

# Feasibility analysis of single wire earth return system for potential application in rural electrification in Nigeria

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## ABSTRACT

Traditionally, three-phase networks are used to transmit electric power to consumers. However, due to its high initial cost, many isolated rural communities are yet to have access to electricity. Thus, the single wire earth return (SWER) architecture, which uses the earth as the return path, attracts significant cost savings. In this paper, the potential application of the SWER system for rural electrification in Nigeria was presented. The cost-effectiveness of the SWER system which is about 70% less than the three-phase configuration, is due to the need for fewer cables, pole-top fittings, switching, and protection devices. Initially, the dynamic modeling of the equivalent SWER system was derived for the MATLAB simulation analysis. The pertinent parameters of the realized system, namely, micro-former leakage reactance, the resistive and inductive value of the single-phase network, were determined and employed for the SIMULINK and the repetitive power flow analyses. The results obtained from the power flow analysis and the simulation models for different loading conditions were found to agree with an error margin of +5%. This demonstrates that the proposed prototype can be adopted to reduce the prevalent energy poverty and thereby improved the quality of life of rural dwellers in Nigeria.

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## 1. INTRODUCTION

Nowadays, our basic social amenities, including schools, hospitals, security, and industries, which help create and sustain wealth, depend much on the supply of uninterrupted electric power from the national grids [1]–[3]. Interestingly, the global electrification rate has been witnessing good progress of an annual rate of 0.8% from 2010 to 2017, representing an increase of 83% to 89%, respectively. Thus, if the rate remains stable as the record witnessed between 2015 and 2019, the universal projected access could be achieved by 2030 [4]. However, despite the promising achievements, electrification in rural communities, particularly in sub-Saharan Africa, has been afflicted with numerous challenges which makes it difficult for the rural communities to access electric power [5]. One of these challenges includes the high cost of power transmission from the grid to isolated rural areas. Also, due to the limited power consumption in these areas, the distribution companies (DISCOs) find gaining profit very challenging as a result of the consumers' meager incomes [6]. Thus, electric power supply to small communities in isolated areas, using the traditional

3-wire 3-phase medium voltage (MV)/4-wire low voltage (LV) distribution technique, is not cost-effective. Hence, a single-phase 2-wire MV technique is by far more cost-effective [7]. However, a cheaper distribution network scheme of supplying electric power to rural and scanty settlements can be achieved by using the single wire earth return (SWER) distribution scheme that requires just a single aerial conductor on the MV grid part [8]. Conversely, single-phase schemes, SWER schemes, in particular, are not widely used in parts of the African continent despite economic efficacy.

SWER was initially proposed in the 1940s by New Zealand's electrical engineer Lloyd Mandeno and developed in New Zealand for a rural electrification scheme [9]. SWER is usually employed in an area with a sparse population and can be integrated to support the existing power generation [10]. The SWER network topology is shown in Figure 1. A single conductor is used to convey electrical energy at medium voltage (2.4 kV) between sending and receiving end distribution transformers, which are solidly grounded to the earth. Herein, the earth mass provides a return path for the current flowing in the single conductor to return to the supply source. SWER network has possessed many advantages like its simplicity in design that allow the use of a single wire to be struck, low initial capital cost unlike the conventional three-phase concepts, and reduced maintenance cost [11].

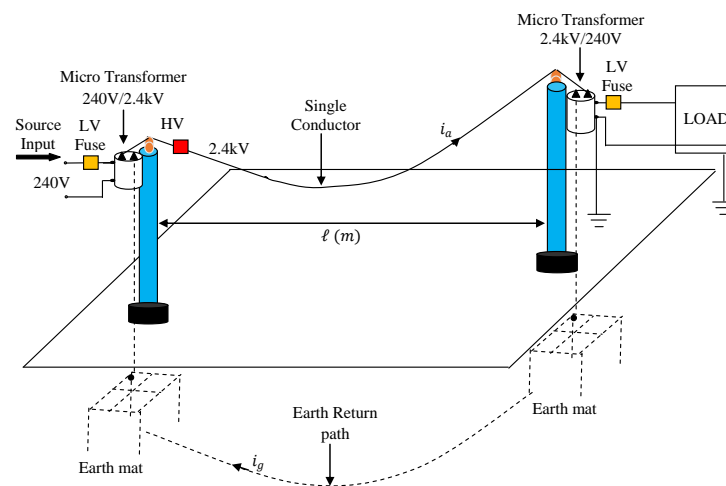


Figure 1. The 3D sketch of the SWER prototype distribution system, where a single conductor is used to convey electrical energy at medium voltage (2.4 kV) using the mini pole-mounted micro-transformers to consumers

