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Proposal for Single Wire Earth Return Distribution System for Homboza Village Electrification

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***Abstract*— Rural Electrification Rate (RER) in Tanzania is still low. This is because of huge costs to install conventional three-phase or single-phase power supply to dispersed rural loads. However, there are great efforts done to address this by the Rural Energy Agency and the National utility: Tanzania Electric Supply Company (TANESCO). To this end, this paper proposes a Single Wire Earth Return (SWER) electrification scheme to electrify one chosen village called Homboza. Field data are collected and are used to design the possible SWER distribution network. Mathematical model is developed, representing the SWER for Homboza, and simulations are carried out to establish the earth potential and earth resistance. These two are important whenever a SWER line is to be installed. Further, a techno-economic comparison is carried out to establish the low costs of proposed SWER against those of existing Single Phase Two-Wire (SPTW) system. The simulations are performed using MATLAB/Simulink 2013b. Simulation results give SWER earth potential around 18.15 V, and earth resistance of j0.0017 Ω/km. The techno-economic analysis shows that the proposed SWER system can realize a cost savings of 36.9% as opposed to installing SPTW system for Homboza electrification.**

Keywords—power distribution network, RER, SPTW, SWER

I. Introduction

Distribution networks supply three types of load which are residential, commercial and industrial loads with varying total demand proportions [1]. They supply power to three phase or single-phase systems. The single-phase two-wire (SPTW) and three phase three-wire (TPTW) or four-wire systems are the used power distribution network for rural electrification in Tanzania. Single-phase two wire is used more than TPTW due to small loads in the rural areas. However, rural electrification rate (RER) in Tanzanian still remains less than 20% [2] – [3] despite use of those systems. High investment and maintenance costs, and low benefit-cost ratio to the utility are just some of the challenges behind low RER [4] – [5]. These has prompted the Tanzanian government, through Rural Energy Agency (REA) and Tanzania Electric Supply Company (TANESCO) to look for cheap alternatives to address these challenges. This is the research gap this paper wants to address.

Faced with such challenges, research on low cost distribution systems commenced, or improvement of existing distribution systems to cater for un-electrified areas [6]. Lloyd Mandeno pioneered the first study on single wire earth return (SWER) distribution networks in 1925 and took place in New Zealand [7] – [8]. Soon enough, the SWER system became widely used method for rural electrification in Australia at affordable costs [7]. However, its applicability requires specialized attention such as following. SWER system installation requires careful earthing and bonding to prevent flow of ground currents which may cause dangerous potential gradients along ground surface as well as on the earthing rods [9]. The ground potential, i.e. product of load current and earth resistivity should not exceed 30 V, the maximum earth potential for SWER to be considered feasible. Lower resistive soils could therefore allow for heavier loads to be supplied [10]. Ground electrodes are used to connect the SWER system to the earth thus establishing and securing the return path [8].

II. SWER Components, Design and Operation

The SWER distribution system has a number of components including the isolation transformer, the distribution transformer, and the earth return path. A SWER distribution system configuration is shown in Fig. 1.

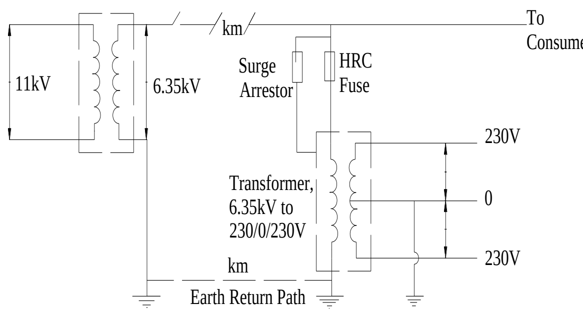

Fig. 1. Configuration of SWER distribution system.

The isolation transformer carries the line and load current from the grid to the customer. The distribution transformer has its primary connected from the SWER overhead line to the earth. Its secondary's terminal voltage is the operating consumer's voltage. Several poles carry the wire on pole-top, which also hold the SWER transformers and any voltage/power quality improvement equipment. The SWER overhead conductor and the pole-top assembly are the arrestors for protection against surges and lightning.

