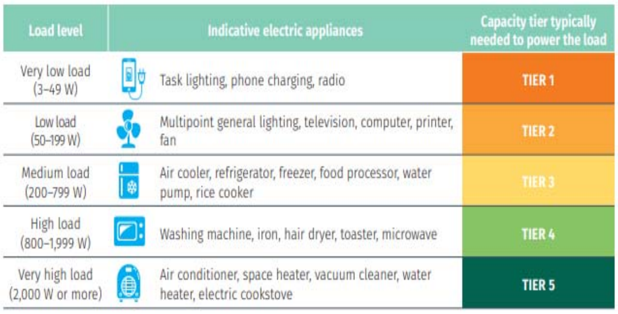
***Abstract*- This paper investigates the network topology for distributing electricity in the remote village using solar PV with DC microgrid. The expansion of the national grid electricity into rural villages remains a challenge due to the increased costs of distribution and transmission systems. The optimum selection of the network topology is important, relative to the density of the population, village size, and the group arrangement of a particular village. The modified Newton–Raphson's algorithm (N-R) has been programmed in MATLAB to evaluate the voltage drop and system efficiency, obtained with different types of the distribution system and the nominal voltages to be used. In this paper, the methodology to decide the best distribution topology, nominal operating voltage level, and the conductor size (based on voltage drop and total cost) was addressed for a specific remote village in Rwanda.**

***Keyword:* DC microgrid, network topology, rural electrification, cable selection.**

I. INTRODUCTION

Energy access is regarded as the most significant key point for worldwide development as a certain percentage of habitats around the world without electrical energy access with basic livelihood standards in 2017 has fallen below one billion [1]. As reported in [2], approximately 1.20 billion of worldwide people lack electricity access, where more than half of them are living in Sub-Saharan Africa (SSA). For instance, the current installed generation capacity in Rwanda is about 218.0 MW, and the estimated rate of electrification is 30 % (where 12 % is for rural areas, and 72 % for urban areas) [3]. Electrification in remote rural areas through the national grid is challenged for two reasons: i) high cost of infrastructure, ii) a limited power generation capacity in developing countries. However, solar PV has become a suitable solution for SSA countries including Rwanda due to the availability of solar the resource [4], (more than 2000.00 kWh/m²/ year). Then, this energy resource can be easily used to fulfill the basics household energy needs. To successfully deliver energy to households, it is key to develop reliable distribution networks [5]. Proceeding with the electrification pathway, it is crucial to recognize the significance concept of a multi-tier framework (MTF) used for quantifying the access to electrical energy in Rwanda [7] seen in Table I [8]. The energy access in a remote village is classified as Tier 0. Nevertheless, by promoting the use of solar PV microgrids in these remote villages, the can be upgraded to Tier 1 or 2of electricity access [6].

Table I: Measuring the households' electricity access [6].



Load level	Indicative electric appliances	Capacity tier typically needed to power the load
Very low load (3–49 W)	Task lighting, phone charging, radio	TIER 1
Low load (50–199 W)	Multipoint general lighting, television, computer, printer, fan	TIER 2
Medium load (200–799 W)	Air cooler, refrigerator, freezer, food processor, water pump, rice cooker	TIER 3
High load (800–1,999 W)	Washing machine, iron, hair dryer, toaster, microwave	TIER 4
Very high load (2,000 W or more)	Air conditioner, space heater, vacuum cleaner, water heater, electric cookstove	TIER 5

The power distribution in a microgrid can be done using an AC or DC system, and the advantages and disadvantages of these two systems are compared in [9]. During the implementation of the energy storage system (ESS) in a microgrid, a bidirectional charge controller for controlling the charging/discharging state of the storage battery will be installed in the circuit, where Lithium-ion batteries have been selected as ideal ESS, where its advantages are in discussed in [10] The current manuscript focuses on the analysis of Rwanda's rural village electrification through a microgrid. The study is performed in the selected village presented in the case study. The system modeling was done using a modified N-R algorithm such that the power line losses, percentage power line losses, percentage voltage drop, and corresponding system efficiency were calculated to select the suitable system voltages and conductor sizes to be used in the microgrid system. These parameters are also used to determine the optimum network topology: either ring-main distribution system (RMDS) or radial distribution system (RDS). Therefore, the main focus of this paper is to analyze possible network distribution architectures and determine the most suitable configuration to be used in rural villages of Rwanda.