Although the SWER system has several advantages, it is also associated with some setbacks. Lima and De Conti [12] discuss the issue of earth grounding characteristics and it is worth noting that frequency-dependent soil parameters decrease the attenuation of the signal in the high-frequency range. Fernandes *et al.* [13] discussed this issue and suggests the need for exploiting the power line communication (PLC) channel as a solution that offers reliability and better communication scrutiny over the power grid scenario. In a SWER system, earthen electrodes play a vital role, and its failure could cause a cascading effect that may lead to severe damage or poles catching fire. Thus some measures were proposed to prevent the wooden pole from catching fire, especially during drought season in [14]. Besides, the SWER system needs characterization of high-frequency earth path, this is worth noting that the use of analytical terminologies in estimating earth paths' high-frequency characteristics may lead to erroneous outcomes [11], and hence the use of a hybrid method of empirical-analytical characterization provides better results.

Jarrett *et al.* [15] investigated the problem of voltage regulation and suggests the use of voltage support equipment using four quadrants distribution static compensators (DSTATCOMs). The study was supported by [16] and further revealed that setting the DSTATCOM to run on an optimum operating point will deliver maximum voltage level support during heavy load scenarios. The compatibility issue of three-phase supply in the SWER system was discussed and many solutions were proposed in [17]. Also, Hosseinzadeh *et al.* [8] presented an economic balancing structure for balancing improvement in the three-phase feeder, which has been implemented in Queensland Australia. Besides, the application was also discussed in [18], which signifies that the use of a unified power quality conditioner (UPQC) topology of single-phase to three-phase technology would repress grid voltage harmonics, and deals with voltage sagging for good power factor.

Moreover, as a cost-effective power delivery system for rural communities, the SWER system can be installed in an area with no existing grid system or as an add-on for sharing generated power [19] and has been in use in several developed countries long ago. Thus, considering the economic hardship and nature of dispersing settlements found in Africa, the use of the SWER distribution system is long overdue. This was also pointed out by Nkom *et al.* [20], who carried out a financial survey and compared a normal three-wire distribution with a SWER grid of Tuhua, New Zealand. The work highlights the need for accelerated large-scale use of the SWER system in Africa through the implementation of monitoring policies used by the existing users.

To the best of our knowledge, the SWER system has not been deployed in Nigeria for rural electrification schemes. Thus, this research investigates the significance of rural community electricity development via a cost-effective SWER system for possible application in Nigeria's rural communities. The prime goal is to reduce the prevalent energy poverty and thereby improve the quality of life of rural dwellers. The study is expected to serve as a pioneer stage that will pave the way for a total overhaul in rural electric access. In the succeeding sections, the mathematical modelling and the corresponding MATLAB simulation analysis were presented. The micro-former was designed and constructed as a substitute for an isolating transformer and the aluminium conductor coupled with the safety and protection requirements were used in a single-phase conductor. Results for both field power flow analysis and the simulation measurements were found to be correlated and fluctuate within an error of 5%. The remainder of the paper is organized as follows. Section 2 discusses the description and development of the model SWER prototype. Section 3 discusses the simulation results while the concluding remark was introduced in section 4.

## 2. DESCRIPTION AND DEVELOPMENT OF THE MODEL SWER PROTOTYPE

The equivalent circuit diagram of the SWER system is shown in Figure 2, where the mathematical model of the SWER distribution network is based on a unit length of a single conductor, placed above earth surface and carrying current with return path through the ground. As described in [19] the earth return is represented as a single conductor buried under the earth's surface with a 1.0 m geometric mean radius (GMR) having uniform resistivity and of infinite length. However, the geometric mean distance (GMD) between the overhead conductor and the earth return path is assumed to be a function of the soil resistivity,  $\rho$ , with the self-impedance per unit meter length of the single overhead conductor,  $Z_{aa}$  given in (1). The self-impedance,  $Z_{gg}$  of the earth return conductor, and mutual impedance,  $Z_{ag}$  between the overhead and earth return conductors, are represented in (2) and (3), respectively.