SWER has a number of advantages as compared to the other power distribution networks mentioned in Section I. Firstly, SWER's design and construction is simple as it is a single wire system with noncomplex electrical protection scheme and uses a few number of poles [6]. The single wire configuration enables SWER not to suffer line-to-line faults,

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thus it is less fault-prone in comparison to the SPTW and the TPTW systems [11]. SWER's reliability index is higher as compared to the SPTW and the TPTW. Despite these advantages, the SWER system is met with a few setbacks including the inability to supply three phase loads [12]. Also, the SWER system can only supply low load density areas, and it is best used for areas with slow growth. Further, SWER system can be incrementally upgraded to three-phase to accommodate future load growth by simple and cheap methods [13] – [14]. The cases of low voltage profile encountered in SWER application are easily improved using capacitors [12] or distribution static compensators [15] installed at predetermined locations along the distribution network.

III. Mathematical Line model

The SWER line model is developed based on the earth return path taken as a conductor with geometric mean radius (GMR) of 1 m, with uniform resistivity, and of infinite length [8], [16]. The return path beneath earth's surface is parallel to the single overhead conductor of length b carrying current I_b [4]. Fig. 2 shows a representation model of SWER overhead line with earth return path.

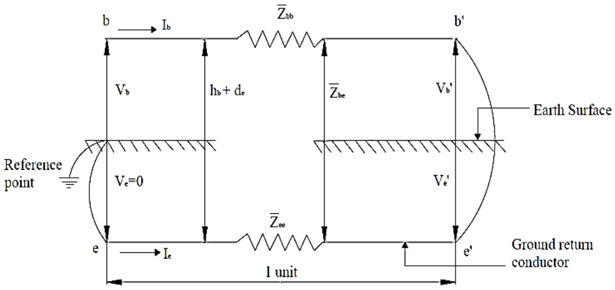

Fig. 2. Carson's line model with earth return [4].

Equation (1) presents the overhead conductor potential V_b due to the current flow [4];

$$V_b = (z_{bb} + z_{ee} - 2z_{be}) * I_b \quad (1)$$

where V_b is the overhead conductor's voltage, z_{bb} is the overhead line self-impedance, z_{be} is the mutual impedance between the ground and the overhead line, z_{ee} is the ground self-impedance. Calculating for Z_{bb}, the overall line impedance Equation (2) is applied [4]. The self-impedance of the overhead conductor, z_{bb} is given in (3) according to [7];

$$Z_{bb} = (z_{bb} + z_{ee} - 2z_{be}) \quad (2)$$

$$z_{bb} = R_b + j4\pi f * 10^{-4} * \ln[\frac{2(h_b+d_e)}{r_b}] \quad (3)$$

where R_b is the resistance of the SWER line conductor, f is the system frequency (50 Hz for Tanzania), h_b is the height of the conductor above the ground, d_e is the depth of the ground return path from the earth surface, r_b is the external radius of the conductor. The self-impedance of the ground conductor, the mutual impedance between the overhead line and the ground return conductor, and the earth potential can be determined by (4) – (6) [7], [17].

$$z_{ee} = 10^{-4} * f * [(\pi^2) - j(0.31\pi) + j4\pi * \ln(356)] \quad (4)$$

$$z_{be} = j2\pi * 10^{-4} * \ln(\frac{h_b}{\sqrt{\rho/f}}) \quad (5)$$

$$V_e = \frac{\rho*(V_b)}{2\pi d_e*(z_{bb}+z_{ee}-2z_{be})} \quad (6)$$

IV. Case Study

A. Homboza Village

Homboza village is found within Pwani Region in Tanzania, East Africa. Homboza village is one among many non-electrified villages. Data collected up to July 2019 showed 171 households within the village. The population is around 5,500 according to Village Executive Officer (VEO). Less than 10% of that population is electrified. The distance from the isolation transformer to the center of the village, the load point is 20 km. Other data were collected on this 20 km source-to-load distance. Its distance from the grid, and dispersed nature of the load is what made it the choice for this study [18] with the aim to electrify it so that its economy can be boosted [19].