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II. EXISTING RURAL ELECTRIFICATION TOPOLOGIES

The ways house inside villages are arranged are key to obtain an efficient off-grid transmission system. These systems should be designed to ensure optimal power flow from generation sources to consumption points. According to [11], two main arrangements are found in developing countries: a) linear arrangement, where houses in the village are typically located alongside the road or central street, and b) cluster arrangement, where houses in the village are independently located in fields with multiple houses. In this case study, it is assumed that houses are grouped in a linear arrangement. Regarding the challenges facing the grid-based electrification, an alternative solution is off-grid electrification, which achieved faster access to basic needed energy compared to the grid-based electrification [7]. Rural microgrids comprise different types: i) grid-connected and off-grid; ii) AC or DC, iii) centralized and decentralized (generation or storage) microgrids [12].

A. Off-grid solar home-based system

The greatest of the population in the countries under development reside in remote areas. As the majority of them live far away from the national grid, kerosene-powered lamps and firewood became their principal power source. The answer can be to propose solar home-based systems (SHS) to power the basic electrical household loads [12]. A typical example of SHS kits from BBOXX company containing a solar PV panel, storage battery, and DC household loads as shown in [7]. According to [8], by interconnecting SHS with DC microgrid enable energy sharing between the SHS, where excessive energy produced from one SHS is needed by other SHSs in a microgrid with low or no energy production, and this is done for improving the overall system efficiency.

B. *Solar PV with DC microgrid systems*

Alternatively, DC microgrids are proposed as an optimum way to reach tier level 4 and tier level 5 of electrical energy access [8] [13]. The DC microgrid topology consists of different distributed DC nanogrids (referred to as distributed generators) with communal or household loads connected to the main DC bus, whereby each nanogrid possesses a renewable energy source (RES) as solar PV for this study, battery energy system for the case of central generation distributed storage topology (CGDST), and loads [14]. Nanogrids are more advantageously deployed in remote villages due to the use of the available RESs to generate electricity for overcoming the absence of grid electricity [15]. Refer to [8] [13], these are the main advantages found by comparing standalone SHS electrification with microgrids:

i) The interconnection of SHSs enables the sharing of excess energy among prosumers households, which is significant for installing communal loads.
ii) The DC microgrid system size is lower compared with SHS for the same load demand.
iii) Higher power comfort as a productive use of electricity supplements the activities of income generation

The use of DC microgrids is preferred to the AC system as they present higher efficiency because the end-to-end efficiency varies from 77 % to 85 % for DC microgrids, with 63 % for AC microgrids. This low efficiency for the AC system is linked to the energy conversion stage, e.g. DC to AC or AC to DC [16]. Conventionally, the installation of the DC microgrid in the rural village can be done through different levels of voltage. A typical example of a microgrid installed in Rwanda by a Meshpower [17] is located in Bugesera district, Gitaraga Village, and uses a distribution line operated at 48 V.