$$Z_{aa} = R_a + j4\pi 10^{-7} \ln \left( \frac{2(h_a + p)}{GMR} \right) \Omega m^{-1} \quad (1)$$

$$Z_{gg} = \pi^2 10^{-7} f - j0.0386f(8\pi 10^{-7}) + j4\pi f \times 10^{-7} \ln \left( \frac{2}{5.1698 \times 10^{-3}} \right) \Omega m^{-1} \quad (2)$$

$$Z_{ag} = j2\pi \times 10^{-7} \ln \left( \frac{h_a}{\sqrt{\frac{\rho}{f}}} \right) \Omega m^{-1} \quad (3)$$

The functional block diagram of the SWER prototype system is illustrated in Figure 3. As shown, it provides a conceptual framework for the development of the SWER SIMULINK model in a MATLAB environment. The imperative for the development of this model is to provide a simulation tool for the validation of experimental results on the prototype SWER demonstration unit. To realize the simulation task, Figure 4 depicts the complete block diagram of the model in the SIMULINK environment. A cursory look at the SWER model reveals that the source input is modelled as a constant voltage source to emulate power supply from either grid or micro-grid for a 240 V fixed voltage. The micro-grid is used as the power supply from an isolated generating set or a photovoltaic (PV) based system with a matching inverter system of appropriate rating. The SWER prototype model has adequately modelled the sending and receiving end micro-formers as a step-up with rated voltages of 240 V/2.4 kV and step-down with rated voltages of 2.4 kV/240 V, respectively. As previously highlighted, the main parameters comprising of leakage and core loss impedances for the micro-formers are determined from their respective short and open circuit tests. The single overhead conductor and earth return path subsystem is modelled as a short line by neglecting the shunt capacitances. The conductor and earth return path network parameters were determined according to (1) to (3). Finally, the load subsystem is modelled as constant power at a specified power factor.