B. Simulation

In this paper, Aluminium Conductor Steel Reinforced (ACSR) conductor is selected for the SWER system due to its lowest unit resistance and largest cross-sectional area compared to other widely available conductors – Galvanised Steel (GS), Aluminium Steel Clad (ASC), which are shown in Table I. The Carson line model for the SWER is simulated in Matlab/Simulink 2013b, for which Fig. 3 shows the simulation display. The distribution transformers in Fig. 3 steps down voltage from 6.35 kV to 0.23 kV. The self-impedance of the overhead conductor, is computed to be $z_{bb} = (0.893 + j0.09398)\ \Omega/km$ using Equation (3). The self-impedance of the assumed ground return conductor is computed to be $z_{ee} = (0.0049 - j0.0122)\ \Omega/km$ using Equation (4). The mutual impedance between the overhead line and the earth return conductor is computed to be $z_{be} = j0.0017\ \Omega/km$ using Equation (5). The overall SWER line impedance is then computed as $Z_{bb} = (0.9040\angle 5°)\ \Omega/km$ by Equation (2).

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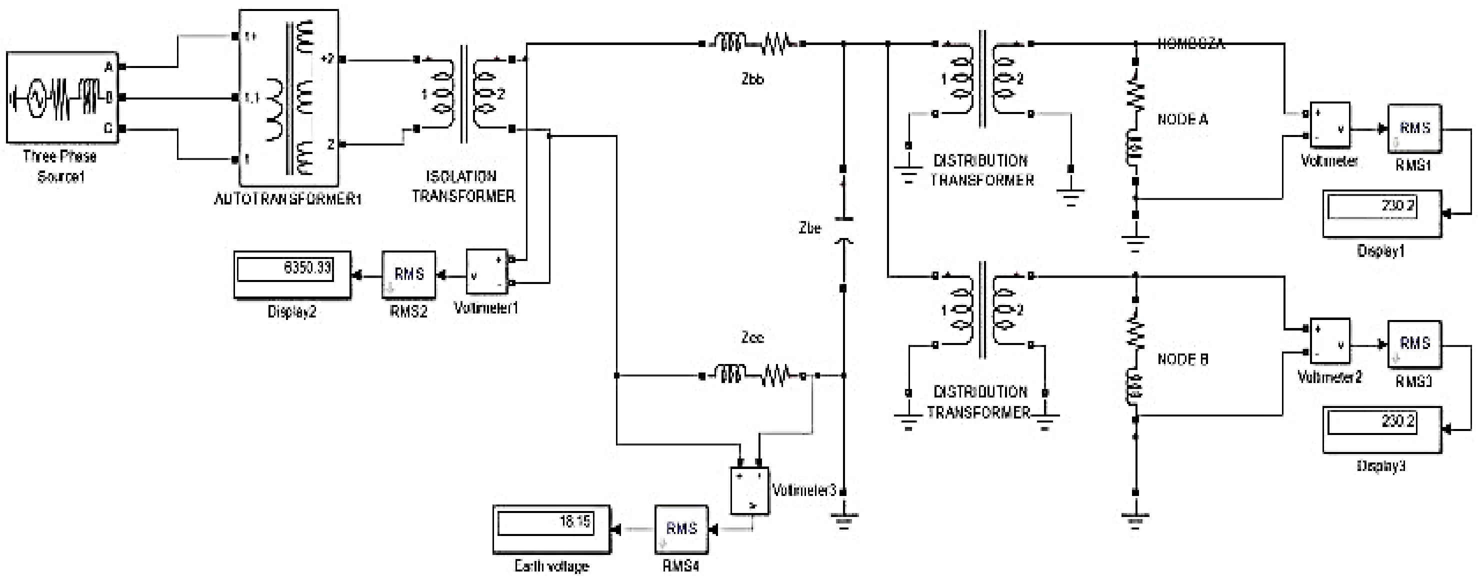

Figure 1. Configuration of SWER distribution system.