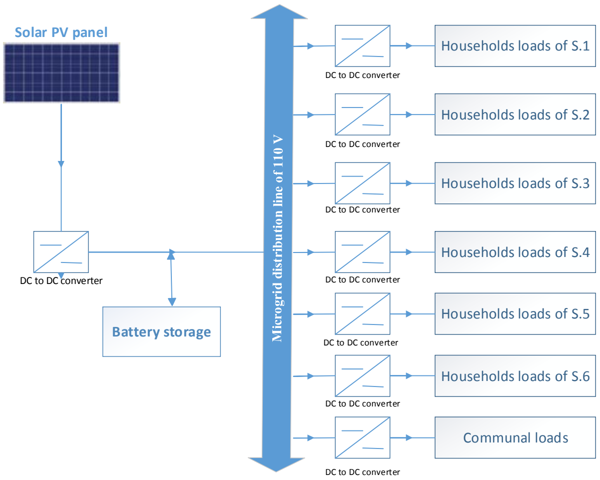

Fig. 1: Proposed central generation central storage microgrid topology with six segments (S).

According to [16], the topologies of a solar PV-based on DC microgrids for remote village electrification are classified as 1) central generation central battery storage topology (CGCST), and 2) central generation distributed storage topology (CGDST). Fig. 1 shows the proposed solar PV CGDST as the DC solar PV system, with the village as the proposed case study of six segments, where the total number of houses in the corresponding segments is given in Fig. 4. According to [16], the CGDST was reported to be more used in comparison with CGCST, and it is proposed to use this CGDST for the remaining analysis.

C. *Ring-main and Radial distribution system*

Fig. 1 shows the RDS whereby power flows in one direction from the generating station to the load centers. This RDS is popularly used due to its simplicity and low construction cost [18]. For this reason, if a particular line is lost, all the power lines downstream will no longer supply power [5]. The main disadvantage of the RDS is the lack of security and continuity of power supply [19].

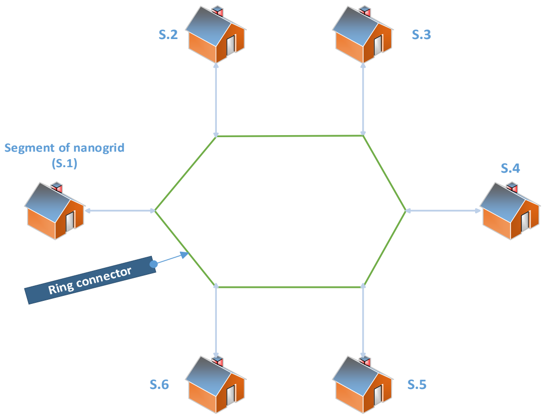

Fig. 2: Proposed RMDS topology of Solar PV microgrid with CGDST.

To address these issues of RDS, it is proposed to use the RMDS structure shown in Fig. 2. Additional to this RMDS, this system will be linked to the CGDST for maximizing the RESs through battery storage in each segment of houses and minimize the microgrid energy exchange. However, the cost of involving the power protection system is increased [19]. A nanogrid as shown in Fig. 2 is considered as a unit building block in the microgrid system, which integrates its energy resources (here, a solar PV is installed on the rooftop of each house) into the power system [16], and in this study, the nanogrid close to each other form a segment. The advantages of RMDS are described in [19] as follow: 1) The RMDS is known to be the most efficient, due to its capability of system continuity of operation during the line fault, due to the presence of its automatic control devices that are detecting the faults. 2) The RMDS topology offers high performance compared to the RDS topology. During the case of fault or maintenance for any conductor, the ring distributor continues to supply other feeders. 3) Any house with solar PV on the rooftop in the microgrid supplied during peak hours can be fed from other houses in the village. Therefore, DC microgrids lack standards and the choice of components is as it depends upon the location and lifestyle of the people. That's why for remote locations in isolated areas it might have the sense to consider a tight design reducing the size of conductors as this might help the people gaining access to energy due to reduced cost.

III. THE LOAD FLOW ANALYSIS THROUGH MODIFIED NEWTON-RAPHSON

In the distribution network analysis, the Gauss-Seidel (GS) and Newton–Raphson's method (N-R) are conventionally used [20]. In the case study presented here, a modified N-R method will be used to analyze the power flow in the distribution power system. Using the feeder and distribution resistance values as shown in Fig. 1, and based on the configuration of a village of the case study shown in Fig. 4, a conductance matrix -*G* for the DC distribution network is modeled as *Y*-admittance matrix (for the case of AC system), where its imaginary part or the susceptance -*B* is ignored. The cable resistance from generation to the slack bus is considered as higher than the one used from the slack bus to the distribution system.