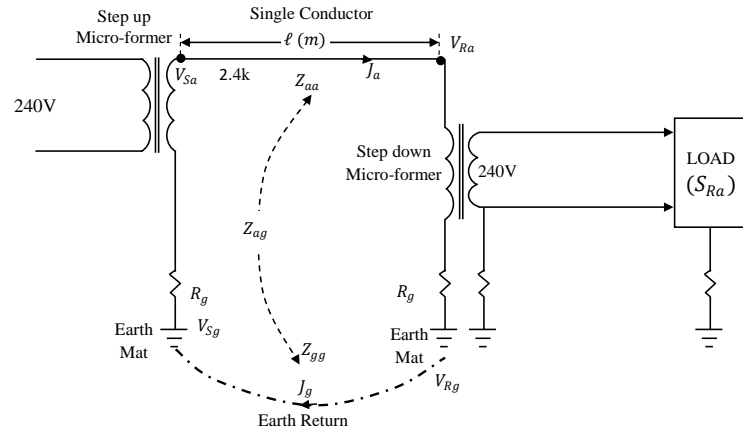


Figure 2. Schematic representation of prototype SWER-network circuit equivalent

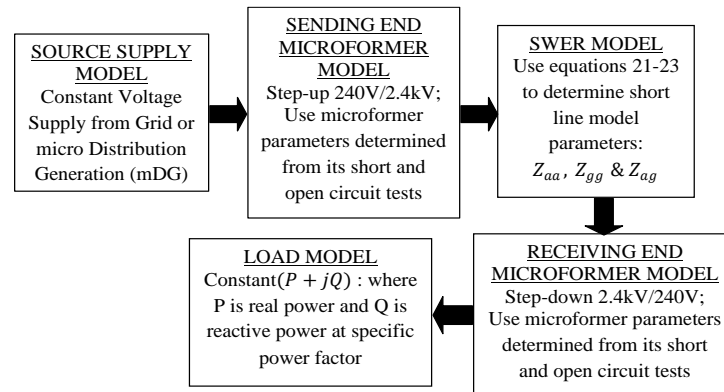


Figure 3. Functional block diagram for prototype SWER model

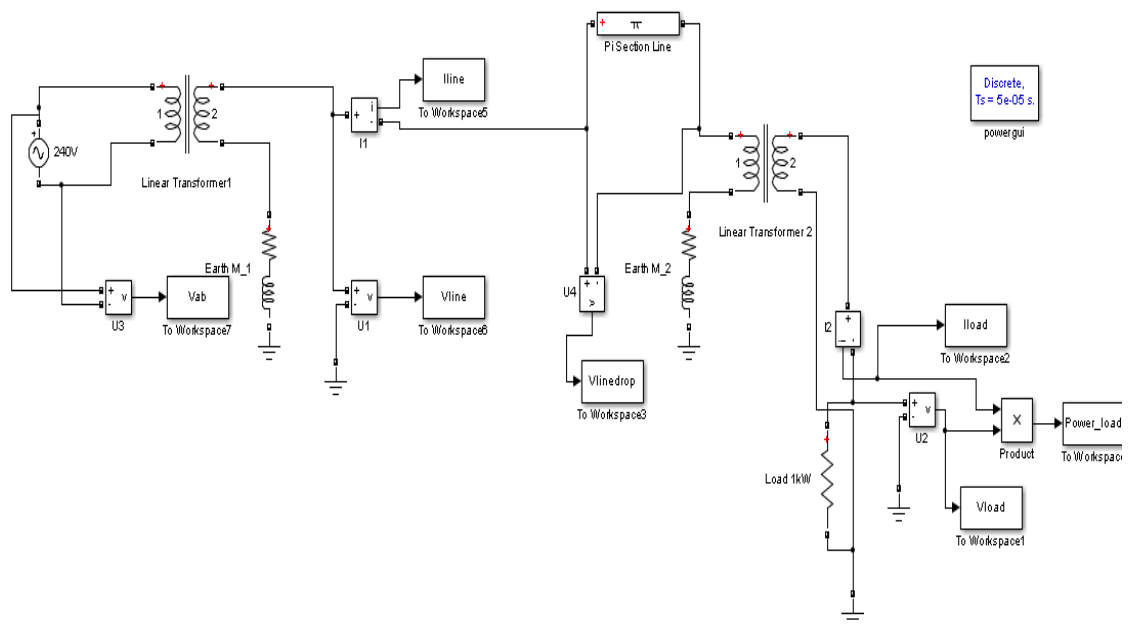


Figure 4. SIMULINK model of the SWER system

### 3. RESULTS AND DISCUSSION

#### 3.1. Results of micro-former and conductor modelling parameter determinations

The modelling parameters of micro-formers and the conductor presented in Table 1 were determined by the established procedure in the literature using 1 kVA and 2.4 kV as base quantities. The open and short circuit tests carried out on the micro-formers yielded their equivalent circuits referred to the LT side of each micro-former. The sending- and receiving-end micro-former losses have been estimated to be 4.9% and 5% respectively based on a 1 kVA rating. The conductor resistance and reactance for the span length of 27 m used are more or less in the same range as each micro-former series resistance and leakage reactance. Of course, in practical SWER, the total conductor length could easily exceed 50 km with significantly higher resistance and reactance than the equivalent series impedance of the matching isolation transformers. Thus, the parameters provided in Table 1 are central to accurate modelling of the prototype SWER in MATLAB/SIMULINK environment.

Table 1. Computed equivalent parameters

	Parameter	Symbol	Ohms ( $\Omega$ ) (Referred to LT side)	Per unit (pu)
Sending end	Leakage reactance	$X_{l1}$	4.75	0.19
	Total winding resistance	$R_{a1}$	1.07	0.045
	Core loss Shunt resistance	$R_{o1}$	1010.7	4.24
	Magnetizing reactance	$X_{m1}$	246.7	10.8
Receiving end	Leakage reactance	32.5	5.13	0.21
	Total winding resistance	33	0.95	0.04
	Core loss Shunt resistance	34.5	960.0	4.0
	Magnetizing reactance	33.5	128.5	5.35
Overhead conductor and earth	Conductor self-impedance	$Z_{aa}$	$0.047+j0.026$	$0.20+j0.11$

#### 3.2. Results of steady-state analysis and MATLAB simulation of prototype SWER unit

The prototype SWER model was implemented in MATLAB/SIMULINK environment based on its relevant previously generated data. The complete SIMULINK model depicted in Figure 4 was implemented using the MATLAB® application. The prime goal is to analyze the measurements on prototype SWER, more specifically, in respect of its load voltage, line current and load current as a function of load size and power factor. The steady-state analysis of the prototype SWER has been carried out with reliance on the power flow analysis of its equivalent circuit of Figure 2. With the slack bus voltage set at 1.0 pu, several power flow solutions were carried out at different loading conditions. More specifically, the load at receiving end of the prototype SWER was varied at a discrete step of 0.1 pu between 0.1 pu and 1 pu concatenated with power factor varied between 0.8 lagging and 1 at the incremental step of 0.025. The preceding gave rise to 90 power flow solutions. Of prime interest is the variation of load voltage profile as a function of the load size and power factor. The parametric variations of load voltage, obtained from multiple power flow solutions that admitted discrete step variation in SWER load concatenated with discrete variation in power factor, resulting in a 3D plot of Figure 5. The 3D column plots of voltage profiles at specific power factors exhibited full load voltage regulations between 16.2% and 25.7% which are approximately 5% lower than the values obtained from the experimental measurements.