TABLE I. SWER CONDUCTORS AND THEIR PROPERTIES [2]

Conductor type	Overall diameter (mm)	Cross section area (mm^2)	Resistance (Ω/km)
GS	5.93	17.82	12.05
ACS	5.93	10.26	5.75
ACSR	9	49.48	0.893

These computed impedance values (z_{bb}, z_{be}, and z_{ee}) form input to SWER simulation model in Fig. 3. The simulation results, give an earth potential of 18.15 V. This earth potential is within the allowable safety limits of less than 30 V, the maximum earth potential for SWER feasibility. This earth potential could be measured across the ground electrodes. SWER application for the Homboza village is possible as the earth potential is within allowable and safe range.

V. TECHNO-ECONOMIC COMPARISON OF SWER VS. SPTW

This Section now compares SWER Vs. SPTW, because the latter has been the existing technology as of to date.

A. Economic Comparison

For SPTW, the pole spacing is 50 meters according to data from REA. This implies that 400 wooden poles are required for the 20 km to the village. On the other hand, SWER pole spacing is 80 meters, hence, 250 wooden poles are required [19]. These costs for SPTW and SWER 11 kV/0.23 kV distribution systems are tabulated in Table II and Table III respectively. Knowing the supply costs for both systems, benefit-cost (B_C) ratio comparison can be evaluated. The TANESCO as other utilities in other countries use the marginal B_C ratio to know if supplying an area with a certain Distribution network would be beneficial [20] – [21]. Currently, TANESCO is faced with low B_C ratio by implementing the SPTW system for rural electrification. With SWER application to the village, the B_C ratio to the power utility, TANESCO is improved. The B_C ratio can be calculated by Equation (7) where C_I is the investment cost and C_N is the number of customers connected.

$$B_C = \frac{C_I}{C_N} \tag{7}$$

TABLE II. SPTW COSTS FOR SUPPLYING HOMBOZA

Material	Unit Price (Tsh)	Quantity	Total Price (Tsh)
Wooden pole (9 m high)	267,500	400	107,000,000
Distribution transformer (100kVA, 11 kV/0.23 kV)	10,878,550	2	21,757,100
ACSR (50/25 sq.mm)	788,000	40	31,520,000
Pole-top assembly	34,000	400	13,600,000
Labour and transportation	121,500	Lumpsum	121,500
Total			**173,998,600**

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TABLE III. SWER COSTS FOR SUPPLYING HOMBOZA

Material	Unit Price (Tsh)	Quantity	Total Price (Tsh)
Wooden pole (9 m high)	267,500	250	66,875,000
Distribution transformer (100kVA, 11 kV/0.23 kV)	10,878,550	2	21,757,100
ACSR (50/25 sq.mm)	788,000	20	15,760,000
Pole-top assembly	20,000	250	5,000,000
Copper earth rod (4 ft)	49,450	4	197,800
Copper earth rod connector	2,575	4	10,300
Labour and transportation	121,500	Lumpsum	121,500
Total			**109,721,700**

From Table II and Table III, the C_I for the SPTW and SWER systems are 173,998,600 Tsh and 109,721,700 Tsh respectively. The C_N is 171 households as explained earlier in Section IV. Therefore, according to Equation (7), the B_C ratio to TANESCO for the proposed SWER system is a cost savings of 36.9% as compared to using SPTW. The connection costs per household comparison for SPTW and SWER is shown in Fig. 4. SPTW's connection cost is around 1,017,536 Tshs per household while that of SWER is about 641,648 Tshs per household. The SWER connection cost is 36.9% cheaper than that of the SPTW and this could help save the power utility a lot of expenditure, at the same time, make it easy for the villagers to buy the electricity provided to them by the utility. The SPTW system could connect 40 Homboza households. With the 36.9% cost savings, SWER would connect 55 households annually, an extra 15 households. The annual connection for both networks with similar investment cost is shown in Fig. 5