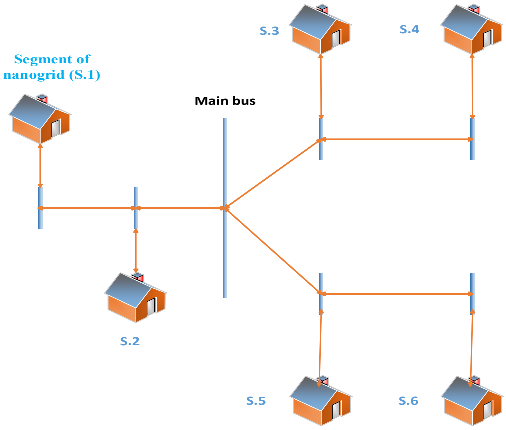

Fig. 3: Radial distribution system with CGDST.

Thus, the conductance matrix –*G* shown in (1) is formulated based on the spatial distribution of the conductor between the power source and the houses. By considering a remote village with n- houses (segments of houses are used here), the elements of the conductance matrix –G and G_{ik} can be expressed from the individual conductance g_{ik}, where these conductance elements vary from 1 to n as seen in (1) and (2).

$$G_{ik} = \begin{bmatrix} \sum_{k=1}^{n} g_{ik} & ; \forall\, i = k \\ k \neq i & \\ -g_{ik} & ; \forall\, i \neq k \end{bmatrix} \tag{1}$$

$$\mathrm{G} = \begin{bmatrix} G_{1\,1} & G_{1\,2} & \cdots & \mathrm{G}_{1,n-1} & \mathrm{G}_{1,n} \\ G_{2\,1} & G_{2\,2} & & \mathrm{G}_{2,n-1} & \mathrm{G}_{2,n} \\ \vdots & & \ddots & \vdots & \\ \mathrm{G}_{n,1} & \mathrm{G}_{n,2} & \cdots & \mathrm{G}_{n,n-1} & \mathrm{G}_{n,n} \end{bmatrix} \mathrm{G} \in \mathrm{R}^{n \times n} \tag{2}$$

From this conductance matrix -G, the power line loss (LL) is calculated in (3), percentage line loss (% LL_g) in (4), percentage voltage drops (% VD_g) in (5), and system efficiency (η_g) in (6).

$$LL = \frac{1}{2}\sum_{i=1}^{n}\sum_{k=1}^{n} G_{ik} \times [V_i(V_i - V_k) + V_k(V_k - V_i)] \tag{3}$$

$$\%\, LL_g = \frac{LL}{P_G} \tag{4}$$

$$\%\, VD_g = \frac{V_i^{max} - V_i^{min}}{V_i^{max}} \times 100 \tag{5}$$

$$\eta_g = 100 - \%\, LL_g \tag{6}$$

Note that V_i^{max} is the maximum, and V_i^{min} is the minimum load voltage on each bus after the n^th^ alteration. The power P_L is considered as the power load and V_{min} is the load voltage. Thus, the ratio of the power line loss (P_{loss}) and power load are presented in (7).

$$\frac{P_{loss}}{P_L} = \frac{2\times\left(\frac{P_L}{V_{min}}\right)^2 \times R_l}{P_L} = \frac{2 \times P_L}{(V_{min})^2} \times R_l \tag{7}$$

The voltage drop (V_{loss}) in this study is a variable parameter which depends on the voltage level (V_{level}) and conductor surface -*S*, the nominal voltage levels of 24 V, 48 V, and 110 V are considered for analysis. The resistance R_l represents the equivalent line resistance between the load and the power source. Thus, the ratio of V_{loss} to the source voltage (V_{max}) can be calculated using (8) and (9).