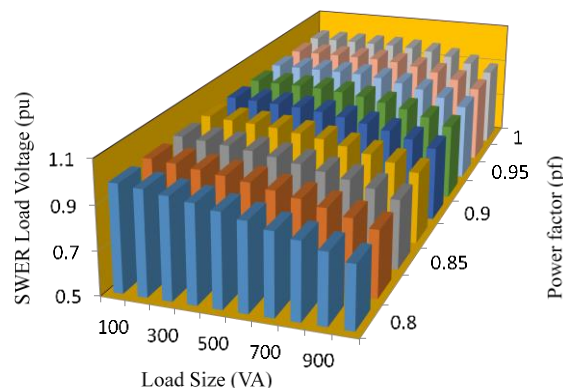


Figure 5. 3D column plots of SWER load voltages for different load sizes and lagging power factors via multiple power flow solutions

Figure 6 depicts the parametric plots of load voltage profile versus load size for some selected power factors. Observe again that for a given power factor, SWER load voltage variation against load size is evident. The voltage variation is quite appreciable for the lagging power factor and the unity power factor exhibit the least voltage variation. Figure 7 offers a graphical comparison of SWER load voltages obtained via power flow solution and field measurements on the prototype SWER rig energized from the grid supply with the load maintained at the unity power factor. The computed root mean squared error (RMSE) between the two graphs returned 2.91% and was adjudged to be quite satisfactory.

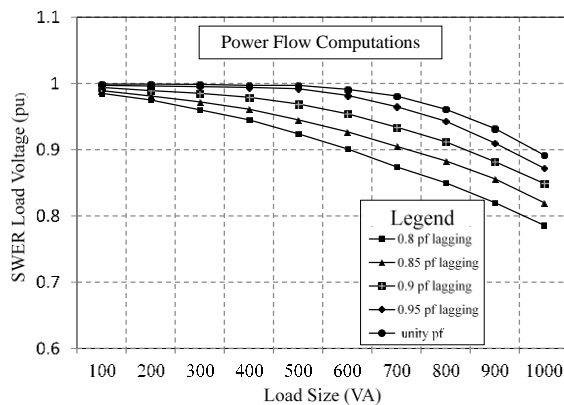


Figure 6. SWER load voltage versus load size for some selected lagging power factors

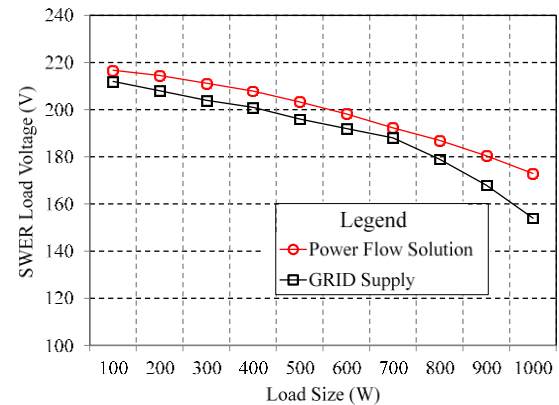


Figure 7. Comparison of SWER load voltage profile from power flow solution and GRID supply with load maintained at a unity power factor

Furthermore, the similarity between Figure 5 and Figure 8 is to be expected as the two simulation approaches made use of the same databases. However, in Figure 8, the computations of their respective full load voltage regulations lie between 14.5% and 23.5%. Note that the preceding range is slightly different from the range returned for the steady-state power flow solution method which is attributable to the solution methodology of SIMULINK software. Figure 9 and Figure 10 are essentially simulated SWER load voltage and conductor current obtained from its SIMULINK model compared with their corresponding experimental measurements carried out on the prototype SWER unit fed from the grid. The computed root-mean-square error (RMSE) that characterizes the dispersion between the simulated and measured load voltages of Figure 9 is 4.5%. In the case of the simulated and measured conductor currents compared in Figure 10, we have computed RMSE as a measure of dispersion between them to be 3.5%. It is noteworthy that RMSEs computed have satisfactorily validated the accuracy of the simulation models developed.