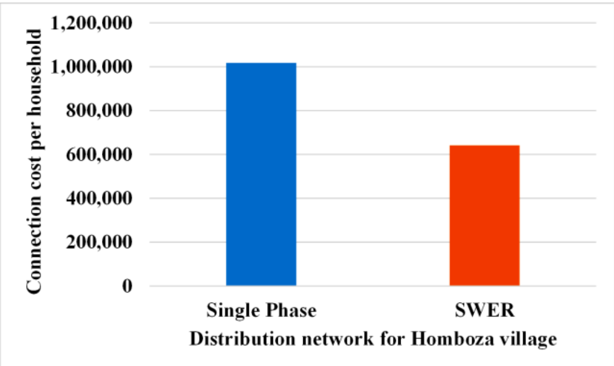

Fig. 4. Comparison of rural household connection costs between SPTW and SWER

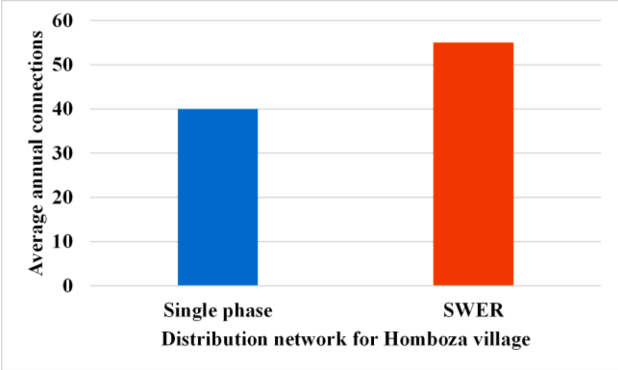

Fig. 5. Comparison of annual household connection between SPTW and SWER with similar investment.

B. *Technical Comparison*

Power loss and voltage drop for both SPTW and SWER distribution networks are calculated over the 20 km of distribution line. The per-unit (p.u.) voltage drops for SPTW and SWER are calculated by Equations (8) – (9) [22] – [23], where V is the operating voltage, x is the reactance per km, l is the power line length, r is the resistance per km, α is the load angle, ΔV is the voltage drop, P is the real power, V_{ph} is the single line to ground voltage, and the earth resistance is r_e. The SPTW and SWER per-unit power losses are computed by (10) – (11) according to [20], where ΔP is the power loss and I is the current flowing in SPTW/SWER line.

$$\frac{\Delta V}{V} = \frac{2Pl}{(V_{ph})^2}(r + x\tan\alpha) \tag{8}$$

$$\frac{\Delta V}{V} = \frac{Pl}{(V_{ph})^2}(r + r_e + x\tan\alpha) \tag{9}$$

$$\frac{\Delta P}{P} = \frac{2I^2 rl}{P\cos\alpha} \tag{10}$$

$$\frac{\Delta P}{P} = \frac{I^2(r + r_e)l}{P\cos\alpha} \tag{11}$$

Based on Equations (8) – (9), Fig. 6 is presented to show the per-unit voltage drop for both the SPTW and SWER networks for the 20 km line. Single wire earth return shows less voltage drop than SPTW. Based on (10) – (11), Fig. 7 is presented to show the per-unit power loss for both the SPTW and SWER for the 20 km line. SWER shows less power loss than SPTW.

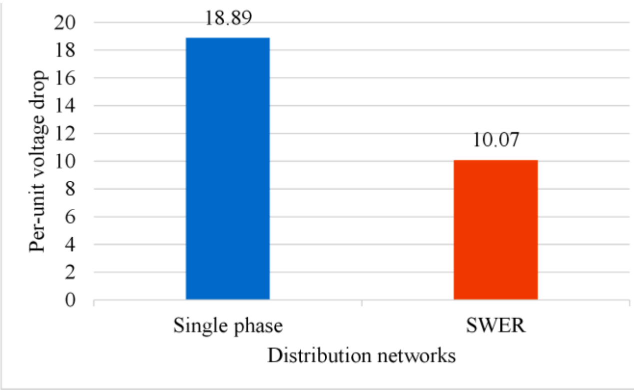

Fig. 6. Comparison of 20 km line voltage drop between SPTW and SWER.