$$\frac{V_{loss}}{V_{max}} = \frac{V_{max} - V_{min}}{V_{max}} \approx \frac{2 \times P_L}{V_{min}^{\ 2}} \times R_l \tag{8}$$

$$\frac{V_{loss}}{V_{max}} \approx \frac{P_{loss}}{P_L} = \frac{2 * P_L}{V_L^{\ 2}} \times \frac{\varphi l}{S} \tag{9}$$

where ρ and l are resistivity and line length, respectively.

IV. ECONOMICS OF SELECTING A CABLE SIZE

Refer to [21], an increase in the cable section results in a higher total cost of the microgrid from the source to the loads. According to [22], the solar PV microgrid shall be sized with a 5% maximum voltage drop (V_{drop}) at rated system array current. The important parameters for finding total costs (C_{Invest}) on the cables to be used are modelled in (13), E_{loss} for Energy loss in (10), and C_{loss} (11) for the cost of energy losses, and also the feed-in-tariff (FIT) expressed in FRw/kWh in Rwanda is found [23]. This E_{loss} is the annual energy lost in the microgrid cable which helps to obtain total cost of the cable.

$$E_{loss} = P_{loss} \times T \tag{10}$$

$$C_{loss} = FIT \times E_{loss} \tag{11}$$

The cable section (A) can be calculated according to the voltage drop as shown in (12).

$$A = (L \times V_{loss}) \times \left(\frac{\mathrm{I}}{\gamma}\right) \tag{12}$$

where:

A: The cross-section area (mm^2), L: The cable length (m),
I: Nominal current of each cable size (Amp), γ: Copper conductivity (m/Ω. mm^2), *and* V_{loss}: voltage drop (V).

The total cost is calculated according to the cable standards ($\mathrm{A_{standard}}$) areas refer to [24]:

$$C_{Invest} = (L \times P) + \{\mathrm{C_{loss}} \times \left(\frac{\mathrm{A_{standard}}}{\mathrm{A}}\right) \times \mathrm{T}\} \tag{13}$$

where:

C_{Invest}: The total cost of the cable in microgrid (FRw),
C_{loss}: The cost of energy losses (FRw)
E_{loss}: Energy losses (kWh) during a time T,
T: The time hours of one year (h),
P_{loss}: Power loss in the cable (kW)
L: The length of cable (km) to be used in the microgrid,
P: The cable price (FRw/km),
FRw: The Rwandan francs.

V. OVERVIEW OF THE CASE STUDY

This study is focused on the Kagoma-II village, which is located in Bugesera district, Eastern province, about 4 km away from the national power grid. This location is regarded as a non-electrified, but it has large solar irradiations. It is proposed that for upgrading the living standards of people in this village the available solar energy should be exploited. The existing local energy sources of this village are based on traditional types such as dry wood (for both cooking and lighting), charcoal (for cooking), and candles.

Fig. 4: Kagoma-II Village as a case study with six segments (source: Google Earth Pro).

About the solar PV system specification of this microgrid, the solar panels are of two parallel strings connected to a junction box. Also, every string consists of six PV modules connected in series, where each module is with 250 W_p each and $V_{mp} = 31.41$ V, $I_{mp} = 7.96$ V. In this study, 43 houses are groups into six segments as shown in Fig. 4 (form S.1 to S.6). Then, each segment has six, seven, or nine houses, and the total number of houses considered in this village is forty-three. These houses close to each other are grouped to form a segment. In this case, we assumed that the loads in all houses are of the same power ratings.