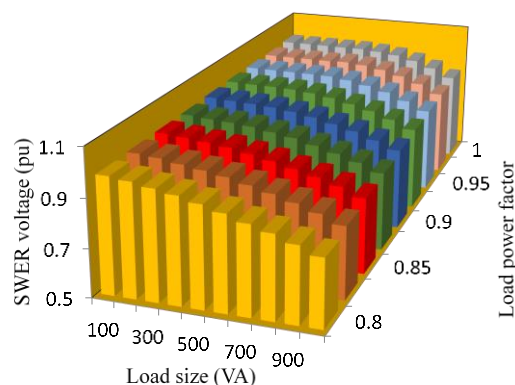


Figure 8. 3D column plots of SWER load voltages for different load sizes and lagging power factors via SIMULINK model simulation

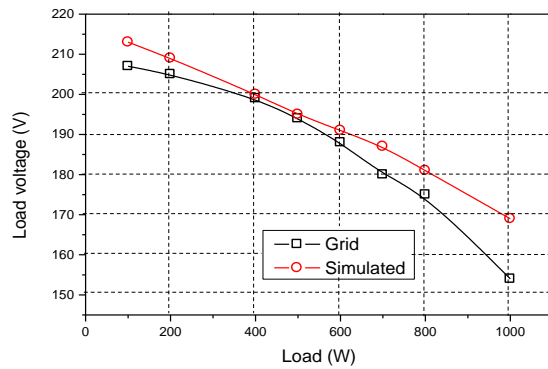


Figure 9. Comparison of SWER load voltage profile from MATLAB/SIMULINK simulation and grid supply with load maintained at a unity power factor

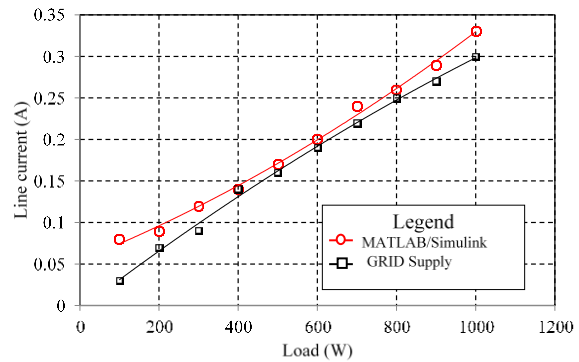


Figure 10. Comparison of SWER current flow from MATLAB/SIMULINK simulation and grid supply with load maintained at a unity power factor

Finally, Table 2 provides, at a glance, the results obtained from field measurements and simulation of the prototype SWER test rig delivering electricity to a unity power factor load bank. The significance of this table is to facilitate the comparative evaluation of experimental measurements with the simulation results. It can be verified that the results of the simulation results are within  $\pm 5\%$  error margins of their corresponding experimental measurement results.

Table 2. Comparison of simulation and power flow analyses

Load at 0.8 lagging PF (VA)	MATLAB/SIMULINK				Power flow analysis			
	$V_{LOAD}$ (V)	$I_{LOAD}$ (A)	$I_{COND}$ (A)	$P_{LOSS}$ (W)	$V_{LOAD}$ (V)	$I_{LOAD}$ (A)	$I_{COND}$ (A)	$P_{LOSS}$ (W)
100	212	0.28	0.03	2.1	209	0.24	0.04	1.9
200	207	0.66	0.05	4.6	205	0.67	0.06	4.2
300	205	0.91	0.12	10.6	203	0.96	0.10	9.4
400	203	1.32	0.14	15.2	201	1.26	0.14	14.2
500	198	1.69	0.17	18.6	196	1.64	0.16	17.9
600	188	2.05	0.20	24.1	185	1.98	0.19	23.2
700	184	2.28	0.24	30.4	181	2.15	0.22	28.2
800	173	2.55	0.26	35.1	171	2.32	0.25	32.2
900	167	2.97	0.29	39.2	165	2.53	0.27	37.2
1000	163	3.1	0.33	55.1	161	2.75	0.30	52.4

#### 4. CONCLUSION

The main objective of this work was to develop a low-cost SWER prototype as an alternative to the expensive three-phase network for rural electrification. Thus, a MATLAB simulation analysis was conducted to investigate the possible application of SWER in Nigeria. The pertinent parameters of the realized system, namely, micro-former leakage reactance, the resistive and inductive value of the single-phase network, were determined and employed for the SIMULINK and the repetitive power flow analyses. The results obtained from the power flow analysis and the simulation models for different loading conditions were found to agree with an error margin of  $\pm 5\%$ . Finally, it is concluded that based on this analysis, the developed prototype SWER can be adopted for the supply of electricity to several clustered rural settlements in Nigeria.

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