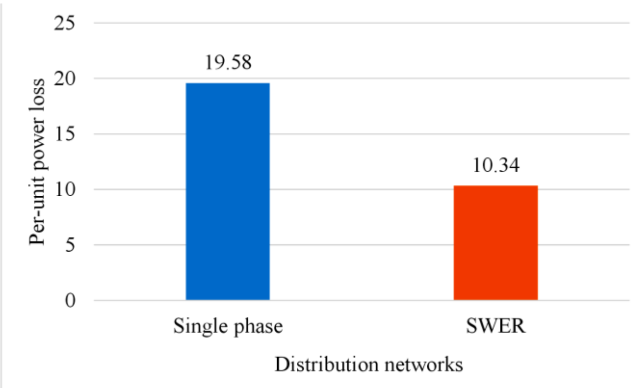

Fig. 7. Comparison of 20 km line power loss between SPTW and SWER.

VI. Conclusion

This paper proposed SWER implementation in the village of Homboza in Tanzania. Based on the simulation that displayed an earth potential of 18.15 V, the basic requirement for SWER implementation is fulfilled and it can be used for the Homboza village. SWER's power loss and voltage drop over 20 km of distribution line are 10.34 per unit and 10.07 per unit respectively. SPTW's power loss and voltage drop over 20 km of distribution line are 19.58 per unit and 18.89 per unit respectively. Technically, SWER is better than SPTW for the village electrification. The SWER B_C ratio to TANESCO shows a cost savings of 36.9% as compared to SPTW usage. The cost per household connection using SPTW network is 1,017,536 Tshs while the cost per household connection using SWER network is 641,648 Tshs. SWER distribution network application is advantageous for Homboza village inhabitants and the power utility.

Future researches should focus on load forecasting for rural communities, actual soil resistivity measurements, and optimal selection of components for the installation of the SWER system.

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References

[1] K. Prakash, A. Lallu, F. R. Islam, and K. A. Mamun, "Review of power system distribution network architecture," IEEE 2016 3rd Asia-Pacific World Congress on Computer Science and Engineering (APWC on CSE), pp. 124 – 130, 2016. DOI: 10.1109/APWC-on-CSE.2016.030.

[2] H. Ahlborg and L. Hammar, "Drivers and barriers to rural electrification in Tanzania and Mozambique: grid-extension, off-grid, and renewable energy sources," Elsevier Journal of Renewable Energy, 61, pp. 117 – 124, 2014. https://doi.org/10.1016/j.renene.2012.09.057

[3] IEA, IRENA, UNSD, WB, WHO, Tracking SDG 7: The Energy Progress Report 2019, Washington DC.

[4] I. O. Momoh, Y. Jibril, B. Jimoh, A. S. Abubakar, O. Ajayi, A. Abubakar, S. H. Sulaiman, and S. S. Yusuf, "Effect of an optimal conductor size selection scheme for single wire earth return power distribution networks for rural electrification," ATBU Journal of Science, Technology and Education, 7 (3), pp. 286 – 295, 2019. ISSN 2277-0011. Available at: http://www.atbuftejoste.com/index.php/joste/article/view/845. Date accessed: 14 Aug. 2020.

[5] D. Chattopadhyay, "Electrification of remote villages in Assam (India): issues and case studies," 2013 IEEE Power & Energy Society General Meeting, 2013. DOI: 10.1109/PESMG.2013.6672080.

[6] T. R. Brooking and N. J. V. Rensburg, "The improved utilisation of existing rural networks with the use of intermediate voltage and single wire earth return systems," IEEE 3D Africon Conference. Africon '92 Proceedings (Cat. No.92CH3215), pp. 228–234, 1992. DOI: 10.1109/AFRCON.1992.624461

[7] M. S. Nirere, C. M. Muriithi, and C. Wekesa, "Voltage profile improvement using switched capacitors: case of single wire earth return distribution network," International Journal of Modern Engineering Research (IJMER), 7 (2), pp. 78-85, 2017.