VI. RESULTS AND DISCUSSION

The solar PV power generated from each segment of houses was set to 5 kW as per the design specification of solar PV discussed above, which is regarded as the power consumption that corresponds to the highest power in tier 1 level access, according to TableI, and this power is used to supply the household DC loads like lighting, TV, and phone charging. The perimeter or boundary of this village is measured as 500 m, and this is important for the length of the distribution wiring system of that village. The modified Newton Raphson's method is applied to evaluate various voltage levels and different cable sizes. After system modeling, a MATLAB program was used for calculating the percentage voltage drops, the line losses, and the system efficiencies for both RDS and RMDS. Each network configuration is important for the selection of voltage levels and conductor sizes of a microgrid. Fig. 5 shows the comparison between RMDS and RDS topologies for DC microgrid of six segments (bus) data. The comparison of these two systems is done by assuming that both systems have the same voltage levels and the same power load. The line losses with RDS of 10.06 % are higher than that of 3.70 % for RMDS, while the system efficiency is 89.94 % for RDS and that of RMDS is 96.30 % as shown in Fig. 5. From this result, the RMDS is suitable for the distribution system in DC microgrid. The reasonable selection of voltage standards is a precondition for village electrification through DC microgrid. The used voltage levels for the DC microgrids were compared for choosing the optimum system voltage level based on voltage losses and the cable sizes.

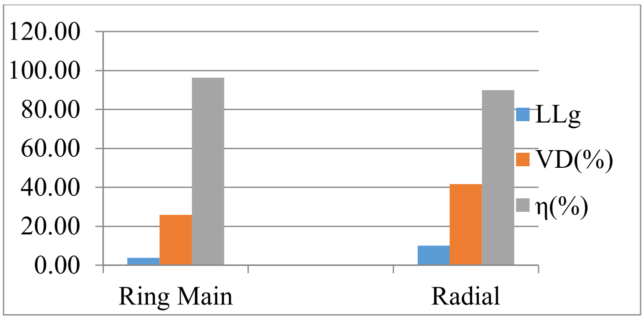

Fig. 5: Ring main and radial distribution systems comparison.

For this case study of DC microgrid based on solar PV, the power from battery storage is boosted from 24 V to 48 V and 110 V subject to the selected microgrid topology. The conductor size is chosen to allow if possible the future microgrid upgradability of the line distribution without any wiring replacement. The variation of the voltage drop with varying conductor sizes and distribution levels are shown in Fig. 6 and Fig. 7. Thus, the 24 V is not recommended for the DC distribution in a microgrid due to its high voltage drop compared with 48 V and 110 V levels. Thus, both 48 V and 110 V was optional for the microgrid DC distribution network, but 110 V is recommended as more efficient than 48 V due to its lower voltage drop during power distribution.

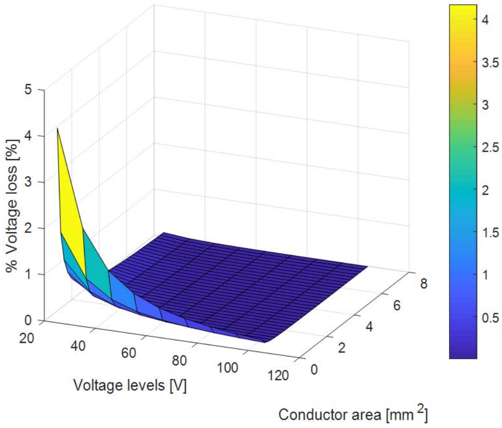

Fig. 6: Ring-main distribution system with voltage levels for conductor size selection with voltage drop.

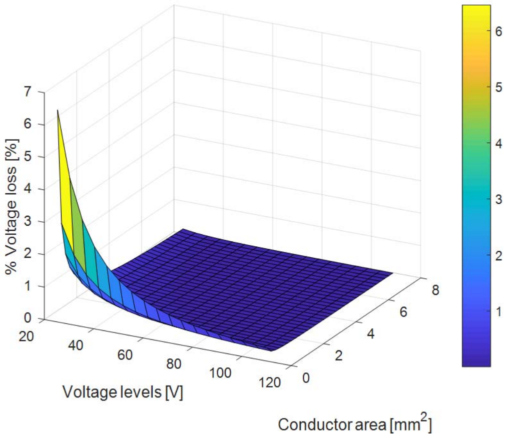

Fig. 7: Radial distribution system with voltage levels for conductor size selection with voltage drop.