[8] L. Mandeno, "Rural power supply especially in back country areas," Wellington: New Zealand Institute of Engineers, 1947.

[9] M. C. Da Silva, P. M. Franca and P. D. B. Da Silveira, "Long-range planning of power distribution systems: secondary networks," Elsevier Journal of Computers and Electrical Engineering, 22(3), pp. 179 – 191, 1996. https://doi.org/10.1016/0045-7906(96)00001-8.

[10] B. Nkom, A. P. R. Taylor, and C. Baguley, "Narrowband modeling of single wire earth return distribution lines," IEEE Transactions on Power Delivery, 33(4), pp. 1565 – 1575, 2018. DOI: 10.1109/TPWRD.2017.2775189.

[11] R. M. Ciric, L. F. Ochoa, and A. Padilha, "Power flow in distribution networks with earth return," Elsevier Journal of Electrical Power and Energy Systems, 26(5), pp. 373–380, 2004. https://doi.org/10.1016/j.ijepes.2003.11.006.

[12] N. M. Solange, Design of a single wire earth return (SWER) power distribution system and improvement of its voltage profile using capacitors, M.Sc. Dissertation, 2017. Nairobi: Pan African University.

[13] N. Hosseinzadeh and S. Mastakov, "Load modeling for medium voltage SWER distribution networks," 2008 Australasian Universities Power Engineering Conference, 173, pp. 1 – 5, 2008.

[14] P. J. Wolfs, N. Hosseinzadeh, and S. T. Senini, "Capacity enhancement for aging single wire earth return distribution systems," 2007 IEEE Power Engineering Society General Meeting, pp. 2-4, 2007. DOI: 10.1109/PES.2007.385451.

[15] S. J. Mirazimiabarghouei, A. Ahfock and A. Helwig "Single wire earth return (SWER) system voltage support using four quadrant DSTATCOM." 2016 IEEE International Conference on Power and Energy (PECon), pp. 228 – 233, 2016. DOI: 10.1109/PECON.2016.7951564.

[16] J. R. Carson, "Wave propagation in overhead wires with earth return," The Bell System Technical Journal, 5(4), pp. 540 – 543, 1926. DOI: 10.1002/j.1538-7305.1926.tb00122.x.

[17] E. Nedi, H. Yuskel, D. Sagir, et al., "Feasibility of distributing electric power through single-phase transformers at rural regions of Turkey based on rural characteristic indices." 2017 IEEE Power and Energy Conference at Illinois (PECI), pp. 1 – 6, 2017. DOI:10.1109/PECI.2017.7935728.

[18] M. E. Irechukwu and A. T. Mushi, "Feasibility analysis of using SWER for Homboza village electrification," 6th International Conference in Mechanical and Industrial Engineering (MIE' 2020), pp. 1 – 9, 2020.

[19] M. E. Irechukwu, Feasibility analysis of using single wire earth return medium voltage distribution network for homboza village electrification, M. Sc. Dissertation, 2020. Dar es Salaam: University of Dar es Salaam.

[20] R. Ranjan, B. Venkatesh and D. Das, "A new algorithm for power distribution planning," Elsevier Journal of Electric Power Systems Research, 62(1), pp. 55 – 65, 2002. https://doi.org/10.1016/S0378-7796(02)00044-5.

[21] R. Song, S. Lu, T. Sirojan, et al., "Power quality monitoring of single-wire-earth-return distribution feeders," 2017 International Conference on High Voltage Engineering and Power Systems (ICHVEPS), pp. 404 – 409, 2017. DOI: 10.1109/ICHVEPS.2017.8225879.

[22] C. Ratnayake, "Low cost grid electrification technologies: a handbook for electrification practitioners," EU Energy Initiative, 2015.

[23] K. Qian, C. Zhou, M. Allan and Y. Yuan, "Effect of load models on assessment of energy losses in distributed generation planning," Elsevier Journal of Electrical Power and Energy Systems, 33(6), pp. 1243 – 1250, 2011. https://doi.org/10.1016/j.ijepes.2011.04.003.