It was found that as the conductor size is increased, also voltage drop is reduced as shown in both Fig. 6 and Fig. 7 respectively, and TableII. In this study, the main purpose is to select the optimal solar cable size by considering the total cost of cables. The larger conductor sizes result in reduced energy losses because of lower resistance. However, the total cost and energy losses in the larger cable will be higher as shown in Fig. 8.

Table II: Conductor size, voltage level, and voltage drop in both RMDS and RDS

Conductor size (mm^2)	Voltage levels (V)	% Voltage drop (RDS)	% Voltage drop (RMDS)
2.5	24	0.531	0.422
	48	0.162	0.133
	110	0.026	0.021

Therefore, in this analysis with the selected parameters in this specified remote village, 110 V with a conductor of size 2.5 mm^2 and through RMDS is optimum to implement the DC microgrid as shown in both Fig. 8 and TableI. Depending upon the load categories in other types of the village, this proposed topology may return in other voltage levels than 110 V, subjected to other parameters such as distribution costs and the safety protective equipment.

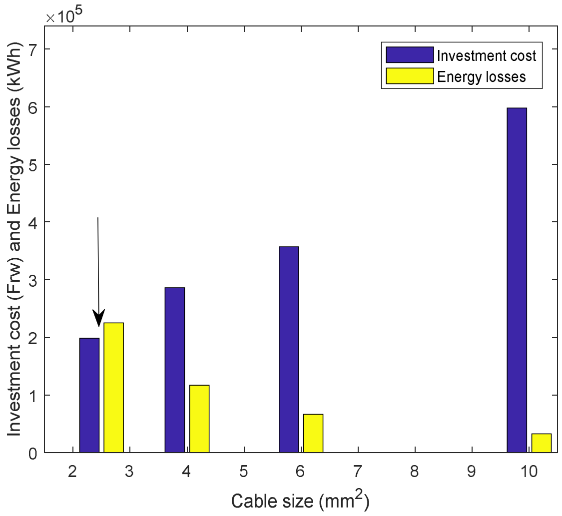

Fig. 8: Cable size selection based on total cost and energy losses for the case study.

Refer to the Fig. 8, as the conductor size is increasing, its total cost also is increasing, while its corresponding energy losses are decreasing for this case study of Kagoma village with 500 m length of proposed microgrid, and it is important to select a 2.5 mm^2 cable as its total cost is 198,380.0 FRw, while for 10 mm^2 in this microgrid will cost 597,770.0 FRw. In this paper, the low total cost in the 2.5 mm^2 with its high energy losses can be preferred by comparing it with the 10 mm^2 cables of high total cost with low energy losses.

VII. CONCLUSION

This paper proposed a suitable topology for the typical DC microgrid based on solar PV for the rural village in Rwanda. The results also suggest that the design of cable from the proposed DC microgrid model is might satisfy both the voltage drops and the total cost of the selected cable to be used. It can be concluded that for a small remote village, RMDS with CGDST is regarded as a suitable distribution topology compared to RDS due to its high efficiency and low voltage drop. It was found that for RDS the line losses are 10.06 % and 3.70 % for RDS and RMDS respectively, while the system efficiencies are 89.94 % and 96.30 % for RDS and RMDS respectively. From this paper, the solar PV with DC microgrid topology using RMDS at 110 V with 2.5 mm^2 of the cable, and distribution efficiency of 96.3% of RMDS is selected for electrifying the remote village for the case study. This is also linked to the low total cost of 2.5 mm^2 of the cable in comparison with the higher size cables. This proposed topology is ideal for electrifying a specific remote village in developing countries.

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